

ADVANCES IN PROCESSING TECHNOLOGY OF FLAT STEEL PRODUCTS (APT-FS 2024)



Editors:

Santosh Kumar | P.S. Rahul
Gadadhar Sahoo | B. Sunita Minz
D.K. Saxena | Manohar Lal



Advances in Processing Technology of Flat Steel Products

(APT-FS 2024)



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The Indian Institute of Metals
Bokaro Chapter

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Advances in Processing Technologies of Flat Steel

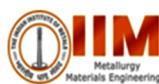
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Editors

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Preface

Over the past twenty years, the flat-steel production industry has achieved remarkable success through the adoption of new technologies and advancements in both hot and cold steel-rolling processes. These innovations have led to significantly lower production costs and enhanced product quality. Recent industry consolidation has further facilitated the sharing of technological breakthroughs between plants, creating an ideal environment for implementing these advancements.

The advancements in steel technology like automation & robotics application, IoT sensors, innovation in data analytics & simulation, eco-friendly surface treatment and coating technology, instrumentation and control required for quality assurance, sustainable design techniques are encouraging the plant engineers in association with researchers, scientists and academicians to constantly look for ways to optimize its potential and minimize its negative impact on environment. With innovations like hydrogen-based steelmaking and carbon capture technology, the steel industry is working towards reducing its carbon footprint. These developments are supporting steel fraternity to optimize their manufacturing processes, enhance efficiency, decrease waste, and enhance sustainability.

The industry's progress is thoroughly examined in "Advances in Processing Technology of Flat Steel Product" which compiles insights from more than 30 industrial and academic experts in steel production technology and flat steel product manufacturing. This assessment highlights the challenges and recent solutions in four key areas:

- Advances in processing Technologies in Steel Making, Secondary Refining and Continuous slab Casting
- New concept of Hot Rolling and Cold Rolling of High Strength Steel
- Quality Control and Material Characterization
- Advances in Coating Technology
- Energy and Environment Control in Steel Plant

As technology continues to advance, the flat steel industry will likely see further innovations that enhance product quality, efficiency, and sustainability. The ongoing evolution of flat steel products reflect their critical role in modern industry and their impact on society at large.

Offering expert analysis on technological progress, this book provides valuable insights into the current state of flat steel production, its evolution, and future prospects.

Team of Editors

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SECTION-I
**Steel Making, Secondary Refining
and Continuous Casting**

Detection and Analysis of Clogging in a Submerged Entry Nozzle Using Deep Learning

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ABSTRACT: *In the continuous casting process, the flow of steel from tundish to the mould is critical and is regulated by a submerged entry nozzle which has a tendency to get choked i.e. clogging due to a buildup on the refractory surface, which can have implications on the productivity due to process interruption, steel quality and aggravate the % of product rejections downstream.*

The problem statement identified was to detect clogging which was challenging. Clogging is typically defined through a deviation in stopper rod position and mould level. However, stopper rod position rise can be attributed to events other than clogging. What cannot be identified, cannot be quantified. And, what cannot be quantified, cannot be controlled. Clogging needs to be controlled as it affects both production and productivity downstream. Preliminary analysis was done to identify percentage of missing values and identification of the repetitive event which best captures clogging. Qualitative analysis was done to establish clogging in terms of sensitivity analysis on lead parameters and unique identifiers of clogging. Quantitative analysis on clogging characteristics in terms of stopper rise and fall (using moving mean) and their delineations to quantify degree of clogging. Qualitative identification of clogging was challenging leading to the requirement of a Machine Learning model for better classification. Classification required delineation of good and bad data (using moving standard deviation) in order to train the model.

A deep learning model (LSTM – Long Short-Term Memory) was successful in establishing superior model performance of accuracy, precision, recall and F1 score above 0.9. The hyperparameters considered and their impact on the final model performance were also documented. The model is used for root cause analysis in identifying the factors leading to clogging and dynamic intimation to the operator for corrective action within a single cast itself. This led to a combined savings of 3.5 Cr because it also helped in giving a probabilistic likelihood of sliver downstream which impacts product rejections.

Keywords: Deep Learning, Clogging, Submerged Entry Nozzle.

1. INTRODUCTION

Clogging [1] has been a perennial source of trouble ever since the continuous casting

process has existed. In Tata Steel, we have 6 blast furnaces generating hot metal for three LD shops which then cater to long and flat

products. The outsourcing is then managed by a planning team in conjunction with marketing and sales and outbound logistics. This work is concerned with LD2 and Caster A in Tata Steel. Last sample analysis is done prior to casting. In catering to the customer requirements we have the RH [2], OLP [3] and Desulphurisation [4] processes as well.

Identifying clogging graphically can be challenging. Stopper rod position rise can be attributed to events other than clogging. What cannot be identified, cannot be quantified. And, what cannot be quantified, cannot be controlled. Clogging needs to be controlled as it affects both production and productivity downstream.

The primary objective of the project is to detect clogging through classification in

machine learning. The theoretical criteria for clogging are a) mold fluctuation after clogging (during flushing) b) Stopper rise during clogging at constant casting speed and c) Steep drop in stopper position at the end of clogging. The variables needed to establish clogging are stopper position, casting speed, mould level and tundish change.

2. PRELIMINARY ANALYSIS

Data was analysed shift wise (770 records) and day-wise (8000 records). Data is at a 5 sec frequency. Standardised plots used to check for initiation of clogging, missing values analysis, change in stopper position and mould level fluctuation as target variable, as well as identification of repetitive event. Figure 1 contains the

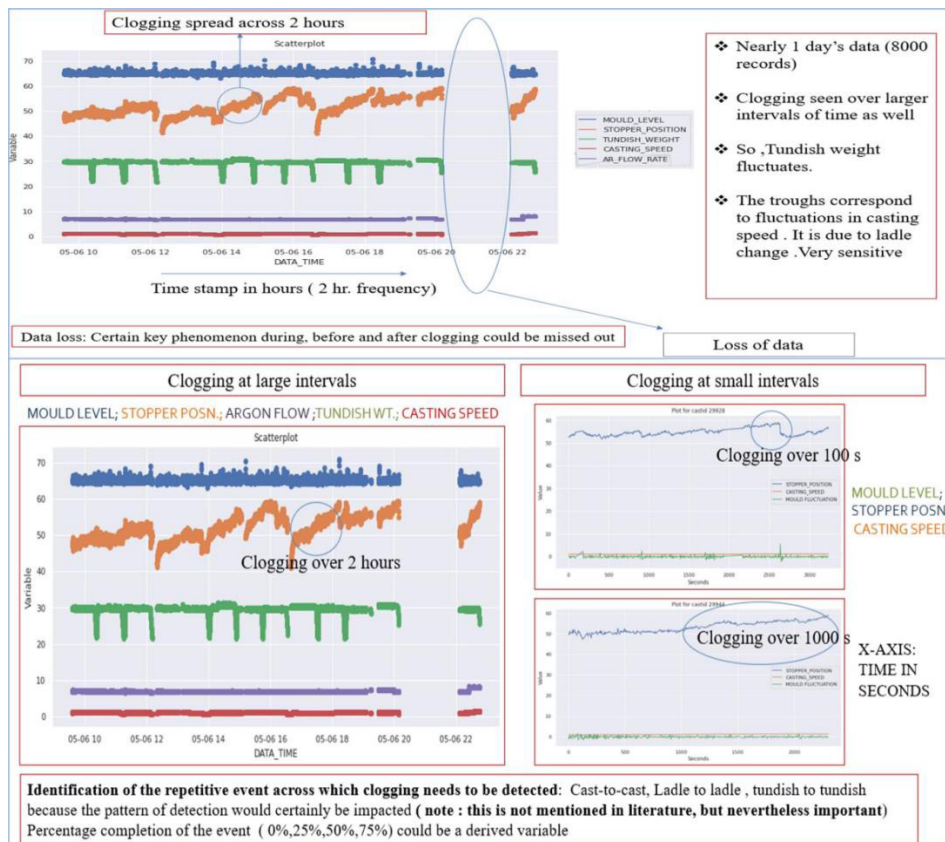


Figure 1: Preliminary Analysis on the % of Missing Values, Frequency of Clogging and the Identification of the Repetitive Event to Capture Clogging

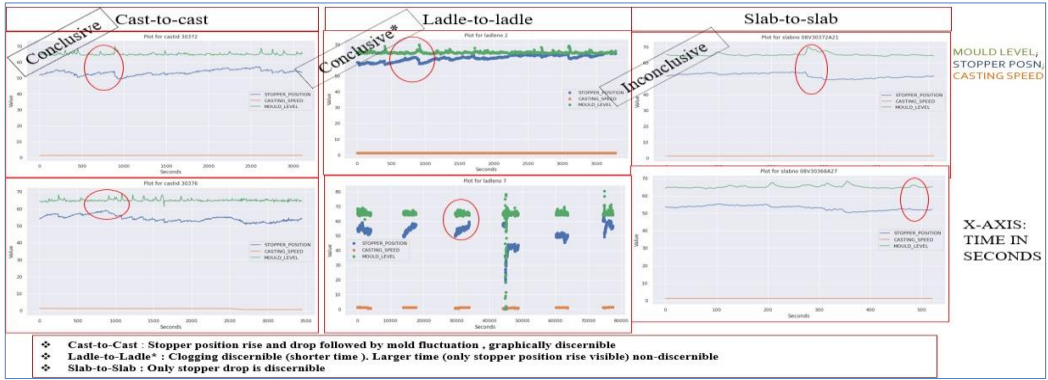


Figure 2: Identification of the Repetitive Event

preliminary analysis which was done to identify percentage of missing values. Missing values in all variables to the tune of 2–4 hours in Google Cloud platform on certain days, but only 0.2% missing data in the Level2 database, which was hence considered. Level 2 database is also stored on Google Cloud but has a retention capacity of memory storage for at a certain level of data granularity. The axis for multivariate plots corresponds to mould level, stopper position, tundish weight, casting speed and Argon flow

rate on y-axis. X-axis corresponds to time for all the plots. Figure 2. shows the identification of the repetitive event. Clogging was the most discernible on a cast-to-cast basis.

3. ESTABLISHING CLOGGING

A 3 days analysis (51000 records) on clogging sensitivity, unique identifiers of clogging and mould level patterns was done to establish clogging. Figure 3 contains the qualitative analysis done to establish clogging in terms

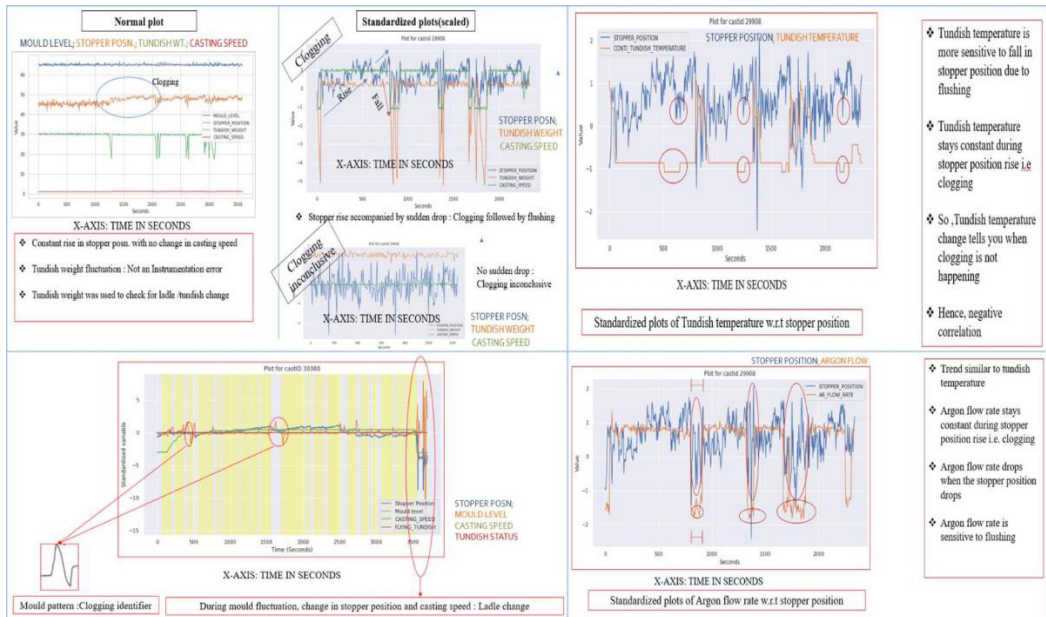


Figure 3: Establishing Clogging Qualitatively Through Sensitivity Analysis on Lead Parameters and Unique Clogging Identifiers

of sensitivity analysis on lead parameters and unique identifiers of clogging. Argon flow and tundish temperature are observed to be sensitive to flushing. It was observed that mould level fluctuations almost always correspond to drop in stopper position with no time-lag between these 2 events. The steeper the drop in stopper position, the larger the mould fluctuation. The mould fluctuation showed remarkable sensitivity to stopper position drop because even smaller peaks were picked up. Certain unique patterns in the mould level unique to clogging have been captured and indicated.

3. ANALYSIS ON CLOGGING CHARACTERISTICS

A 3 days analysis (51000 records) on sensitivity of parameters to clogging, analysis on clogging and flushing and mould patterns. Figure 4 contains quantitative analysis on

clogging characteristics in terms of stopper rise and fall (using moving mean) and their delineations to help in quantifying degree of clogging. The conclusions from the above figure a) We were able to identify the mould peaks (from noise) using rolling standard deviation b) Successfully able to capture the clogging event (using rolling mean) graphically and analytically (shaded regions) to uniquely identify those regions c) End of clogging (flushing) acts as a unique identifier d) The parameters (Start and end time; Start and end position of stopper; Start and end position of mould level) could potentially help in capturing the degree of clogging e) The correlation between lead parameters : casting speed change can also cause change in mould level fluctuations f) Simple rules cannot completely classify clogging. So model building (classification) is required (i.e. bad data/good data delineation).

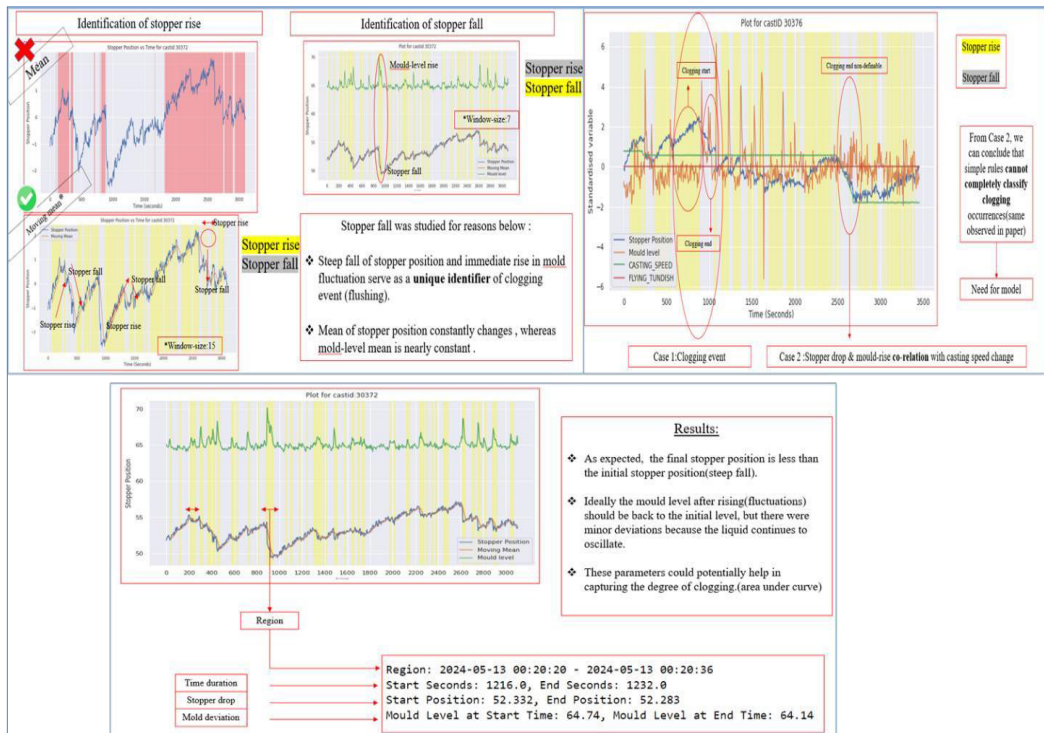


Figure 4: Establishing Clogging Quantitatively Through Stopper Rise and Fall and Curve Characteristics

4. DELINEATION OF BAD AND GOOD DATA

An 18-day analysis (3 lakh records) was done to develop an understanding of clogging and non-clogging classes. Figure 5 shows why qualitative identification of clogging was challenging leading to the requirement of a Machine Learning model for better classification. Classification required delineation of good and bad data (using moving standard deviation) to train the model. It was also observed that the ‘good data’ that is sliver-free still exhibits tendency for clogging.

Establishing the end of bad data was challenging and we have considered hereto as the start of good data. Good data (non-clogging), as per analysis is defined as the region where rolling standard deviation is near zero. These regions tend to be observed at the near beginning of a ladle change. This also indicates that the clogging nearly begins at the casting end and non-casting parameters either do not have a significant role or they play a delayed role as far as clogging is concerned. We have also observed that there are no early indicators of clogging.



Figure 5: Delineation of Bad and Good Data

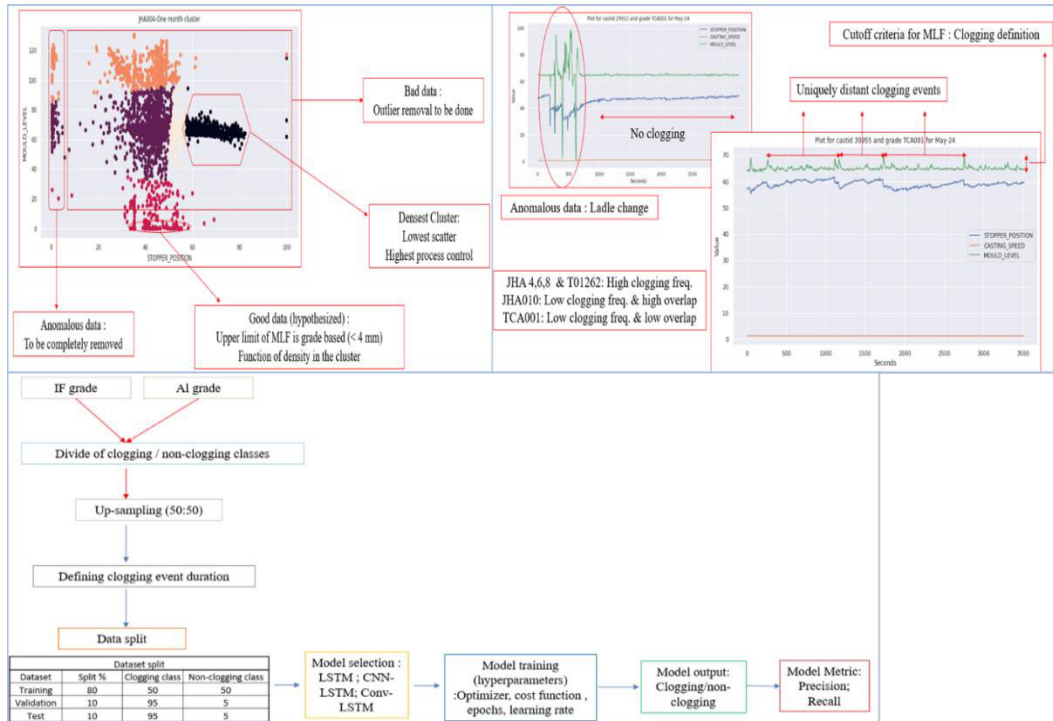


Figure 6: Approach to Model Building

5. MODEL BUILDING

A 9-month data (2 Crore+ records) has been used to develop a deep learning[5] model (Long Short-Term Memory) for a certain grade TCA001. Figure 6 captures the modeling approach adopted. Analysis was done on 6 different steel grades to check for clogging frequency and overlap. The conclusions based on the analysis are stated as follows :a) Able to find regions of anomalous data (Stopper position =0, mould level> 0) which are outliers b) Able to delineate regions of clogging class and non-clogging class c) Able to find regions of high process control. TCA001 grade happens to have a relatively low clogging frequency and low overlap of clogging events which makes it amenable to modelling.

6. MODEL PERFORMANCE

The model is now assessed as per model performance metrics. Figure 7 shares the

model performance for different modelling approaches based on the definition of start and end of clogging. As seen, the model gives better performance for larger deviations in stopper position. Final precision and recall were 0.95 and 0.96. Accuracy was always above 0.95. The results of the hyperparameter tuning are as follows: a) When epoch increased from 10 to 30 to 100, mild improvement in precision and recall by 0.02 units each b) When timestep reduced to 10, accuracy and recall have improved by 0.4 and 0.45 units respectively c) Increasing Patience from 5 to 15 reduced recall by 0.3 and improved precision by 0.4 units d) Adding standard deviation of stopper position for classification, precision and recall fall to zero. Here the end of a certain clogging event is considered to be mould level rise accompanied by stopper drop. As graphical discernability of start of clogging is difficult, we have considered multiple approaches centred around calculation of start

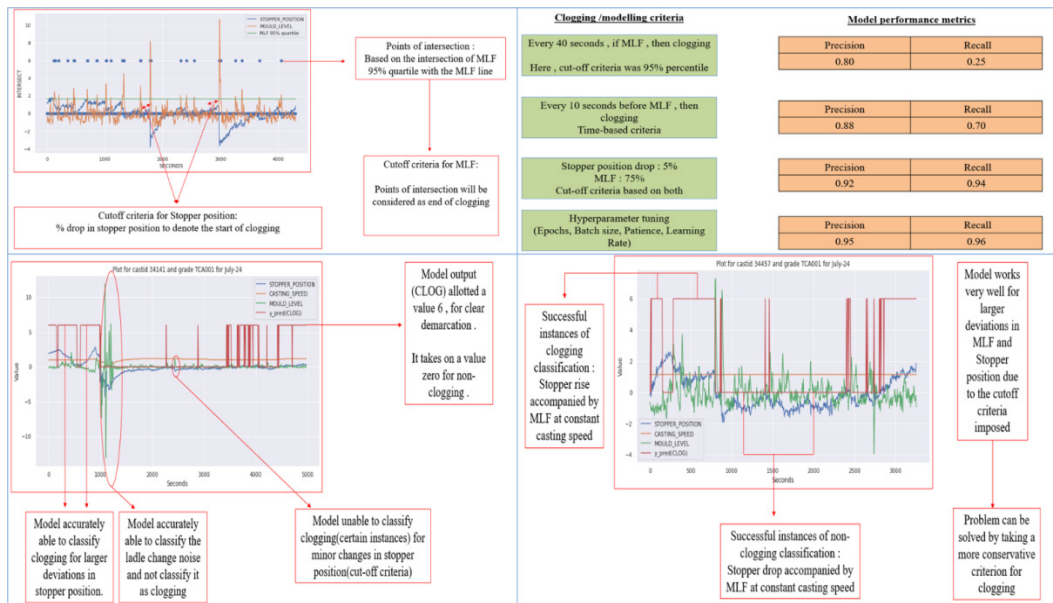


Figure 7: Model Performance

of clogging for example the drop in stopper position from the end of clogging. Another approach being, taking a certain time t (in seconds) before end of clogging. Multiple approaches have given different model performances, that have been captured. Here % drop refers to % drop in stopper position, MLF refers to mould level fluctuation and % MLF refers to the quartiles of mould level

data considered for modelling (so as to exclude the anomalous data).

7. MODEL UTILITY

The model was used to evaluate the ‘**clogging index**’ which accounted for the total time spent during clogging for every castID as shown in Figure 8. There are

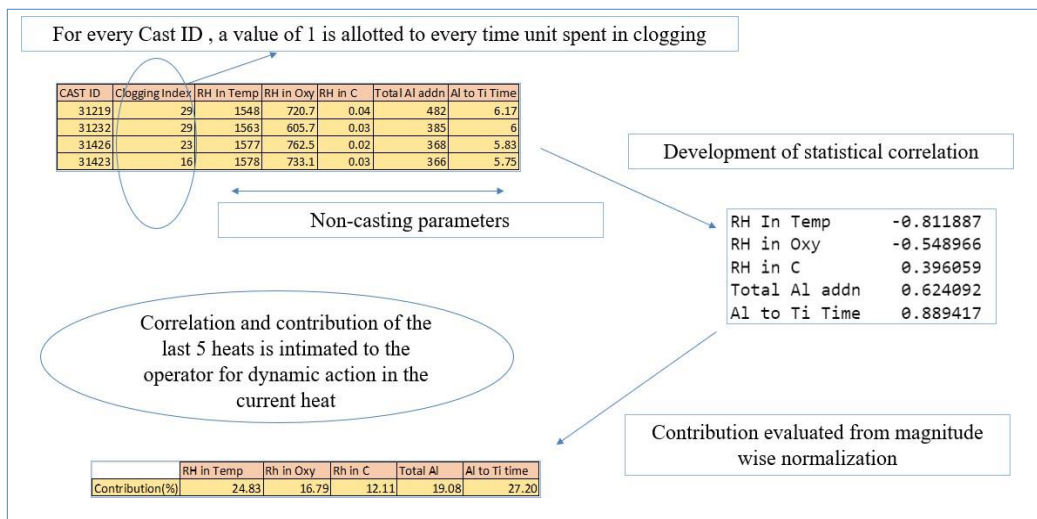


Figure 8: Model Utility

various other methods to evaluate clogging index[6-8]. The non-casting parameters are from the RH process consisting of RH temperature, oxygen, carbon levels, Aluminium addition and time taken from Aluminium to Titanium addition. These are believed to have significant impact on clogging. A correlation between these parameters is developed which is converted to equivalent contribution. The correlation and contribution are then used by the operators for dynamic action during the ongoing cast ID.

8. CONCLUSIONS

Model strengths are it's good precision and recall, and scope for improvement would be to detect very fine changes in mould level fluctuations and stopper positions which can however be addressed by finetuning the cutoff criteria for defining clogging. There's also scope for having change in stopper slope as a criteria. Due to the imbalanced divide between clogging and non-clogging classes (80:20 at times), there is less scope for prediction. However, this model could work as diagnostic tool to check for factors leading to clogging and degree of clogging from cast to cast and post- mortem analysis of defects e.g. sliver analysis

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Optimization of Process Parameters to Reduce the Incidences of Nozzle Clogging in Slab Caster

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ABSTRACT: SMS-New of Bokaro Steel Plant (BSL) has come up after brown field modernization of existing SMS-I shop. The shop is making mainly low carbon aluminium killed steel grades (LCAK) through BOF-Twin LF-CC route. In the initial phases the new shop faces issues like Sub Entry Nozzle (SEN) clogging leading to abrupt abortion of sequence casting. Critical analysis of process parameters revealed that there is need to redesign flux and de-oxidation practice during tapping and refining parameters in Ladle Furnace (LF). The flux and deoxidation practice has been redesigned. Initial de-oxidation by carbon has been introduced & conventional practice of addition sequence of Al has been redesigned. The modified flux, de-oxidation and alloying practice during tapping is incorporated in plant trials. The existing platform has been modified by shop keeping in view ease of Al bar addition from side chute during tapping. Change in practice of Al addition at LF such as addition of Al wire for deoxidation have been implemented.

Optimum Calcium addition window for different grades of steel has been designed using Thermodynamic simulation software FactSage. The Calcium-addition windows have been suggested keeping in view of different sulphur, aluminium and total oxygen level. Optimisation of CaSi treatment was carried out soft purging for inclusion flotation was made mandatory. Calcium treatment in high sulphur heats was put to an end. Modification of process has resulted in reduction in incidences of nozzle clogging.

Keywords: Ladle Furnace (LF), Sub Entry Nozzle (SEN), Bokaro Steel Plant (BSL).

1. INTRODUCTION

Steel secondary refining is critical in determining the final quality of steel products. The primary operations in a Ladle Furnace (LF) include temperature and chemical homogenization, desulfurization, inclusion modification and flotation, and the precise control of temperature within a narrow range to meet the quality requirements of casters. Calcium treatment is performed as the final LF operation to modify alumina inclusions into liquid calcium aluminates. In continuous casting of low-carbon, aluminum-killed steel using a

slide gate-operated tundish, a high level of cleanliness is essential. This is because any build-up of non-metallic inclusions in the Submerged Entry Nozzle (SEN) cannot be easily removed, unlike in the case of a stopper rod system. Inclusion build-up in the SEN can lead to poor product quality and reduced productivity due to clogging. The presence of non-metallic oxide inclusions is a significant factor affecting the cleanliness of many commercial steel grades. When the inclusion load in the steel is high, these inclusions may deposit on the SEN walls, gradually impeding steel flow. In general,

inclusions degrade the mechanical properties of steel, reducing ductility and increasing the risk of mechanical or corrosion failure in the final product [1-5]. Oxide inclusions originate from two main sources: (i) residual products from intentionally added alloying elements used to deoxidize molten steel after oxygen treatment (indigenous or micro inclusions), and (ii) products resulting from reactions between the melt and the atmosphere, slag, or refractory materials (exogenous or macro inclusions) [1, 2, 3, 6, 7]. According to Oertel *et al.* [8] the effectiveness of the steel refining process is heavily dependent on the characteristic of the slags employed in these processes. The selection of the most effective slags for ladle furnace treatment to achieve ideal non-metallic inclusions precipitation are typical problems that can only be solved if the slag behaviour and its equilibrium with the liquid metal can be evaluated. Among the quality factors, resulting directly from metal-non-metallic phase equilibrium, are: (i) the prevention of nozzle clogging in continuous casting [5,8,9], (ii) the increase in critical applications steel fatigue life [7,8], (iii) the improvement of steel drawability [4,8], (iv) the achievement of high formability for sheet steel [4,7,8].

To prevent nozzle clogging in continuous casting by solid inclusions, calcium is added to steel to modify alumina inclusions and to some extent desulphurize the liquid steel. Optimum addition of Calcium will convert solid alumina (Al_2O_3) inclusions into lower melting point liquid calcium Aluminates, which will help prevent the clogging of the nozzles [9,10]. However, when calcium is added to steel, it also reacts with oxygen and sulphur and modifies the shape of sulphide inclusions. If the oxygen content in steel is very low and sulphur content of the steel is high, calcium will react with sulphur forming solid CaS , which also clogs the continuous casting nozzle [7].

There are many ways to modify the non-metallic inclusions: such as (1) the use of

specific elements such as Ca and rare earth metals; (2) the control of the composition of molten steel (Ca/Al, Mn/Si ratio etc.) and (3) the control of solidification conditions in tundish and mould (tundish furniture and mould stirring etc) etc.. Among the various practices adopted in industries to counteract the effect of solid inclusions, modification through calcium treatment is one of the widely used methods. Calcium has a strong ability to form oxides and sulphides. In Al-killed steels, the most common inclusions are alumina (Al_2O_3) inclusions, which are solid at steelmaking temperatures. After rolling, in aluminium killed steels, the inclusion population will generally include elongated manganese sulphides, dispersed alumina inclusions or even clusters and some silicates. However, after calcium treatment, the inclusions are mainly calcium Aluminates of the type $\text{CaO} \cdot \text{Al}_2\text{O}_3$. The sulphur in the steel is also associated with these inclusions either as calcium sulphides or as sulphides containing manganese. Two purposes of making Ca-Aluminates oxide is to liquefy the inclusions so that it can be removed easily and even if the inclusions remain it will be globular in nature and tend to retain their shape on hot rolling so that stress concentration does not occur.

Figure 1 shows the castability curve as a function of the steel's composition. A steel containing inclusions consisting of pure alumina has only a moderate castability. Castability deteriorates drastically at the start of conversion of inclusions into calcium Aluminates. Only when the first liquid phases occur, i.e., at calcium to total oxygen ratio of approximately 0.4, does castability improve.

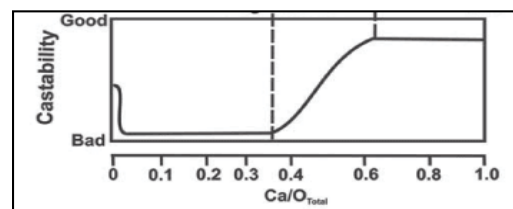


Figure 1: Steel Castability
Dependent on Oxide Composition

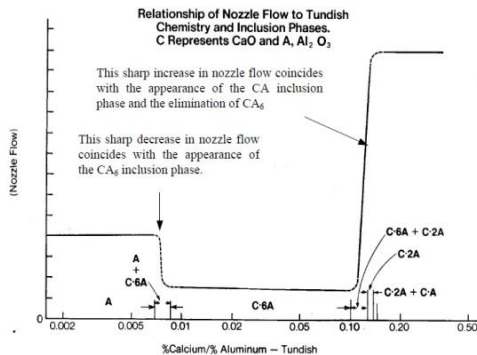


Figure 2: Steel Castability Dependent on Ca/Al Ratio

When the calcium to total oxygen ratio reaches 0.6, the castability is better than that of steel containing inclusions of pure alumina [9] (e.g. for 50 ppm total oxygen effective Ca should be 20-30 ppm for good castability).

Figure 2 showed the castability of steel depending on Ca/Al ratio. It showed that up to Ca/Al ratio 0.10 the castability was on the lower side. This is due the formation of solid Ca-Aluminates phases (C.6A and C.2A). When the ratio improved above 0.10 it indicates appearance liquid Ca-Aluminates phases. This resulted in improvement in castability.

SMS-New at Bokaro Steel Plant (BSL) primarily produces low-carbon, aluminum-killed steel grades (LCAK) through the BOF-Twin LF-CC route. In the initial phases, the

new facility encountered challenges such as Submerged Entry Nozzle (SEN) clogging, which led to the premature termination of sequence casting. In the present study, the issue of nozzle clogging was investigated by sampling clogged SEN material, Ladle Furnace (LF) steel samples, and final product samples. Metallurgical analysis was conducted using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS), X-Ray-Diffraction analysis (XRD) to identify the root cause of SEN clogging. This study also aims to mitigate the SEN clogging issue and determine the optimal casting window for the production of LCAK grades.

2. EXPERIMENTAL

2.1 Investigation of the SEN Clogging Material

As the steel cleanliness affect the castability by inclusion build up in SEN and ultimately clogging the SEN, so the analysis of the SEN deposit is carried out. Some part of the SEN clogging samples was collected and mounted for SEM-EDS investigation and some part was grinded for XRD analysis. The SEN clogging material and the mounted sample were shown in Figure 3. In the SEN clog material it was appeared that there was some amount of entrapped of steel in the deposit.



Figure 3: The SEN Clog Material (indication of entrapped steel) and Mounted Sample of Clog Material

Some amount of clog material was grounded into powder form for phase analysis in the XRD.

2.2 SEM & EDS Investigation of the Clogged Material in SEN

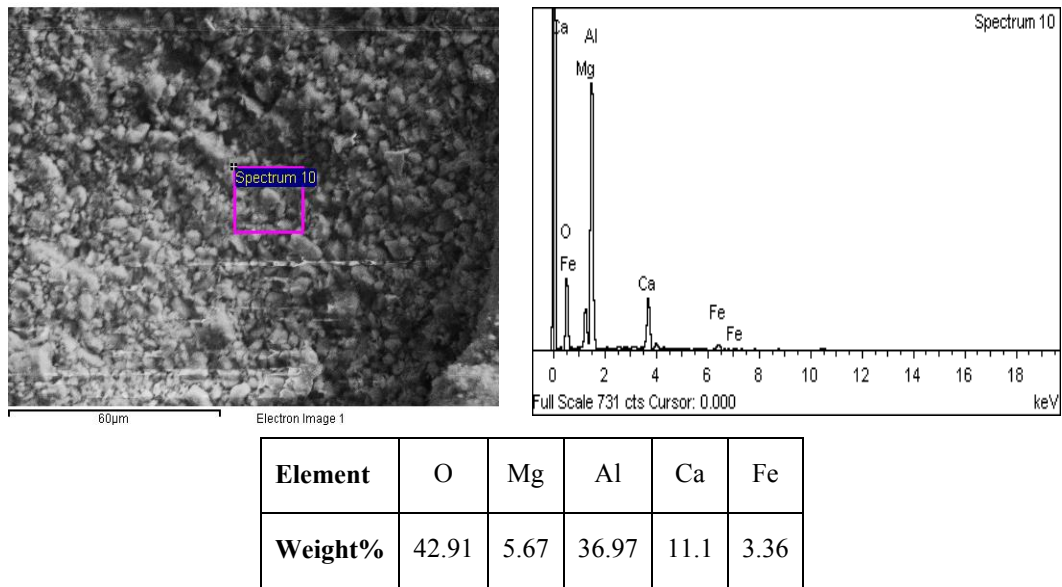


Figure 4: Secondary Electron Images of the Clog Material with EDS Spectrum and Semi-quantitative Analysis of the Clog Material

From SEM-EDS analysis it was found that the clog material is mainly aluminium-calcium oxide along with some magnesium oxide and steel entrapment.

2.3 Phase Analysis of Clog Material in XRD

X-Ray-Diffraction analysis of the clog material has been carried out to determine the phases in the clog sample. The analysis showed present of Alumina-MgO spinel, Calcium-Aluminates, iron oxide is the main deposition in the clog material (Figure 5 & 6).

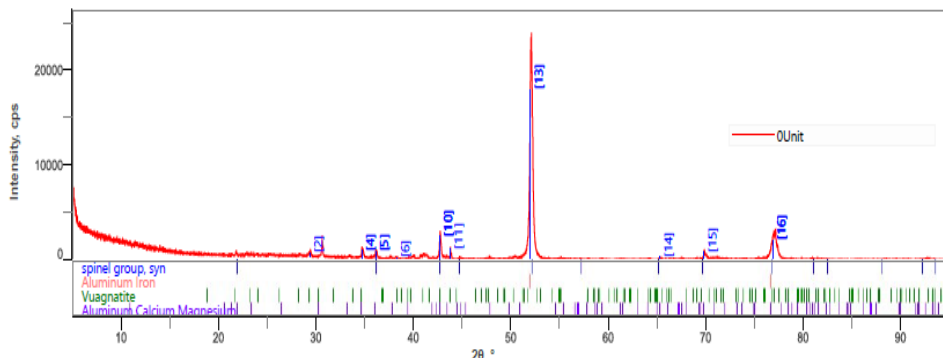


Figure 5: XRD Peaks of Phases Present in Clogging Material

2.4 Peak List in XRD

No.	2 θ , °	d, Å	Height, c...	FWHM, °	Int. I., cps*	Size, Å	Phase Name	Chemical Formula	Card No	Norm. I.
1 : S...	21.828(9)	4.7243(19)	242(30)	0.08(3)	21(7)	1257(4...	Vuagnatite: 0 1 1	Ca Al (Si O4) (...)	04-012-...	0.34
2 : S...	29.43(4)	3.522(5)	291(35)	0.25(4)	90(12)	395(61)	Vuagnatite: 2 0 0	Ca Al (Si O4) (...)	04-012-...	1.44
3 : S...	30.644(5)	3.3851(5)	1818(139)	0.050(8)	175(8)	2010(3...	Unknown			2.81
4 : S...	34.741(6)	2.9961(5)	696(74)	0.19(2)	183(10)	523(56)	Vuagnatite: 2 0 1,Aluminum Calcium Magn...	Ca Al (Si O4) (...)	04-012-...	2.94
5 : S...	36.16(2)	2.8821(19)	660(80)	0.17(3)	165(10)	611(118)	spinel group, syn: 2 2 0,Aluminum Calcium...	Mg Al2 O4,Ca...	04-014-...	2.66
6 : S...	38.32(4)	2.726(3)	62(14)	0.6(2)	63(17)	158(58)	Vuagnatite: 2 2 0	Ca Al (Si O4) (...)	04-012-...	1.01
7 : S...	40.00(2)	2.6154(13)	146(27)	0.44(6)	75(7)	233(33)	Unknown			1.21
8 : S...	40.71(2)	2.5714(12)	119(23)	0.10(5)	13(5)	1015(5...	Unknown			0.21
9 : S...	41.288(16)	2.5372(9)	257(41)	0.60(6)	181(17)	170(16)	Unknown			2.91
10 ...	42.708(7)	2.4566(4)	2348(189)	0.123(11)	462(11)	839(74)	spinel group, syn: 3 1 1,Vuagnatite: 2 2 1,Al...	Mg Al2 O4,Ca A...	04-014-...	7.43
11 ...	43.782(7)	2.3992(4)	1012(118)	0.058(8)	75(6)	1804(2...	Vuagnatite: 1 3 1	Ca Al (Si O4) (...)	04-012-...	1.20
12 ...	50.457(13)	2.0986(5)	181(33)	0.15(8)	50(7)	718(369)	Unknown			0.81
13 ...	52.036(5)	2.03918(...)	17815(484)	0.257(4)	6215(34)	418(6)	spinel group, syn: 4 0 0,Aluminum Iron: 1 1 0	Mg Al2 O4,Fe0...	04-014-...	100.00
14 ...	65.33(2)	1.6573(6)	180(44)	0.12(2)	23(5)	955(174)	Aluminum Calcium Magnesium: 3 0 1	Ca Mg0.66 Al1.34	04-018-...	0.37
15 ...	69.834(6)	1.56276(...)	659(86)	0.16(3)	186(8)	751(122)	Aluminum Calcium Magnesium: 0 0 12	Ca Mg0.66 Al1.34	04-018-...	3.00
16 ...	76.950(17)	1.4377(3)	1990(165)	0.566(12)	1410(21)	217(5)	spinel group, syn: 4 4 0,Aluminum Iron: 2 0...	Mg Al2 O4,Fe0...	04-014-...	22.69

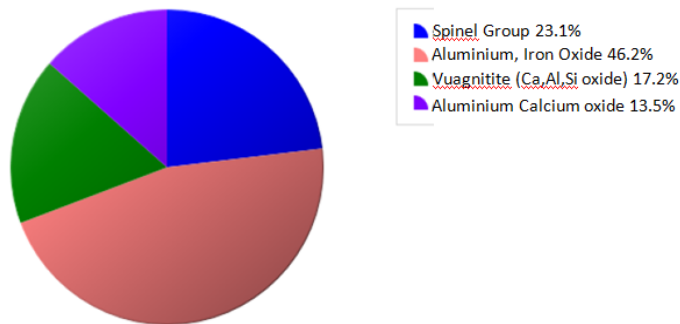


Figure 6: Relative Proportion of Phases Present in Clogging Material

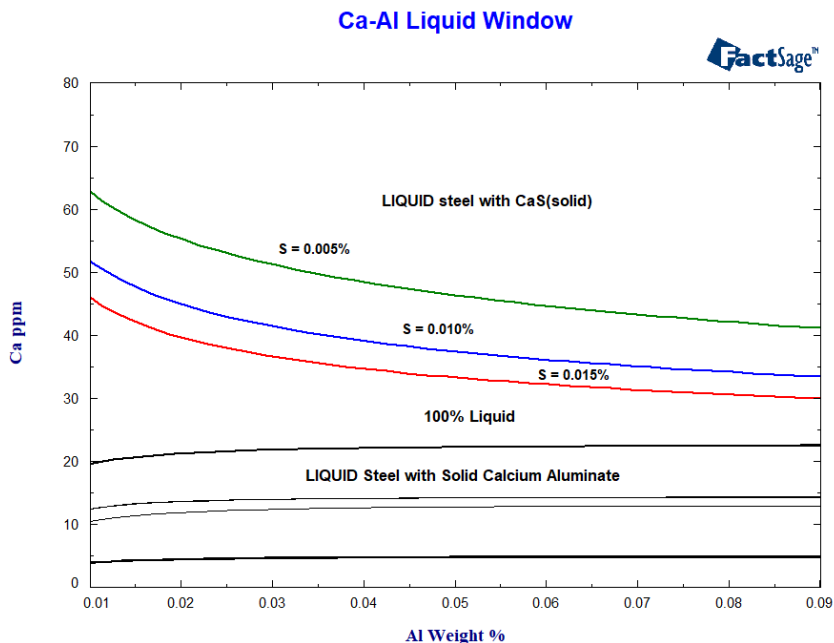


Figure 7: Calculated Ca-Al Liquid Window in Low Carbon Al-killed Steel using FactSage

2.5 Thermodynamic Assessment of Calcium Treatment in Steel

Calcium is added to the steel to modify the alumina inclusion into liquid calcium-Aluminates. The calcium addition is need to be done very precisely as low Ca level in steel will be resulted into solid calcium Aluminates phases and higher Ca level may resulted into solid CaS phases. Both the solid phases largely hamper castability of steel. To determine the optimum calcium addition window thermodynamic calculations have been carried out using FactSage thermo-dynamic database software. The low carbon aluminium killed steel produced at Steel Melting Shop has been taken as input for calculation in FactSage. The Ca-Al diagram for 100 % liquid window has been calculated for different sulphur level in steel (Figure 7).

It showed minimum 20 ppm Ca is required to achieve liquid calcium-Aluminates. The upper range of calcium depends on the sulphur level in steel. It was found that when Sulphur level is higher than 0.015% the liquid window become very small and chances of building solid inclusion become higher.

2.6 Inclusion Characterization in SEM and EDS

To characterize the inclusion nature, investigation has been carried out using SEM and EDS. After final preparation the samples were cleaned ultrasonically in acetone to remove out any foreign impurity that may enter during the processing. Then the samples were mounted and placed on the sample holder directly on the SEM Vacuum chamber for study.

Table 1: Semi-quantitative Elemental Analysis of Inclusion in Ca-treated Steel in EDS

Element	O	Al	Ca	Fe
Weight%	22.29	30.17	10.01	36.53

The SEM and EDS analysis showed that the inclusions are calcium-Aluminates oxide

(Figure 8 & Table 1). The solid calcium Aluminates may form due to low Ca amount or not sufficient time for inclusion floatation after calcium treatment. However the globular shape indicates that the inclusions were in liquid form in steelmaking temperature.

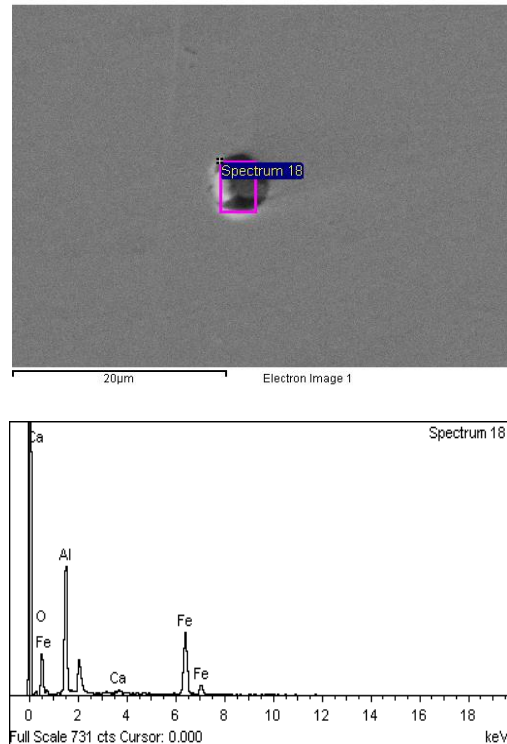


Figure 8: SEM Image and EDS Spectra of the Inclusions in Steel

2.7 Trials with Modified Practice and Evaluation of Samples

Based on the founding of the metallurgical investigation the current practice was modified to reduce alumina load and optimize the de-oxidation practice. Al bars in ladle bottom before tapping was modified and practice of initial de-oxidation by carbon has been introduced. The modified flux, de-oxidation and alloying practice during tapping is as pet Coke ~ 50 kg in ladle bottom, Al ~220–260 kgs during tapping based on oxygen blowing (from side chute), Lime ~800-1000 kgs, other ferro-alloys as per grade

specific requirements. The existing platform has been modified by shop keeping in view ease of Al bar addition from side chute. At the end of LF treatment Ca addition was mandatory but in high Sulphur case Ca-addition advised to be avoided. Soft purging is a mandatory requirement for Al-killed Ca treated steels. Soft purging for at least 3-5 minutes is necessary for floating out the modified inclusions.

3. RESULTS AND DISCUSSION

Characterization of the steel inclusion in SEM and EDS showed that the inclusions were mainly calcium-Aluminates oxide and sometimes along with some MgO associate with it. The likelihood for the presence of solid calcium Aluminates may be due to low Ca amount or not sufficient time for inclusion floatation after calcium treatment. However presence of globular shape indicates that most inclusions were in liquid form in steelmaking temperature. The SEN clogging material also been characterized though SEM-EDS and XRD analysis. The nature of the clogging material was very close to the nature of the inclusions present in the steel, it was mainly Calcium-Aluminates, Alumina-MgO spinel and iron oxide. To assess the Ca-treatment in thermodynamic point of view simulation of calcium treatment in FactSage thermodynamic software has been carried out for different Sulphur level in steel. Thermodynamic simulations showed that around 20 ppm Ca in steel is required to achieve liquid Calcium-Aluminates. The sulphur level is also playing very important role for getting 100% liquid steel window. With increasing sulphur level the window became narrow and became very critical for above 0.015% sulphur level. Control of Aluminium level is also found to be beneficial to minimize the chances of SEN choking. Plant trial with modified process parameters has been carried out as the results found from metallurgical investigation and thermodynamic simulation results. It was found to be beneficial as the

nozzle choking tendency has been come down by controlling the parameters.

4. CONCLUSIONS

- The metallurgical investigation of the samples revealed that the inclusions in the steel are mainly globular oxide. The SEM-EDS analysis showed that the inclusions are solid calcium-Aluminates.
- The clog material analysis showed the material are close in chemical nature with the inclusion in steel. High amount of calcium Aluminates in both inclusion and clog material is found.
- Thermodynamic simulation of the operating condition has carried out to find the optimum window for Ca-treatment. A consistent level of 20ppm Ca is required be added to convert Calcium-Aluminates into liquid phase. Al level above 0.04% also showed high chances of solid CaS formation.
- Modification in operating parameters had been made to achieve optimum casting window for current steelmaking practice. Implementation of the above measures showed improvement in cleanliness and reduce chances of SEN clogging. A soft purging after Ca-treatment found beneficial to float out the Ca-Aluminates from steel

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Study the Impact of Modified Steel Refining Techniques on the Longevity of Refractories in Steel Ladle

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ABSTRACT: *With stabilization of newly commissioned Hot Strip Mill-2 at RSP production of high quality hot rolled coils has been ramped up since last 2 years. To meet the stringent quality criteria of customers RSP along with RDCIS has taken several modifications in steel refining process at SMS-2 for producing cleaner steel with less inclusion. These process modifications include changing addition practice of flux and de-oxidisers during steel tapping, introduction of double porous plug system in place of single porous plug in steel ladles and establishing a foamy slag practice by replacing calcined lime with limestone during refining at LF. The modified practices not only improved steel cleanliness but also improved ladle top slag quality in terms of its chemistry, basicity, fluidity and solubility. A less corrosive, aluminous slag of creamy consistency with saturated refractory fluxes, lower FeO & MnO, higher basicity and optimum fluidity could be generated that enhanced the slag zone refractory life of steel ladle by 20%. In this study three practices were simultaneously investigated, slag samples were analysed and refractory was characterized to examine the influence of modified refining practice on refractory degradation.*

Keywords: Ladle, Refractory, Slag, Basicity, Steel Refining.

1. INTRODUCTION

In secondary metallurgy, the steel teeming ladle acts as a metallurgical reactor rather than molten steel carrying vessel.^[1] In Steel Melting Shop (SMS)-II of Rourkela Steel Plant (RSP) the secondary steel making process runs through steel ladle in BOF-LF-RH (OB)-CC route. As present, approx. 15% of total heats are produced through RH-OB. The whole process of SMS-II is depicted in Table 1. Various metallurgical tasks, carried out in steel ladle in every cycle are shown in Figure 1. The secondary steelmaking requires extreme chemical, thermal and mechanical conditions that demand a high performance

refractory material ^[2]. Refractory wear in steel ladle is a complex phenomenon that includes various metallurgical process variables such as a) reaction with steel/slag/fluxes/alloying materials, b) reaction with atmosphere and vacuum, c) electric arc radiation, d) thermo-mechanical erosion caused by purging, tapping, fluid flow and e) thermal shock due to slow ladle circulation etc. Magnesia-carbon (MgO-C) refractory bricks are used as working lining in steel ladles to withstand the harsh basic slag and high temperature environment. It is a composite material consists of MgO grains, graphite and resin or pitch binder. MgO has a strong corrosion resistance for basic slag, and

graphite has non-wetting property and thermal shock resistance. Slag zone of steel ladle is the most vulnerable area which is exposed to slag corrosion and thermo-mechanical erosion.^[3] For maximizing the slag zone life, zonal lining concept with better corrosion resistant MgO-C bricks has been adopted in steel ladles. Bricks with higher thickness and

higher graphite (12–14%) are applied in slag zone. To maximize the performance of steel ladle bottom, Alumina-Magnesia Carbon bricks are used in the impact area. In safety lining Mag-Chrome bricks are used in slag zone and 42% Al_2O_3 based bricks are used in metal zone and bottom. The ladle refractory design is depicted in Figure 2.

Table 1: Secondary Steel Making Process at SMS-II, RSP

<i>Secondary Steel Making Process</i>		<i>Average Time (mins)</i>	<i>Average Temperature (°C)</i>
BOF	→ Steel sample → Slag sample		
Tapping	← Alloying additions	8	1670
	← Slag forming additions		
	← De-oxidation agents		
Waiting Period		22	
LF	← Alloying additions	47	In: 1584 Out: 1586
	← Slag forming additions		
	← De-oxidation agents		
	← De-sulphurization agents		
	→ Steel sample		
	→ Slag sample		
Waiting Period		10	
RH-OB	← Alloying additions	20	
Waiting Period		10	
CC	→ Steel mass	55	1540–1560

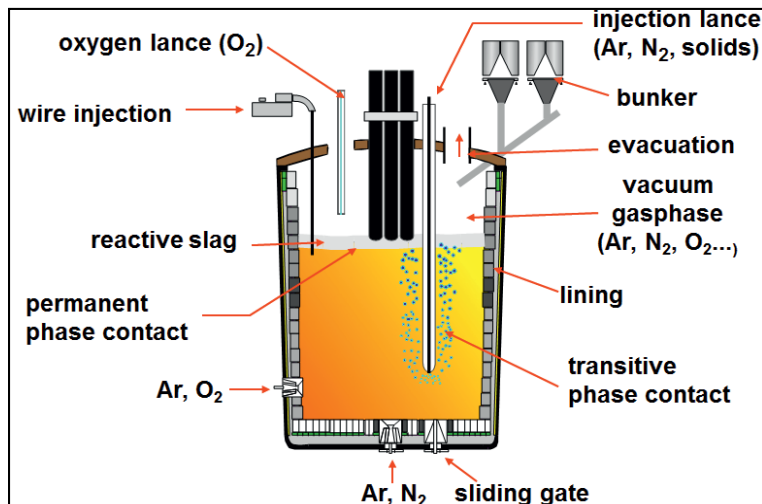


Figure 1: Metallurgical Tasks in Steel Ladle

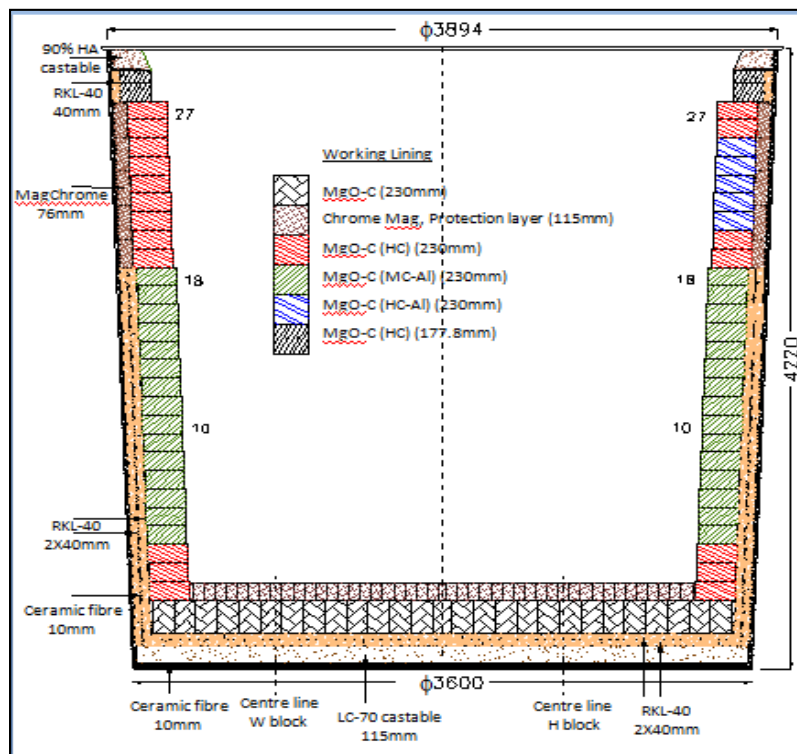


Figure 2: Refractory Design of Steel Ladle

The wear mechanism of magnesia-carbon materials of steel ladle in contact with liquid slag is a cyclic phenomenon and has been well documented through various investigations although it varies in different operating practices.^[4] Several reactions between refractories, steel and slag can

contribute to the degradation of refractory.^[5,6] Chemical attack of solid refractories by liquid slags is a complex process that exhibits both penetration (simple permeation of liquid slag via open porosity) and dissolution (reaction of the slag with the refractory phases) as depicted in Figure 3.^[7]

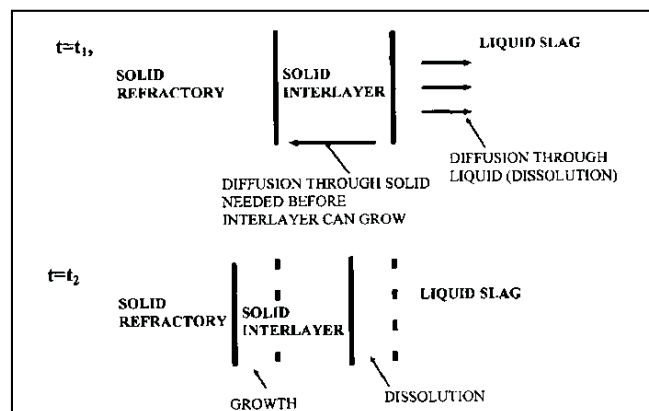


Figure 3: Illustration of Corrosion by Penetration and Dissolution of Refractory into Slag at the Interface

The corrosion process is a function of many variables including refractory composition, porosity, non wetting characteristics of refractory, slag basicity, slag temperature, slag viscosity, slag composition, oxygen potential, and degree of agitation. The chemical potential between the refractory and the steelmaking slag determines the driving force for refractory corrosion. The common sequence of refractory degradation in steel ladle is as follows:

1. Oxidation of carbon on the surface of the refractory material with oxygen originating from a mixture of gases surrounding the material, oxygen dissolved in the steel or oxidized slag containing Fe and Mn oxides;
2. Formation of a porous layer of the material adjacent to the surface as a result of the reaction in equation 1

$$\text{C(s)} + 0.5\text{O}_2(\text{g}) \rightarrow \text{CO}(\text{g}) \text{ or } \text{C(s)} + \text{O}_2(\text{g}) \rightarrow \text{CO}_2(\text{g})$$
3. Infiltration of the liquid slag into the decarburized and porous layer adjacent to the surface of the refractory material;
4. Surface rinsing of small fragments of the refractory material as a result of washing the refractory lining with the ladle slag;
5. Dissolution of the main (periclase) and accompanying (silicates, spinels, ferrites, aluminates) phases in slag with varying basicity;
6. Convictional removal of liquid products of dissolution from the surface of the refractory material into the slag.^[8]

In the initial process (Stage I of corrosion) refractory is penetrated by slag. Penetration is aided by capillary suction as the smallest pores in the refractory (diameter <10 microns) draw the liquid slag behind the hot face. In time, extensive corrosion of the refractory takes place in Stage II which is characterized by two phenomena: (1) full penetration of the refractory and (2) extensive disruption by corrosion of the hot face region. Stage II follows Stage I only if there is a sufficiently broad temperature gradient to allow penetration. In a very steep temperature gradient, very little penetration of slag is seen with corrosion reactions more or less restricted to the immediate slag and refractory interface. For broader temperature gradient the slag penetration is deeper where the slag freeze plane may be located in a zone of 40-75 mm behind the hot face.^[4] In Stage II, the direct bonding between the matrix and the aggregate particles is disrupted by...slag penetration that can result in densification spalling. This type of spalling occurs because the thermal expansion coefficient in the slag penetrated zone is different than that in the un-penetrated cold face region. In stage-III, the slag itself “appears” to be the only phase holding the residual aggregate particles in place. This is probably a result of the higher viscosity of the slag in the hot face region created as a consequence of dissolution of the refractory in the slag.^[4] All three stages are depicted in Figure 4. Refractory matrix dissolution into slag is the rate determining step for corrosion as the matrix containing C

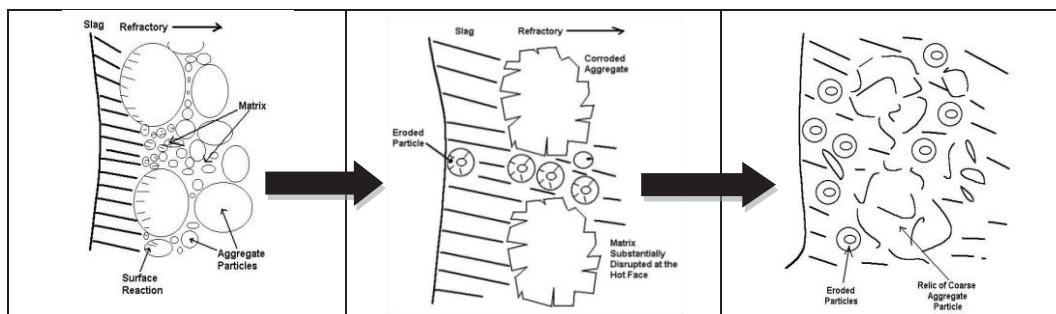
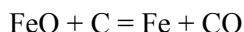


Figure 4: Stages of Refractory Corrosion by Steel Making Slag

is corroded faster than the MgO grains by the slag containing FeO.^[9,10] Corrosion can be both active and passive. Direct (congruent or homogeneous) slag attack is controlled by the rate of diffusive transport of species through the slag leading to active corrosion. Indirect (incongruent or heterogeneous) slag attack is controlled by diffusive transport through a new solid phase, which forms at the original slag-refractory interface which leads to passive corrosion.^[11]

Corrosion of refractory can be resisted by both slag modification and improving refractory quality. Slags can be classified as (i) crusty, (ii) fluffy, (iii) creamy, and (iv) watery. Crusty slag has too much CaO (and/or MgO). Fluffy slag is CaO/MgO saturated, and is satisfactory for refractories but not optimum for desulphurization. Creamy slag is just CaO/MgO saturated, it is a slag that is still fluid enough to refine the metal but not to fluid to cause accelerated wear on the refractory is considered good for secondary metallurgical operation and refractories (ideal).^[12] Watery slag is too liquid, aggressive to the refractories. Well designed ladle top is not only beneficial towards slag metal reactions, ferro-alloys recoveries and steel cleanliness it also improves the ladle lining life. The composition of the slag, in particular its phases changes significantly during the dissolution of refractory and consequently the corrosion rate is not constant throughout the lining life.^[9] FeO in the slag attacks refractory in the first place followed by MnO and CaO.^[7] Similarly, Slag with lower MgO solubility can limit MgO corrosion.^[13-16] Slag MgO solubility decreases with increasing basicity, decreasing temperature, and decreasing FeO.^[17] It has been observed that if the final slag after LHF treatment is not saturated with MgO and is completely liquid at the process temperature it can be the main causes of corrosion and lining wear.^[18,19] Similarly, if the initial slag before LHF treatment is saturated with MgO but contains a higher level of FeO can increase the slag fluidity

which break down the slag silicate network and promotes the brick matrix decarburizing, as shown in equation 2:



The CO(g) from the above equation creates bubbles in the pores and its detachment causes stirring in the vicinity of pores resulting in rapid dissolution of MgO grains.^[10] Corrosion of MgO-C refractories is also enhanced when slags are strongly stirred.^[20,14,21] Under the scope of refractory, increasing the resistance of MgO to slag attack and reducing contact between slag and MgO can limit corrosion.^[22-25] Refractories that employ larger MgO grains have also been found to exhibit better slag resistance because they have less surface area to attack.^[26,27] Sintered MgO has been observed to have less slag erosion resistance than fused MgO due to the presence of intergranular silicates which assist slag penetration^[16,28] Akkurt found that decreasing wetting between refractory and slag reduced slag corrosion.^[13] Akkurt *et al.* and Resende *et al.* found that increasing carbon content reduces slag attack because carbon limits slag contact with oxide and prevents slag penetration.^[13,15,25] Porosity, higher temperatures, and longer contact times also increase slag penetration.^[29,30,28] Surface irregularities such as grooves and porosity have a significant effect on slag penetration while other micro structural features such as crystal orientation, grain boundary phases and grain shape are neglected in dissolution.

At Steel Melting Shop, Rourkela Steel Plant, mostly aluminium/silicon killed steel grades are processed and the average slag basicity (CaO/SiO₂) is maintained 3-4. With the commissioning of new Hot Strip Mill and to meet the customer's demand of stringent quality assurance, SMS-2 has taken several initiatives to improve steel cleanliness. Three modified practices has been adopted in steel refining which aids in cleaner steel, good slag making and also improved the refractory life of steel teeming ladles. With this

modification in steel refining process the average lifespan of slag zone brick and overall campaign life has been improved from 50 heats and 133 heats (2022–23) to 60 heats and 145 heats (2023–24) respectively. This assignment seeks to study the effect of modification in refining practices in ladle refractory life. Specifically, the effect of slag basicity and slag chemistry for corrosion in steel ladles has been studied. Physical characterization of refractory materials has also been carried out for this study for better analysing the effects of modified refining practices.

2. EXPERIMENTAL

Under this assignment, the following three modifications in steel refining practices were correlated with the improvement in ladle refractory life.

- (a) **Re-designing of flux and de-oxidation practice during tapping at BOF:** Under this modification, the sequence of tapping addition was i) 50 kgs of pet coke in ladle bottom, ii) after 1 min of tapping start addition of 300 kgs of Al bars and subsequent addition of 1000 kgs of calcined lime and iii) finally, ferro alloy addition as per requirement. With this modification, gas purging regime in

Ladle Furnace could be optimised for better slag - metal interaction.

- (b) **Introduction of double porous plug:** All ladles have been converted from single porous plug to double porous plug arrangement for efficient gas purging, homogenization of temperature and chemical composition and inclusion floatation: Operation of trial ladle has been monitored throughout the campaign. Opening of the porous plugs, flow from the porous plug, lining condition after completion of casting and ladle life have been monitored for the campaign. Bottom of existing and modified ladle is shown in Figure 5.
- (c) **Introduction of foamy slag practice in ladle furnace:** limestone chips (–30 mm) addition was carried out in all the ladle heating furnace of SMS-2 in place of calcined lime to maintain foamy slag at the ladle top as shown in Figure 6. Analysis of ladle top slag has been carried out in Table 2. The melting point and viscosity was calculated using Factsage software and through empirical equations has been shown in Table 3. The comparative slag analysis with respect to $Al_2O_3\%$, $SiO_2\%$, $FeO+MnO\%$ and basicity is also presented in Figures 7–10.



Figure 5: Steel Ladle with Single and Double Porous Plug

Table 2: Ladle Top Slag Analysis in SMS-2, RSP

	<i>FeO</i>	<i>SiO₂</i>	<i>CaO</i>	<i>MgO</i>	<i>MnO</i>	<i>Al₂O₃</i>	<i>TiO₂</i>	<i>BASICITY</i>	<i>FeO+MnO</i>
Before Modification									
Average	1.9	12.86	42.79	12.52	1.33	22.77	0.58	3.5	3.23
Min	1.74	11.33	40.94	12.51	0.97	21.63	0.5	3	2.7
Max	2.07	14.39	44.64	12.52	1.7	23.91	0.66	4.02	3.77
After Modification									
Average	0.73	7.71	45.04	10.72	0.44	28.29	0.45	6.20	1.17
Min	0.25	4.25	32.31	5.63	0.10	19.73	0.17	3.08	0.35
Max	1.83	12.92	53.74	19.06	3.92	37.11	0.72	10.53	5.75

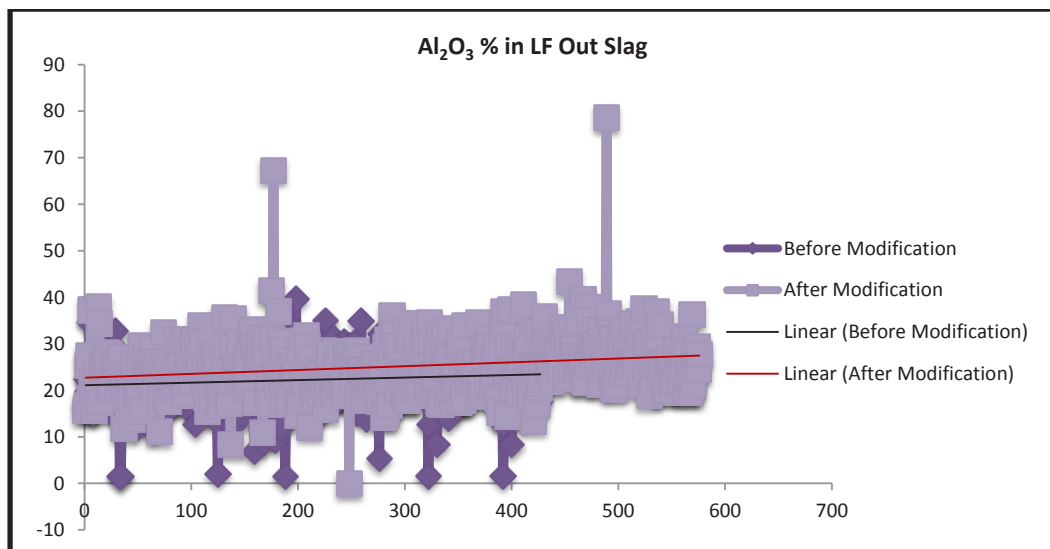
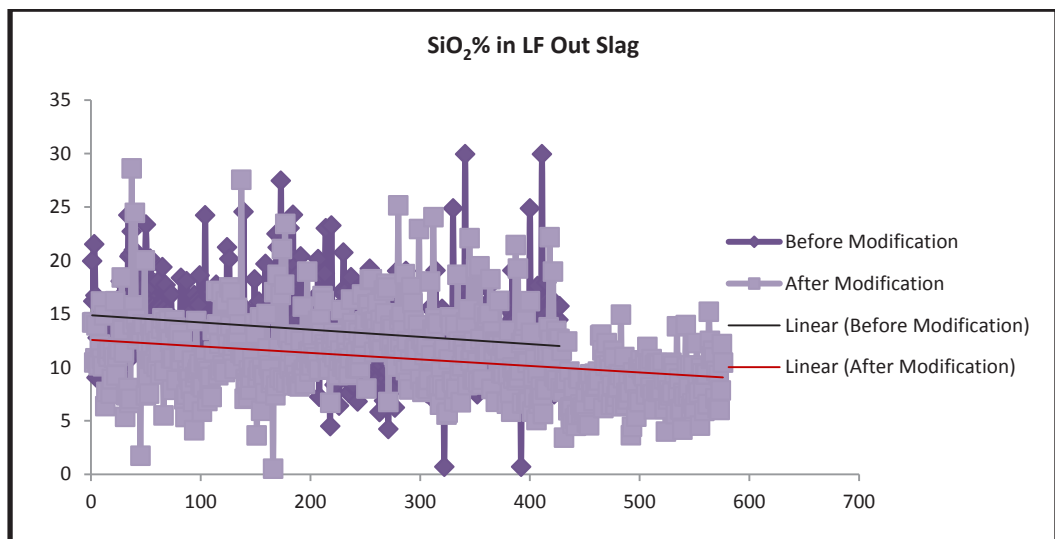
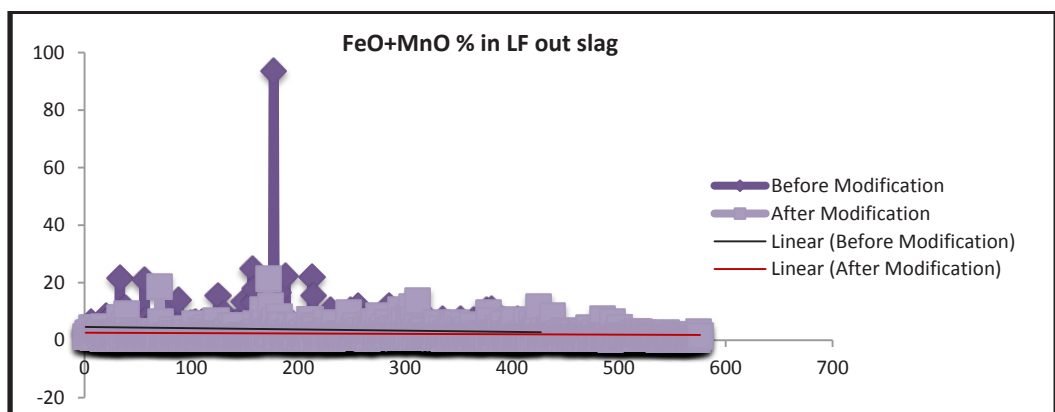
**Figure 6:** Limestone Chips (–30 mm) Used in Foamy Slag Practice**Figure 7:** Trends of Al_2O_3 % in LF Out Slag

Table 3: Calculated Viscosity of Slag Before and After Modification

	Melting Point (°C)	Viscosity, PaS		
		1575°C	1600°C	1625°C
Before Modification				
Average	1432.5	0.552	0.444	0.363
Max	1434	0.555	0.454	0.381
Min	1431	0.548	0.435	0.346
After Modification				
Average	1417.22	0.297	0.224	0.169
Max	1398.87	0.114	0.085	0.063
Min	1435.24	0.514	0.393	0.310

**Figure 8:** Trends of SiO₂% in LF Out Slag**Figure 9:** Trends of FeO+MnO % in LF Out Slag

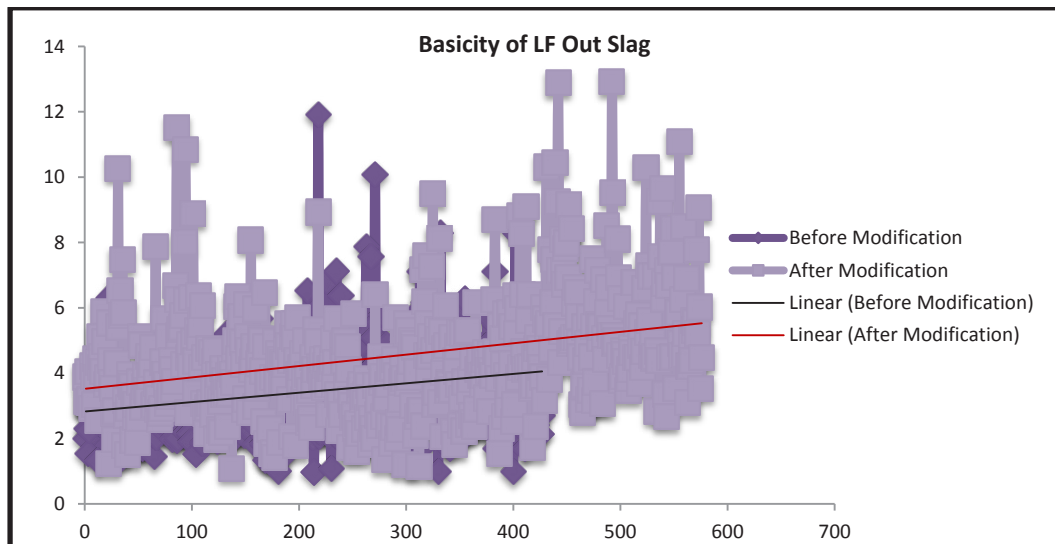


Figure 10: Trends of Basicity in LF Out Slag



Figure 11: Slag Corrosion Test of Slag Zone Brick with Old and New LF Out Slag

Thermo-mechanical characterisation of ladle slag zone refractory has been carried out as depicted in Table 4. Changes in refractory life, specific consumption of refractory and erosion pattern of steel teeming ladle has been

monitored throughout the period and shown in Tables 5 and 6. Slag corrosion test of MgO-C brick has been carried out with both old and new slag which is shown in Figure 11.

Table 4: Characterization of Slag Zone Refractory Before and After Modification

<i>Sources</i>	<i>Apparent Porosity (%)</i>	<i>Coked Apparent Porosity (%)</i>	<i>Bulk Density (coked) gm/cm³</i>	<i>Coked CCS (Kg/cm²)</i>	<i>HMOR (Kg/cm²)</i>	<i>Coking Loss in %</i>	<i>RC %</i>
Before Modification							
Supplier A	2.82	7.55	3.02	168.61	22.17	0.69	14.92
Supplier B	1.89	7.28	3.05	309.41	76.96	1.54	13.77
Supplier C	3.97	11.71	2.91	184.44	32.40	2.80	9.93
After Modification							
Supplier A	2.86	7.61	2.91	198.82	44.03	1.36	7.93
Supplier B	2.45	7.23	3.04	286.23	67.56	1.25	12.56
Supplier C	3.27	9.62	3.00	196.33	42.32	1.98	10.32

Table 5: Comparison of Ladle Life and Slag Zone Life (1st repair) Before and After Modification

<i>Before Practice Modification</i>			<i>After Practice Modification</i>		
<i>Month</i>	<i>Ladle Life</i>	<i>Slag Zone Life (1st repair)</i>	<i>Month</i>	<i>Ladle Life</i>	<i>Slag Zone Life (1st repair)</i>
2022-April	136.62	53	2023-April	138.5	60
2022-May	130.65	50	2023-May	139.7	57
2022-June	136.29	51	2023-June	142.8	62
2022-July	134.55	50	2023-July	142.9	58
2022-Aug	133.40	47	2023-Aug	146.5	61
2022-Sep	128.08	49	2023-Sep	144.7	66
2022-Oct	129.36	44	2023-Oct	146.5	59
2022-Nov	129.15	51	2023-Nov	147.7	59
2022-Dec	134.43	51	2023-Dec	146	59
2023-Jan	134.11	47	2024-Jan	147	59
2023-Feb	139.44	53	2024-Feb	145	61
2023-Mar	137.41	58	2024-Mar	148	58
Average	133	50	Average	145	60

Table 6: Overall improvement in Steel Ladle Refractory Before and After Modification

<i>Parameters</i>	<i>Before Modification</i>	<i>After Modification</i>
Total crude steel production (MT)	3.55	3.62
Total Ladles Relined (Nos)	170	162
Total Ladles Repaired (Nos)	525	416
Sp. consumption of refractory in ladle (Kg/tcs)	3.43	3.24
Sp. cost of refractory in ladle (Rs/tcs)	267.75	245.50
Ladle campaign life (heats)	133.41	144.70
Slag zone straight life (heats)	50	60
Slag Zone erosion rate (mm/heat)	3.5	2.8
Difference between PP and NPP side slag zone erosion rate (%)	17	4

3. RESULTS & DISCUSSION

Slag conditioning and the optimization in slag quality in the ladle refining process is essential to produce better quality steel economically and improve ladle refractory life. A 'creamy' slag with a creamy consistency of latex paint is ideal in refining metallurgy. The fundamentals behind an optimized slag for the ladle metallurgy facility are (i) to limit slag carry-over to the ladle, (ii) to reduce FeO and MnO content to less than 1%, which is corrosive to ladle brick and carries oxygen to the steel, (iii) to maintain basic slag with the basicity ratio of 3 or higher, and (iv) to have slag with the correct quantity of lime and MgO to improve desulfurization and to protect refractories. In a nutshell, secondary steelmaking process requires a slag based on CaO and Al₂O₃ with non-oxidizing character which does not cause oxidation of steel components with high oxygen affinity. Presence of high FeO and MnO % in ladle top slag which comes from carryover slag is undesirable as it adversely affects the ladle lining life, ferro-alloys recoveries and steel cleanliness. The De-S reaction in the ladle is also severely affected by presence of these undesirable oxides.

Addition of flux and de-oxidisers during tapping has improved the slag characteristics which consequently improve the ladle

refractory life. Addition of fluxes (good quality lime) improves fluidity and increase volume of slag which improved the reaction rate in secondary steel making. Addition of de-oxidisers (Aluminium bars) during tapping helps in increasing the solubility of lime in slag by increasing Al₂O₃%, improved alloy recovery and prevents steel fading. The Al₂O₃ in the slag composition also helps in reducing the melting temperature of slag composition. The above mentioned addition during tapping aided in making of creamy slag saturated with refractory fluxes (CaO + MgO) that improved not only refractory life but also improved desulphurisation, steel cleanliness, ferro-alloy recovery and thermal efficiency with good slag volume. Lime and aluminium addition during tapping ensures a decrease in the content of oxygen, sulphur and non-metallic oxide inclusions after the secondary steelmaking process. The sequence of tapping addition played a crucial role in good slag making. Addition of ferro alloys (Si Mn/ Fe Mn) has been kept at the end of the sequence to prevent formation of silica in slag composition which worsens the refining properties of slag by reducing the solubility of fluxes in slag. It is believed that the silica content in slag intended for secondary steelmaking process do not exceed 10%. Less FeO%, MnO% and SiO₂% in slag and increased basicity (as depicted in Figures 8, 9 and 10) after the

modified tapping addition practice has become truly beneficial for refractory life. Improvement in ladle top slag fluidity was also achieved by modifying the de-oxidation practice during tapping altering the slag chemistry.

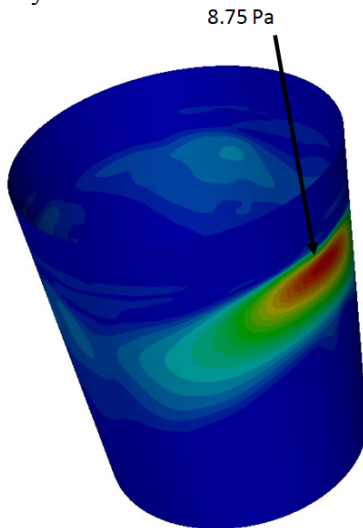


Figure 12(a): Wall Shear Stress Profile in Case of Single Porous Plug Ladle

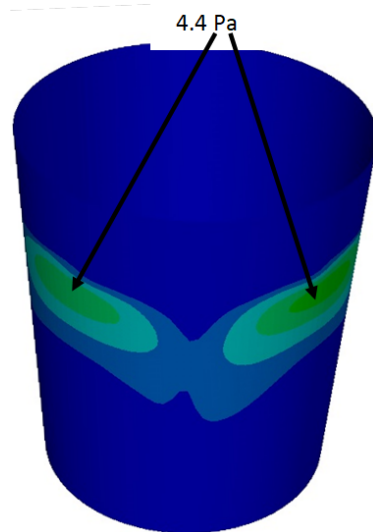


Figure 12(b): Wall Shear Stress Profile in Case of Double Porous Plug Ladle

Introduction of twin porous plugs showed significant improvement in refractory erosion and mixing characteristics. It results in

reduction in wall stresses by splitting the flow in two porous plugs as per Figure 12. Double porous plug improved the homogenization and reduced the mixing time with same gas flow rate. It also prevented the non-uniform erosion in slag zone of ladle. Earlier, the difference between the erosion of porous plug (pp) zone and non porous plug (npp) zone was more than 15% which has been reduced to less than 5%.

In the foamy slag practice in ladle furnace at SMS-2, RSP the addition of limestone chips in place of calcined lime during arcing in batches helped to reduce the oxygen potential of slag (FeO and MnO level) and improved steel quality in the process. The in-situ calcinations of limestone due to high temperature ($> 3300^{\circ}\text{C}$) generated by arc produces CO_2 gas that creates controlled slag foaming during arc reheating. This increases slag volume, covers the arcs and refractory and generates a protective atmosphere above the steel. Ladle top slag analysis in Table 2 has shown many advantages with limestone chips addition in LF during arcing with reduced level of (FeO+MnO) and increased basicity. The average level of FeO+MnO has been improved to 1.17% from 3.23%, average slag basicity increased from 3.5 to 6.20 as per Table 2. The calculated average viscosity and melting point of ladle top slag through Factsage software and empirical equations have also been reduced from 0.552 Pa.S to 0.297 Pa.S at 1575°C and from 1432.50°C to 1417.22°C as shown in Table 3. This reduction in viscosity is responsible for fluid slag which enables slag coating on refractory walls during emptying of ladle while casting. This coating in turn helps in improvement of ladle refractory life. This improvement in ladle top slag fluidity can be attributed to in situ calcinations of limestone chips and its dissolution in ladle top slag. Improvement in slag oxygen potential and basicity coupled with cooling efficiency helped to improve ladle life from 133 heats (base period) to 145 heats. Foamy slag also

improved the straight life of slag zone from 50 to 60 (Table 5) by insulating refractory from high temperature generation during arcing. No crust or top ring formation was also seen in ladles. The condition of ladle lining at 148th heat is shown in Figure 13.



Figure 13: Ladle Lining Conditions after 148th Heat

4. CONCLUSION

With recent modifications in steel refining practices in SMS-2, RSP a non-corrosive, basic, fluid and reducing refining slag could be formulated for better desulphurization and absorption of non-metallic inclusions. The change in slag quality also reduced the refractory corrosion and improved ladle life without changing the refractory composition. Addition of flux and de-oxidisers during tapping increased the basicity of ladle top slag, improved slag fluidity with creamy consistency and made the slag more aluminous than silicious. The double porous plugs reduced the wall stress and consequently reduced the wall erosion. Higher erosion in the porous plug side of slag zone has been reduced. Foamy slag practice at LF also improved the basicity with better dissolution of in-situ calcined lime in the slag. The foamy slag also protected refractory slag zone from high temperature exposure during arcing. A significant improvement of slag zone straight life and overall campaign life could be therefore achieved without significant changes in refractory quality and maintenance practices.

ACKNOWLEDGEMENT

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SECTION-II
**Hot Rolling of High Strength
and Advanced High Strength Steel**

Development of Centrifugally Cast High-Speed Steel Rolls and the Study of Influence of Alloying Elements on Properties of Microstructure, Fracture Toughness and Hardness

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ABSTRACT: Rolling Mill Rolls Steel industry is the back bone of industrialisation and growth of any country. India being a developing country must have a robust iron & steel industry and is on the path of being the second largest producer of steel. Soon it will touch 150 million metric tons of steel. Iron and steel industries comprise of iron making, coke making, sinter making, steel making (SMS) and finally rolling mills in integrated steel plants. In case of secondary steel manufacturing the plants comprise of induction furnace and rolling mills. The importance of rolling mill can be understood as we know that 90% of liquid steel that is being produced is passed through rolling mill for giving usable shape to steel. Rolling mill rolls are important tools which gives final shape to liquid metal.

Keywords: High-Speed Steel (HSS), Cast High-Speed Steel Rolls, Microstructure.

1. INTRODUCTION

In hot strip mill, flat rolling conditions become more critical because of the increasing demand of stringent quality of thin steel plates for various special applications. To satisfy all these conditions the rolls require suitable quality of stipulated hardness, fracture toughness, excellent wear resistance and higher level of surface finish and higher thermal fatigue resistance. To meet these requirements and improve the roll performance and rolling efficiency, high-speed steel (HSS) rolls have been developed which gradually replaced conventional rolls, nickel grain cast iron rolls as well as high chromium rolls.

The impact of alloying elements on its microstructure influences the mechanical

properties like hardness, wear resistance, thermal fatigue, excellent surface finish and fracture toughness of centrifugally cast rolls of various grades such as nickel grain cast iron rolls, high chromium rolls and high-speed steel (HSS) rolls. Emphasis was placed on the role of hard carbides located along solidification cell boundaries and the type of the tempered martensitic matrix. The roll material containing a small number of inter-cellular carbides and tempered martensitic matrix had excellent fracture toughness since carbides were well spaced. High-chromium cast iron rolls or nickel-grain cast iron rolls in many rolling mills may have some problems such as rolling-friction and fracture-toughness deficits and unstable shell/core interfacial strength. These deficits in turn, limit the available metallurgical design for control of the HSS shell microstructure.

2. EXPERIMENTAL OBSERVATIONS

HSS Roll compositions have been developed in the (Table 1) below for work-roll materials that are widely being adopted to improve hot-band shape and surface quality while extending roll life, thereby enhancing operational productivity of the flat rolling mill. The coarse carbides are segregated along cell boundaries and fracture toughness tends to decrease, although overall roll hardness increases. During rolling, the cyclic temperature excursions due to the roll-bite contact

and coolant exposure results in thermal-fatigue cracking and associated roughening of the roll surface which might lead to unexpected failure. Consequently, microstructural factors such as size, volume fraction, and distribution of coarse carbides as well as characteristics of the tempered martensitic matrix, play an important role in optimizing the roll properties such as hardness, wear resistance, fracture toughness, and thermal-fatigue behaviour. This experiment helps in the correlation between microstructure, hardness and fracture toughness of centrifugally cast HSS rolls.

Table 1: Grade: HSS

Chemistry (Shell)

%C	%Si	%Mn	%S	%P	%Ni	%Cr	%Mo	%V	%Nb	%Co
1.55	0.45	0.25	<0.035	<0.060	1.00	4.20	3.25	3.20	1.20	1.15
2.55	1.20	1.00			Max	8.00	7.00	7.00	4.00	4.00

Chemistry (Inter Core)

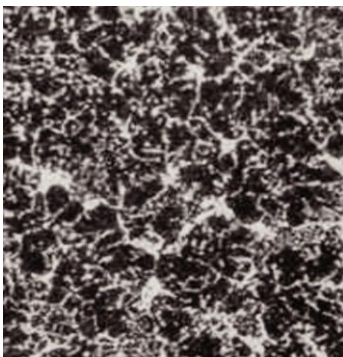
%C	%Si	%Mn	%S	%P	%Ni	%Cr	%Mo
1.25	0.45	0.25	<0.035	<0.060	0.45	<0.25	<0.10
2.20	1.20	1.00			1.00		

Chemistry (SGCore)

%C	%Si	%Mn	%S	%P	%Ni	%Cr	%Mo
2.60	2.55	<0.60	<0.025	<0.10	0.45	<0.25	<0.10
3.60	4.00				1.00		

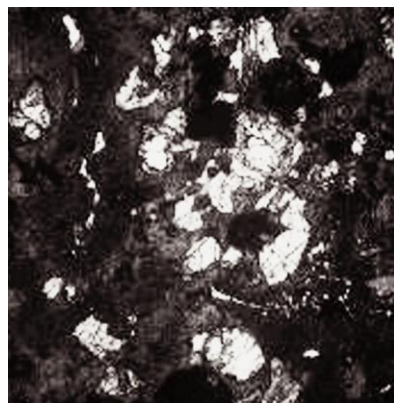
2.1 Microstructure

HSS Shell (Hs 77–82° Sh'C)



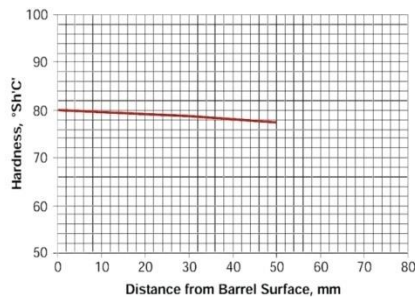
X100

SG Core (Hs 35–45° Sh'C)



X100

Optical micrographs different types of microstructures are present in roll MC (white), M7C3, M6C, and M2C are found. MC carbides are homogeneously distributed inside solidification cells, and M7C3 and M6C carbides are located along cell boundaries. Needle shaped M2C carbides are hardly found here. In roll B, where molybdenum is replaced by tungsten from the basic composition of roll A, MC carbides are observed inside cells, while M7C3, M6C and M2C carbides are observed along cell boundaries.



The HSS rolls generally have by high hardness and superior wear resistance oxidation resistant, and roughness compared with conventional work-roll materials such as adamite, nickel-grain cast iron or high-chromium cast iron. The properties of HSS rolls are determined by various microstructural characteristics such as the distribution of carbides, type, shape, volume fraction, and the characteristics of the tempered martensitic matrix, structure composed of intercellular carbides. Carbides directly influence the wear resistance of rolls and the surface quality of hot-rolled strips. The matrix microstructure contributes to the overall hardness, strength, and fracture toughness of rolls. The solidification cell structure also plays a critical role in determining the overall carbide distribution and directly affects both the fracture toughness and thermal-fatigue properties. Thus, these microstructural factors should be controlled in optimal combinations to manufacture HSS rolls having excellent properties.

3. RESULTS AND PERFORMANCE

Table 2: Finishing Mill Rolls Performance of Various Types of Rolls Production from Starting Diameter to Finishing/Scrapped Diameter in mm

Scrap diameter: 60 mm

Sl. No.	Roll Grade	Production	No. of Runs	No. of Cobbles	Un-productive Grinding (mm)	REMARKS	Roll Life (Ton/mm)
1.	Spun cast iron	201434	142	NIL	NIL	LOW DIA	3357.23
2.	Spun cast iron	201434	142	NIL	NIL	LOW DIA	3357.23
3.	High Crome iron	228599	153	2	7	LOW DIA	3890.98
4.	High Chrome iron	378208	241	NIL	NIL	LOW DIA	6303.47
5.	High Chrome Iron	244413	158	2	11	LOW DIA	4073.55
6.	High Crome iron	369170	238	NIL	NIL	LOW DIA	6152.83
7.	High Crome iron	276962	193	1	17	LOW DIA	4616.03
8.	High Crome iron	276962	193	1	17	LOW DIA	4616.03
9.	High Chrome Iron	264341	168	2	22.00	Shell Separation	4405.68
10.	High Speed steel Roll	558593	344	2	8.25	Shell Separation Low Dia	9309.88
11.	Spun cast iron	195630	129	NIL	NIL	LOW DIA	3260.50
12.	Spun cast iron	195630	129	NIL	NIL	LOW DIA	3260.50
13.	Spun cast iron	179690	119	1	6	Small spall	2994.83
14.	Spun cast iron	183191	117	2	3	LOW DIA	3053.18
15.	Spun cast iron	203229	128	NIL	NIL	LOW DIA	3387.15

Table 3: High Speed Roll Performance (Roll Life) in Rolling Mill

<i>TONS/MM</i>	<i>KM/MM</i>
12169.375	561.875
Service In F2 Stand	

<i>Shift</i>	<i>Roll No</i>	<i>Diameter</i>	<i>Campaigns</i>	<i>KM Rolled</i>	<i>Total Tonnage</i>	<i>Cumm Tonnage</i>	<i>Stock Removed</i>	<i>Cumm. KM Rolled</i>
B	037 036	646.15	1	45	855	855	0.05	45
C	037 036	646.1	1	64	1604	1604	0.05	64
B	037 036	646.05	1	50	932	1768	0.45	89
B			2	39	836			
A	037 036	645.6	1	47	1182	5355	0.15	249
B			2	53	1166			
C			3	62	1312			
B			4	42	802			
C			5	45	893			
A	037 036	645.45	1	34	597	3240	0.45	172
A			2	42	636			
A			3	39	780			
B			4	57	1227			
B	037 036	645	1	61	1323	2373	0.25	118
C			2	57	1050			
B	037 036	644.75	1	45	2017	4274	0.25	151

Shift	Roll No	Diameter	Campaigns	KM Rolled	Total Tonnage	Cumm Tonnage	Stock Removed	Cumm. KM Rolled
C			2	50	1199			
C			3	56	1058			
A	037 036	644.2	1	54	1735	4904	0.55	157
A			2	49	1695			
B			3	54	1474			
A	037 036	643.95	1	71	1360	3385	0.35	223
B			2	65	1296			
A			3	37	729			
A			4	50	984			
A	037 036	643.6	1	64	1393	3812	0.4	173
B			2	54	1139			
B			3	55	1280			
B	037 036	643.2	1	64	1274	5232	0.25	263
B			2	71	1420			
A			3	64	1282			
A			4	64	1256			
C	037 036	642.95	1	47	1143	2140		94
A			2	47	997			

4. CONCLUSIONS

To enhance the roll performance in rolling technology of advanced mills, the flat rolling process with adequate cooling system and suitable alloying elements of roll collectively support a more sustainable and progressive steel industry by increasing rolling efficiency and productivity of mill.

High-speed rolls manufactured by centrifugal casting and its influence of alloying elements on properties of the microstructure, hardness and fracture toughness and the corresponding performance of the rolls has been studied by implementing HSS rolls in rolling mill for flat rolling process.

The HSS rolls contains hard carbides such as MC, M₂C, M₇C₃, M₆C, and fine spherical carbides in the matrix. When carbon content in the matrix is low it consists mainly of lath tempered martensite. When the carbon content is gradually increased in the matrix in a significant amount, the plate tempered martensite with the overall bulk hardness increases. As the amount of plate tempered martensitic matrix and the total carbide fraction increases, it leads to improvement of the roll performance and rolling mill efficiency as well as reduces the roll changing time thereby finally increasing the productivity and high quality of rolling product.

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Improvement in Cooling Bed Efficiency by Introducing Forced Cooling System at Plate Mill

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ABSTRACT: Improvement in efficiency of finishing line is essential in further increasing the production of Plate Mill. High temperature of plates from cooling bed is one of the bottlenecks in increasing the production from finishing section. Plates with temperature $>80^{\circ}\text{C}$ cannot be processed in online UST as it damages the UST probe. Hence, the finishing line is stopped to achieve the target temperature of $< 80^{\circ}\text{C}$ for online UST. Sometime, this also leads to mill stoppage as no space is available in cooling bed to accommodate the plates. The mill stoppage on account of hot plates is around 30 hours annually in one of the Plate Mill. An automatic forced cooling system has been implemented to address the challenge of high plate temperatures in the cooling bed. The key components of the system include top and bottom cooling headers with strategically arranged nozzles to ensure uniform water spray coverage across the entire width of the plates. Sturdy structures have been fabricated and installed to support these headers. The pump motor set, featuring a self-cleaning filter, delivers water at 5 bar to the headers. A level sensor interlocked with the pump control panel guarantees uninterrupted water flow. A comprehensive control system, comprising ON/OFF shut-off valves, flow switches, plate sensors, and a controller, has been integrated to manage the initiation and cessation of cooling water spray as plates enter and exit the headers. Trials with the installed system carried out which has yielded promising results, showcasing a significant reduction in plate temperatures within the targeted range of $40\text{--}50^{\circ}\text{C}$. This reduction has led to no line stoppages on account of high temperature of plates in cooling bed during trial period. This would also help in reduction in annual UST probe consumption with regular use of this system. Intangible benefits, such as improved plate surface finish and enhanced marking, have been achieved during trial period through the installation of wipers in conjunction with forced cooling water.

Keywords: Forced Cooling System, Cooling Bed, UST Probe, Finishing Line, Plate Mill.

1. INTRODUCTION

The Plate Mill is 4.3 metre wide with the capacity of 1.0 MT. It is equipped with state-of-art technology to produce wide range of plates with close tolerances to meet stringent international standards. The 4-HI reversing mill is designed for roll force up to 90 MN, with hydraulic automatic gauge control, roll bending and shifting facilities and provision of on-line thickness, profile

and width measurement. The Plate Mill features an advanced computerized control system for plan view rolling process to maximize yield and an accelerated cooling system to produce high strength rolled plates including pipe grades up to API 5LX 100. The mill is designed with high capacity levellers with hydraulic control and under load positioning system, high capacity trimming and cross-cut-shears up to 50 mm capacity to produce distortion free plates.

The Plate Mill is presently running at more than 90% of its rated capacity. Improvement in efficiency of finishing line is essential in further increasing the production of the mill. There are two cooling beds for cooling the plates rolled in the mill, before further processing. Cooling bed is used for the uniform air cooling of the rolled plates. The cooling bed carefully moves and cools the hot plates after the hot rolling process. The plates are transferred one by one to the connecting roller table. The connecting roller table transfers the plates to inspection bed. The inspection bed is used for detailed visual surface inspection of the cooled plates from the top as well as from the bottom side. After surface inspection, plates are sent to finishing section for further processing such as ultrasonic testing, trimming, cut to size, marking etc. High temperature of plates from cooling bed is one of the bottlenecks in increasing the production from finishing section. Plates with temperature $>80^{\circ}\text{C}$ cannot be processed in online UST as it damages the UST probe. Hence, the finishing line is stopped to achieve the target temperature of $< 80^{\circ}\text{C}$ for online UST. This also leads to mill stoppage as no space is available in cooling bed to accommodate the plates. The mill stoppage on account of hot plates is 27 hours annually. To address high plate temperature, an automated forced cooling system has been implemented to lower plate temperatures preceding online UST.

2. LITERATURE REVIEW

Forced cooling through impingement processes is used to achieve high rates of heat transfer, enabling efficient cooling of materials. Impinging jets are utilized in various applications, including the drying of paper and textiles, cooling of turbine blades, glass tempering, electronics cooling, grinding processes, vehicle windscreen defrosting, and general heat transfer operations. A notable application of jet impingement cooling is

also in the cooling of hot steel plates [1,2]. Steel plates are produced by reheating steel slabs obtained from continuous casting to rolling temperatures of around 900°C . Achieving high-quality steel grades with desired microstructures requires precise cooling techniques. Water jet impingement cooling on the run-out table of a hot rolling mill is a crucial method to control the cooling process. This technique plays a significant role in producing advanced steel grades with desirable microstructures such as fine-grained ferrite, pearlite, and martensite, which contribute to the material's hardness and quality[2–4]. The cooling pattern and intensity on a hot rolling mill significantly influence the microstructural evolution of steel, particularly affecting the decomposition of austenite. Finely grained microstructures are typically achieved through a controlled water jet impingement cooling system. Heat removal is most effective when liquid water directly contacts the steel surface, leading to nucleate and transition boiling. In contrast, cooling is considerably less effective in areas where the steel surface is covered by a water vapor layer, resulting in film boiling[5]. To reduce the long processing time in controlled rolling of plates in one-stand reversible rolling mills, water cooling was applied. Experiments conducted in both a pilot plant and a production mill showed that using heavy water cooling during the holding period did not significantly affect the bulk mechanical properties. However, a thin surface layer with a very fine-grained structure was observed. This surface effect is not considered to impact the bulk properties, except at very low finish-rolling temperatures, where there is a risk of tensile stresses at the surface[6]. New generation thermo-mechanical control process (TMCP) based on ultra-fast cooling is being widely adopted in plate mill to product high-performance steel material at low cost [7]. Online adaptation models have been developed to adjust the cooling water flow rate in a plate mill using feedback and feedforward control algorithms. After being tested on an offline simulator, the model was

implemented in the online process, resulting in a 10% increase in the accuracy of the final cooling temperature [8]. The structure and composition of mill scale on linepipe steel, formed under both accelerated cooling conditions (ACC) and non-ACC, were investigated to assess their correlation with localized corrosion susceptibility [9]. The analysis of the mill scale structure and composition was conducted using scanning electron microscopy with x-ray energy dispersive spectroscopy, electron backscatter diffraction, and x-ray diffraction.

Most research on cooling strategies in hot rolling mills focuses on laminar or accelerated cooling, with the primary goal of achieving the desired properties in the steel. However, there is limited literature available on the cooling of plates after the cooling bed. The concept for developing a forced cooling system was derived from existing literature and then further refined and customized for the current application.

3. DESIGN OF FORCED COOLING SYSTEM

The Forced Cooling System designed considering the following conditions for plate cooling:

- Thickness of the plates to be cooled:
10–50 mm

- Plate Length: 6000–12000 mm
- Plate Width: 1.5–4.1 meter
- Grade of Steel that are processed at New Plate Mill: Low Carbon, Micro alloyed Steel
- Speed of Roller Table 1–2 m/s
- Average target of temperature drop: 40°C min.
- Average cooling rate: 10°C/s

The cooling system is configured to spray water from both the top and bottom onto the moving plate. Employing a full-cone spray type, the system is meticulously designed to ensure comprehensive coverage of the entire plate width, thereby facilitating uniform cooling. The layout of the top and bottom headers for full-width coverage of the plate is illustrated in Figure 1 general arrangement of headers along with supporting structure is shown in Figure 2. The arrangement incorporates precisely positioned nozzles and headers to optimize plate cooling and effectively rinse the plate surface, eliminating dirt and loose scale residue. The nozzle height on the top side is selected to uniformly cover the entire plate width. Following the air cooling system, a wiper is strategically provided to efficiently remove water from the top surface of the plates, contributing to the overall effectiveness of the cooling process.

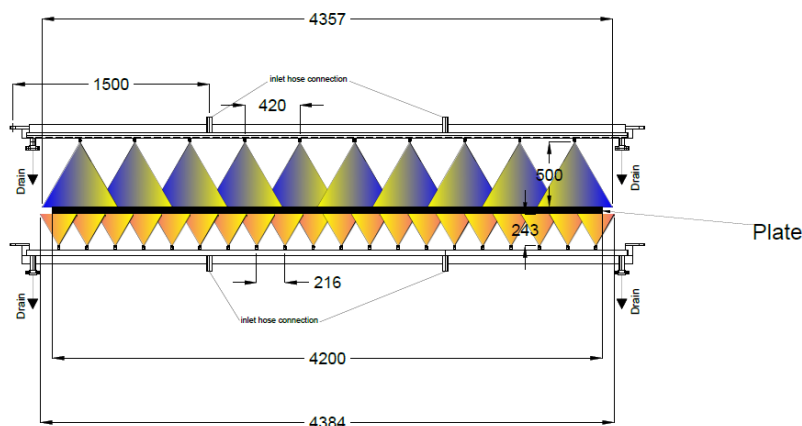


Figure 1: Layout of Top and Bottom Headers for Complete Coverage

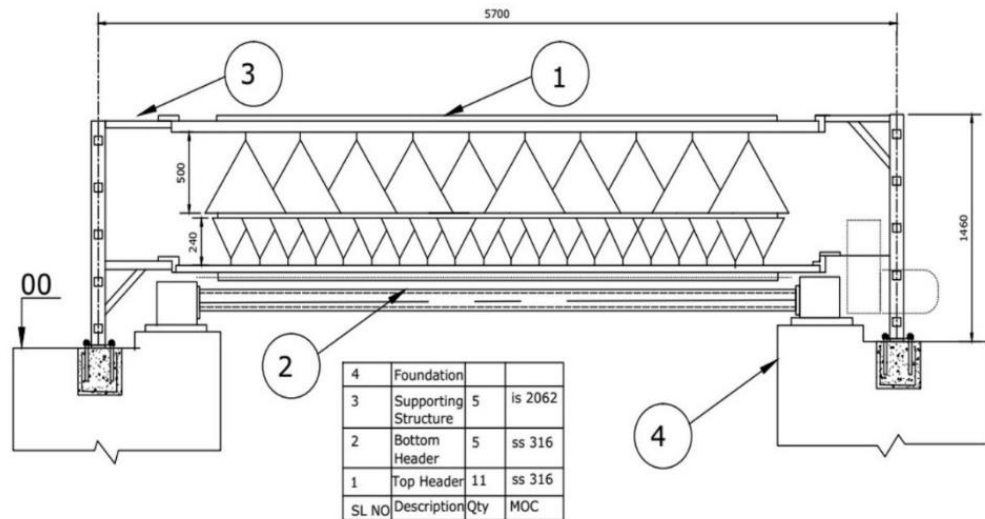


Figure 2: General Arrangement of Top & Bottom Header

4. INSTALLATION OF FORCED COOLING SYSTEM

The system is designed to deliver pressurized water at a range of 4–5 bar. To fulfill this requirement, a centrifugal pump with a capacity of 150 m³/hr at 5 bar has been selected. Additionally, a standby pump is incorporated to ensure uninterrupted system operation in the event of a pump malfunction. To safeguard the pump and prevent nozzle clogging, a self-cleaning filter with a capacity of 200 m³/hr and a filtration level of 250 microns has been installed in the pump's suction line. This self-cleaning filter plays a crucial role in maintaining water cleanliness, reducing the risk of pump failure and nozzle blockages. Furthermore, a pressure regulating valve, complete with a return line, is integrated into the system. This valve allows water to be efficiently returned to the tank when the system is not in use, and the pump remains in the "ON" condition. This feature ensures optimal system performance while conserving water and minimizing unnecessary pressure in the system during periods of inactivity. The combination of these components enhances the reliability and efficiency of the water supply system,

contributing to its overall functionality. Water tank has been provided before the pumping station to store the water and provide uninterrupted water to the cooling system. Tank of 5 m³ has been fabricated and installed in the suction of pumping system. Level sensor installed to indicate lower level of water in the tank has also been provided. Eight numbers of top cooling headers and four numbers of bottom roll cooling headers has been installed at the connecting table of New Plate Mill. Headers has been fabricated using full cone nozzles. The nozzles are arranged such that, water spray cover the total width of the plate without any interference. Proper structure has been fabricated and installed for holding the top and bottom headers. A specially designed collection pit has been fabricated beneath the roller table to collect the water sprayed onto the plate, effectively preventing water spillage in the connecting table area. This pit also serves as a reservoir for the water, which may contain scales washed off from the plates during the process. In order to manage the water in the pit, a slurry pump with a capacity of 50 m³/hr and a head of 15 meters has been installed. This pump comes with a comprehensive control panel and a level sensor in the

collection pit. The level sensor is crucial for monitoring the water levels in the pit, detecting both the “High” and “Low” water levels. The slurry pump operates automatically when the water in the pit reaches the “High” level, ensuring efficient removal. Conversely, it automatically switches “OFF” when the water in the pit reaches the “Low” level, indicating a seamless and automated operation without the need for manual intervention.

Control system has been provided for ON/OFF of cooling water spray, when the plate reaches and leave the cooling headers. The control system mainly consist of ON/OFF Shut Off valve, flow switch, plate sensors and controller. The HMI page for the forced cooling system has been created in the cooling bed operator's pulpit. Within this interface, an "Enable" switch is incorporated, allowing the operator to activate the system for cooling plates traversing the connecting table. Once the "Enable" switch is chosen, the operator must then select one of the two centrifugal pumps. The chosen pump is automatically activated after a 15-second delay. To synchronize the water supply with the plate movement, an optical sensor is strategically positioned at the connecting table, just before the forced cooling headers. This sensor detects the head end of the plate

and signals PLC to activate the “ON/OFF” valve in the delivery line of the selected centrifugal pump. This action facilitates the supply of pressurized water to the headers as the plate moves through the forced cooling section. Upon detecting the tail end of the plate, the optical sensor sends a signal to automatically switch off the “ON/OFF” valve. This closed-loop operation ensures the system functions seamlessly in “Auto” mode. Additionally, a pyrometer is installed at the system’s exit to measure the final temperature of the plate emerging from the forced cooling section. The initial temperature of the plate is recorded by an existing pyrometer installed at the cooling bed. This comprehensive setup allows for precise control and monitoring of the plate cooling process, enhancing the efficiency and automation of the entire system. The entire system functions in “Auto” mode, providing a hands-free operation. For situations where the operator desires additional cooling of the plate using the forced cooling spray header, a manual override switch is conveniently incorporated into HMI. This feature allows the operator to manually activate the forced cooling spray header for further cooling, providing flexibility while maintaining the overall system automation.

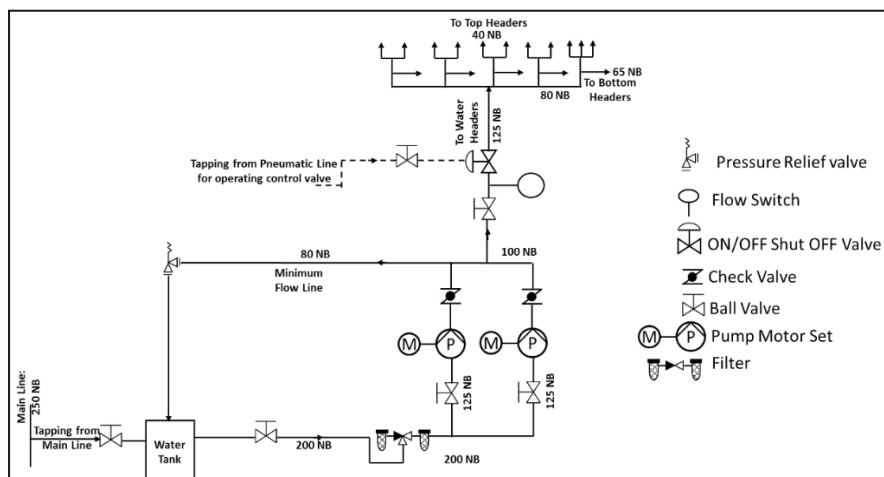


Figure 3: Schematic Diagram of Forced Cooling System

5. RESULTS & DISCUSSION

The installed forced cooling system was commissioned and operated in “Auto Mode”. Indicative control circuit of the installed system is given in Figure 4. A 5 m³ water tank has been installed to supply uninterrupted water during cooling the plates. Within the water tank, high and low-level sensors are implemented to monitor the water levels effectively. These sensors are integral to the system’s operation, providing crucial feedback for maintaining an optimal water level. The level sensors are connected to an “ON/OFF” valve located in the water input line. This valve is actuated in an “Open” position when the water level falls below the low threshold, facilitating water entry into the tank. As the water level rises and reaches the predetermined “High” level, the valve is

automatically triggered to the “Closed” position. This automated interlocking mechanism prevents overfilling of the tank, mitigating the risk of potential overflow issues. The coordination between the level sensors and the valve enhances the system’s efficiency and ensures precise control over the water flow, contributing to the overall reliability of the cooling process. Average time for one plate to pass through force cooling section is 15–25 seconds. The size of tank is calculated taking factor of safety into account so that it can fulfil uninterrupted water requirement for 2 minutes.

The system underwent trials, revealing a notable reduction in plate temperatures within the range of 40–50°C. The recorded data in Table 1 illustrates the effectiveness of the

Table 1: Temperature Drop with Forced Cooling System

Sl. No.	Plate No.	Plate Thickness (mm)	Initial Temp (°C)	Final Temp (°C)	Temp Drop (°C)	Speed (m/s)	Cooling Rate (°C/s)
1.	SCC059271	17.5	145	95	50	1.5	15
2.	SCC059272	17.5	148	100	48	1.5	14.4
3.	SCC059273	17.5	145	100	45	1.5	13.5
4.	SCC059274	18.0	146	97	49	1.5	14.7
5.	SCC059275	18.0	150	105	45	1.5	13.5
6.	SCC059276	18.0	150	102	48	1.5	14.4
7.	SCC059277	18.0	170	125	45	1.5	13.5
8.	SCC059302	20.0	135	85	50	2	20
9.	SCC059303	20.0	160	115	45	2	18
10.	SCC059304	20.0	160	114	46	2	18.4
11.	SCC059305	20.0	165	118	47	2	18.8
12.	SCC059306	20.0	165	115	50	2	20
13.	SCC059307	25.0	170	125	45	2	18
14.	SCC059308	25.0	175	125	50	2	20
15.	SCC059309	25.0	170	128	42	2	16.8
16.	SCC059310	25.0	178	135	43	2	17.2
17.	SCC059328	25.0	175	135	40	2	16
18.	SCC059329	32.0	170	127	43	2	17.2
19.	SCC059330	32.0	165	122	43	1.5	12.9
20.	SCC059331	32.0	168	122	46	1.5	13.8
21.	SCC059332	32.0	175	130	45	1.5	13.5
22.	SCC059333	32.0	175	132	43	1.5	12.9
23.	SCC059334	36.0	180	135	45	1.5	13.5
24.	SCC059335	36.0	185	135	50	1.5	15
24.	SCC059336	36.0	185	138	47	1.5	14.1

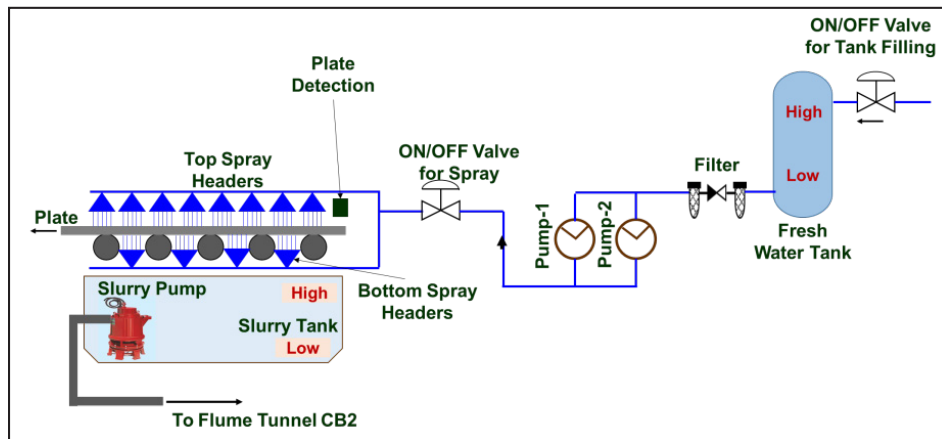


Figure 4: Control Circuit of Forced Cooling System

system in achieving this substantial temperature decrease. As a result of system implementation, there were no delays recorded on the cooling bed due to high plate temperatures. The system is designed for plate thicknesses up to 40 mm, which are sent to the inspection bed and then proceed to online UST. Plates with thicknesses greater than 40 mm are diverted at the connecting table for manual UST. The system is anticipated to contribute to a 70% reduction in the annual delay caused by high plate temperatures, from the existing 27 hours per year.

After processing through a forced cooling system, the plates proceed to the inspection bed and then to the online ultrasonic testing (UST). The forced cooling system reduces the plate temperature by 40–50°C, ensuring that the plates reach the online UST with a temperature below 80°C. This lower temperature is expected to enhance the lifespan of UST probes, as temperatures above 80°C can potentially damage them. Consequently, the introduction of the forced cooling system is projected to reduce the annual consumption of probes by 50%, decreasing from the usage of 36 probes per year before implementation of forced cooling system. In addition to these quantifiable benefits, the system brings about intangible advantages through the installation of wipers.

The forced cooling water not only washes away loose scale from the plate surface but also facilitates effective wiping. This dual action has resulted in an improvement in the surface finish of the plates, contributing to enhanced plate quality. The surface finish is also expected to lead to improved marking on the plates, further adding to the overall positive impact of the system.

6. CONCLUSIONS

- The forced cooling system has demonstrated its effectiveness in enhancing the efficiency and reliability of the plate cooling at connecting table. The system, designed to deliver pressurized water at 4–5 bar.
- The integration of an HMI page in the cooling bed operator's pulpit allows for user-friendly control, with an "Enable" switch, pump selection, and automatic activation based on optical sensor feedback.
- The trials conducted with forced cooling system has shown a significant reduction in plate temperatures within the targeted range of 40–50°C. This reduction has translated into a notable decrease in delays on the cooling bed, further emphasizing the system's positive impact on operational efficiency. No delay

recorded for holding of plates on account of high temperature after installation of the forced cooling system.

- The forced cooling system is anticipated to extend the lifespan of UST probes by mitigating potential damage due to higher plate temperatures. It is expected that there will be minimum 50% reduction in annual probe consumption with the use of this system.
- Intangible benefits, such as improved plate surface cleanliness and enhanced marking, have been achieved through the installation of wipers in conjunction with forced cooling water. These enhancements contribute to overall plate quality, adding further value to the system's implementation.

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Elimination of Edge Sliver Defect from Hot Strip Mill Kalinganagar of Tata Steel India

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ABSTRACT: Tata Steel India was facing issues of huge customer complaints from a customer of South India. The defect was mostly limited to the edges of a hot rolled coil. The product being made by the customer was tubes for hydraulic shock absorbers of earth moving equipment. The customer was using on-line and off-line automatic inspection system during the manufacture of tubes, and this was leading to detection of a lot of defects on the hot rolled coil.

Tata Steel's cross functional team led by Hot Rolling Technology Group and comprised of Quality Assurance, Operations and Product Application Group worked on the problem. The team identified root causes of the problem in both steelmaking and hot rolling areas. Trials were conducted with modified parameters in both the manufacturing locations.

Occurrences of the defect was closely monitored through the Automatic Inspection System at Hot Strip Mill and then at the customer's ends. The corrective actions taken by the team has resulted in zero occurrences and rejections at the customer's end. This has resulted in appreciation from the customer for this long-standing issue and concern.

The paper captures the journey undertaken by the Tata Steel team for reaching the desired outcome and the resulting learnings through the exercise.

Keywords: Hot Rolling Flat, Edge Sliver, Defect, Lateral Spread, Roughing Mill, Cold Charging.

1. BACKGROUND

The customer of Tata Steel utilizes Hot Strip Mill (HSM) Kalinganagar (TSK)'s HR coils for wide-diameter pipe manufacturing in hydraulic shock absorbers for heavy earth-moving machinery. Ultrasonic testing identifies surface defects, but visible edge sliver defects in HR coils led to customer concerns and reduced satisfaction.

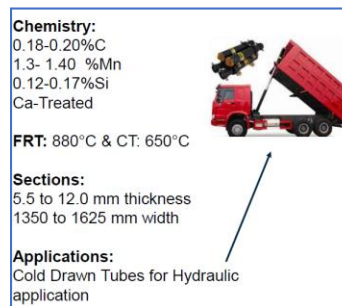


Figure 1: Tentative Chemistry and Mill Process Parameters of the Grade

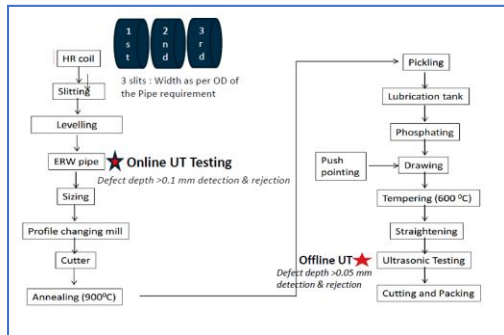


Figure 2: Material Process Flow at Customer's End

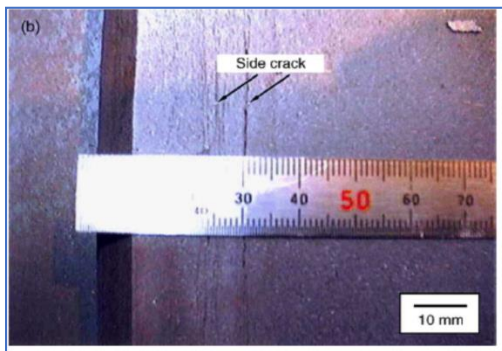


Figure 3: Defect on the Edge of the HR Coil



Figure 4: Defect on the Formed Component at the Customer's End

The defect was found on the online ultrasonic (UT) and offline UT stages of while making tubes out of slit hot rolled coils.

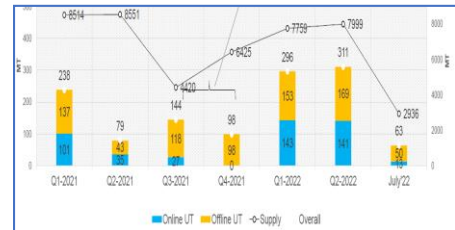


Figure 5: Trend of Rejections in Offline and Online UT at the Customer's Ends

2. ROOT CAUSE IDENTIFICATION

Root cause investigation involved literature review, metallographic study, and statistical analysis, leading to the formation of a cross-functional team. Gemba visits and data analysis pinpointed the issue and proposed essential corrective actions.

2.1 Metallographic Examination

Extensive metallographic investigations were carried out. Samples from both customer's end and internal samples from the manufacturing plant were investigated.

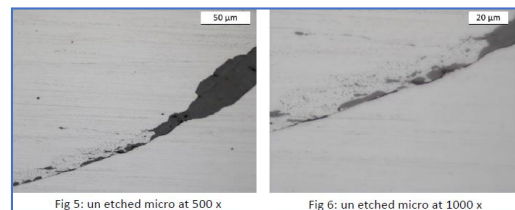


Figure 6: Metallography of Samples

The investigation revealed a strange morphology of internal oxidation present on one side of the crack only. This was found on multiple samples and was established well.

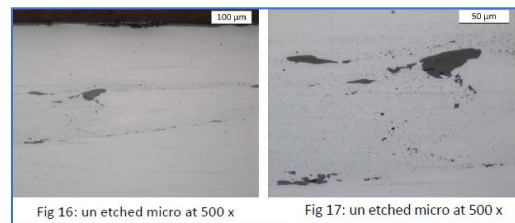


Figure 7: Metallography of Samples

The above microscope shows scale entrapment beyond the crack.

3. LITERATURE REVIEW

Literature review was done to find out the reason for the one-sided internal oxidation in the metallographic samples. A paper of relevance was found in Steel Research International of November 2008. The paper was titled 'From slab corner cracks to edge-defects in hot rolled strip – experimental and numerical investigations.' The paper mentioned that 'During the first rolling pass, the crack opens in rolling direction, which is due to the elongation in this direction, leading to an increasing crack aperture length. After about four passes, the crack bottom is elevated significantly, which leads to a reverse extrusion process of the material initially representing the crack flank. Moreover, the sides of the cracks are bent, folded and overlapped to the rising bottom. In this region the scale will be trapped, which explains the formation of interior oxidation layers. During the subsequent passes, the deformed edge defect will be elongated in rolling direction. It should be emphasized that the formation of tongues occurs in the direct neighbourhood of a "convolution line" which separates the folded bulk material from the bulk material extruded from the crack-bottom.'

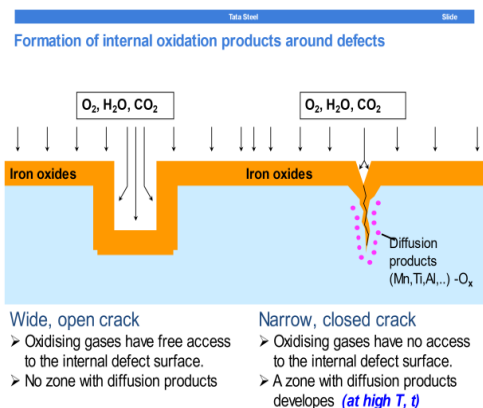


Figure 8: Formation of Internal Oxidation Products around Defects

This explanation helped the team focus on the roughing mill area as a possibility for the origin of the defect.

Another body of work done at Salzgitter plant in Germany suggested that depending on the amount of internal oxidation products around the crack, some inferences can be drawn.

The work also indicated the origin of the defect region based on the extensiveness of the zone of internal oxide products.

$$x = [(2N_O D_O / n N_Z) * t]^{1/2}$$

t = time

N_O = molar fraction dissolved oxygen (O) in the surface layer

D_O = diffusion coefficient of O in the steel

N_Z = molar fraction of the impure alloying element Z in the steel
(Z is e.g. Mn, Ti, Si, Al)

n = ratio of oxygen atoms/Z-atoms in the diffusion product ZO_n

Indicators for time of defect origination

- **x: extensiveness of zone**
 - casting/furnaces: large (~ 100 μm)
 - RM: small (< 10 μm)
 - FM: absent
- **maximum ZO_n particle size**

Figure 9: Indicators for Time of Defect Origination

Analysis:

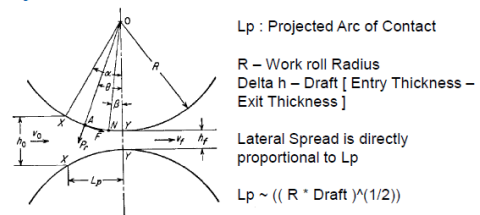


Figure 10: Projected Arc of Contact in a Stand of the Hot Mill

	Case-1	Case-2
Plant	HSM X	HSM Y
L_p [Projected Arc of Contact] : Lateral Spread	1.16 A / 1.17 B	A / B
• Spread in X >> Spread in Y • Edges in X colder [due to more spread]		

Technology

Figure 11: Comparison of the Lateral Spread in 2 Hot Mills of Tata Steel India

4. STATISTICAL ANALYSIS

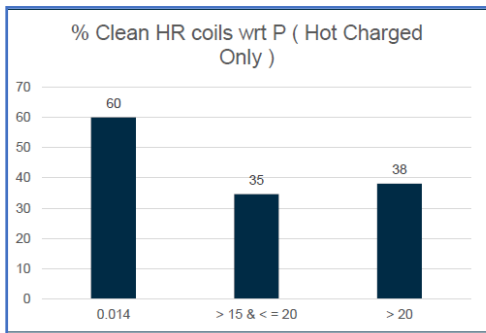


Figure 12: Clean Coil % wrt 'P' Level in Steel

The major factors that influence the high-temperature ductility are steel composition and dendrite orientation. The ductility is reduced by increasing sulphur and phosphorus contents, and for carbon levels in the range of 0.17 to 0.24%. Parallel dendrite orientation i.e. columnar structure, give rise to reduced ductility compared to random orientation characteristic of an equiaxed structure because columnar dendrites separate more easily under the influence of a tensile strain.

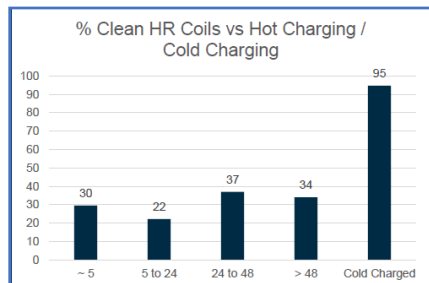
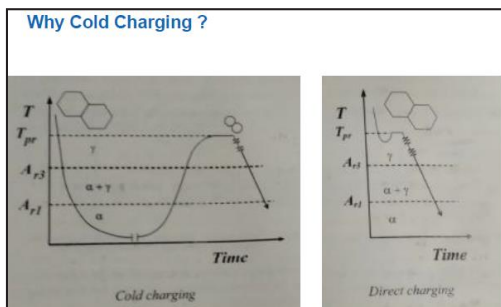


Figure 13: Clean Coil % w.r.t. Cold Charging of Slabs



4.1 Analysis/Actions Taken

1. Phosphorus reduced & Cold Charging only: To ensure thorough soaking.
2. Ensure: Furnace Retention Time & Soaking Zone Retention Time
3. Roughing Mill 1 Pass 1 Reduction set.

5. RESULTS OBTAINED

All the recommendations proposed by the Technology Group were implemented by Operations team beginning in Jan'23. Since then, no customer complaint has been received on this issue.

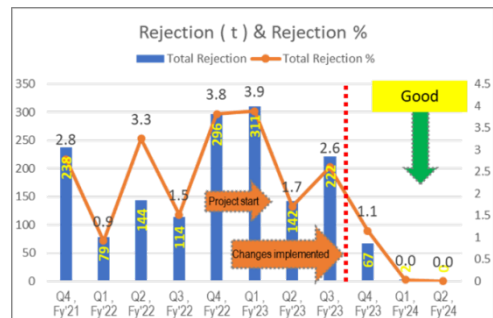


Figure 14: Trend of Customer Claims

ACKNOWLEDGEMENT

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Hot Rolled Fe-Mn-Al-C-Ni Duplex Low Density Steel: Microtexture and Mechanical Properties

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ABSTRACT: An austenitic duplex low-density steel with the composition Fe-18Mn-10.5Al-1C-5.8Ni was produced via induction melting under a controlled atmosphere and cast into plates with dimensions of $150 \times 100 \times 20 \text{ mm}^3$. The material was homogenized at 1200°C , hot-rolled between $1150\text{--}950^\circ\text{C}$, and quenched in water to get duplex microstructure without carbides. The measured density of the alloy was 6.68 g/cm^3 . Electron Backscatter Diffraction (EBSD) analysis revealed a microstructure consisting of 80% austenite and 20% B2 phase. Grain orientation spread analysis indicated that 77.1% of austenite grains were recrystallized, suggesting that the finishing rolling temperature was insufficient for complete recrystallization. The geometrically necessary dislocation density was calculated at $1.80 \times 10^4/\text{m}^2$. Microtexture analysis identified rotated cube texture components in the B2 phase along the $\langle 001 \rangle \parallel \text{ND}$ fiber, specifically (001) [110] at $\phi_2 = 0^\circ$, 45° , and 65° , with texture intensities of 5.2R, 5.1R, and 5.1R, respectively. Additionally, a rotated cube texture component of (010) [101] with an intensity of 5.2R was observed in the $\phi_2 = 0^\circ$ section. Further, an α -fiber component of (113) [110] with an intensity of 6.7R was identified at $\phi_2 = 45^\circ$. In the austenite phase, the texture analysis revealed the predominance of the “S” component with a maximum intensity of 3.22R, along with the “W” component ((001) [100]) with an intensity of 2.3R, the Brass component with an intensity of 2.3R, the “G/B” component ((110) [115]) with an intensity of 1.6R, and the “Copper” component ((112) [111]) with an intensity of 1.6R. Magnetic properties measured under $\pm 0.5 \text{ T}$ revealed a coercivity of 11.35 Gauss and a retentivity of 0.28 emu/g. The Young’s modulus was determined to be 161 GPa, lower than conventional steels due to the presence of aluminum, which reduces the elastic modulus by decreasing the lattice energy of the Fe-Al solid solution but the tensile testing showed a high yield strength (YS) of 1138 MPa, an ultimate tensile strength (UTS) of 1296 MPa, and a plastic elongation of 16.7%.

Keywords: Austenitic Low-density Duplex Steel, Microtexture and Mechanical Properties.

1. INTRODUCTION

The transportation sector is the second major contributor to global CO_2 emissions [1]. Reducing vehicle weight has become a key strategy to lower CO_2 emissions and to improve fuel efficiency [2]. Currently, vehicles are composed of 47 wt% steel [3]. The steel fraction includes 26% mild steel, 7% precipitation-hardened (PH)

steel, 34% dual-phase (DP) and multiphase steels, 9% bake-hardenable (BH) steels, and 24% high-strength low-alloy (HSLA) steels [4]. The UTS of DP steels ranges from 500 to 1200 MPa, while HSLA steels have a yield strength greater than 400 MPa [4]. This presents a significant opportunity to replace these steels with alternative materials, given that steel’s high density—7.8 g/cc for ferritic and 8.1 g/cc for austenitic phases—limits

weight reduction potential. While various steels are used to balance strength, ductility, and cost, achieving further weight reductions is challenging due to limitations in down-gauging, which compromises ductility and stiffness. Alternative materials like aluminum and magnesium alloys, despite their low density, often fall short in terms of strength, cost, stiffness, and dent resistance. Low-density steels, alloyed with aluminum, manganese, carbon, chromium, and silicon, offer a viable alternative for weight reduction. They achieve lower densities through lattice expansion and lighter atomic masses, with yield strengths of 500 to 940 MPa, ultimate tensile strengths of 710 to 1020 MPa, and total elongation of 8 to 78 percent [5]. Zuazo *et al.* demonstrated through finite element front crash simulations that replacing DP 600 steel with austenite and austenite-based duplex low-density steels can reduce the weight of components by over 30% [6]. Incorporating nickel into these steels promotes the ordering of Ni and Al atoms through high-temperature annealing, leading to the formation of B2 precipitates, which further enhances the strength of these steels up to 1400 MPa [7].

Yang *et al.* studied the strain hardening behavior of Fe-16Mn-10Al-0.86C-5Ni high-specific-strength steel (HSSS) during uniaxial tensile deformation, finding that the extraordinary strain hardening rate is due to high back stresses arising from strain incompatibility caused by the microstructural heterogeneity of B2 and austenite phases [8]. G. Parks *et al.* studied the effect of B2 morphology on tensile properties of Fe-15Mn-10Al-0.8C-5Ni and Fe-16Mn-8Al-1C-5Ni steels, finding that a more homogeneous microstructure with fine B2 particles in Fe-16Mn-8Al-1C-5Ni enhances isotropic tensile properties and formability, despite having lower strength than the B2 banded Fe-15Mn-10Al-0.8C-5Ni steel [9]. Wang *et al.* enhanced the strength of nickel-added steels up to 1700 MPa by increasing key element percentages in Fe-29.18Mn-8.82Al-1.2C-6Ni

(wt.%) or Fe-26Mn-16Al-5Ni-5C (at. %) through dual nano precipitation of B2 and kappa carbide via cold rolling and short-time annealing [10]. Zargarani *et al.* addressed the challenge of controlling B2 phase morphology in hot-rolled lightweight steels by using κ -carbide nanoparticles to promote B2 formation, resulting in uniformly distributed B2 nanoparticles (20-500 nm) within the austenite matrix [11]. B. Mishra *et al.* found that Ni-free Fe-Mn-Al-C low-density steels with fine κ -carbides had better ductility compared to Ni-containing steels with coarser κ -carbides and B2 phases, which had higher strength but lower ductility [12]. Pavan Kumar *et al.* found that electropulsing refines and reprecipitates the B2 phase in Fe-18Mn-10.5Al-1C-6Ni low-density duplex steel, enhancing yield strength to 1077 MPa, tensile strength to 1355 MPa, and plastic elongation to 21.6% by reducing size of B2 phase and improving uniformity [13].

Existing literature on nickel-added low-density steels primarily addresses achieving a balance between strength and ductility through refinement of B2, changes in morphology, and uniform precipitation. However, there is a notable gap in research on the evolution of texture in these steels. Additionally, there is a lack of literature on the magnetic properties of these austenite based duplex low-density steels. It is known that combining recrystallized grains with non-recrystallized grains enhances strength without significantly compromising ductility. Thus, during hot rolling, the final pass is conducted slightly below the recrystallization temperature of austenite to retain some non-recrystallized grains, followed by water quenching to prevent the formation of coarse κ -carbides. Thus, the objective of the present investigation is to characterize the microtexture of hot-rolled and water-quenched duplex low density steel and evaluate their magnetic properties. The microstructure and microtexture of the hot-rolled and water-quenched steel were examined using EBSD

analysis, and its tensile properties were evaluated. Additionally, the magnetic properties were analyzed.

2. EXPERIMENTAL PROCEDURE

An austenite-based duplex steel with a composition of Fe-18%Mn-10%Al-1%C-6%Ni (by mass %) was designed and produced using an induction melting furnace under controlled atmospheric conditions. The detailed melting process was explained in author's previous work [13]. Thermo-Calc software guided the selection of a homogenization temperature of 1200°C (1473 K), within the austenite (FCC_A1) and ordered delta ferrite (BCC_B2) stability regions. Rectangular bars (100 mm × 15 mm × 12 mm) were sectioned from the cast plate using wire-cut EDM, homogenized at 1200°C for 1 hour, and then hot-rolled with a 75% reduction to refine the microstructure. Rolling was conducted with 1 mm reductions per pass at elevated temperatures and a final 2 mm pass at 950°C (1223 K), followed by immediate water quenching to maintain high dislocation density and avoid precipitate formation. Designated as PD1, the hot-rolled material was analyzed for carbon content via LECO CS744, and other elements via inductively coupled plasma-optical emission spectroscopy, confirming a composition of 18.17% Mn, 10.51% Al, 1.04% C, 5.88% Ni, 0.21% Si, and 0.24% Cr. The density of PD1 was determined using Archimedes' principle. Elastic modulus was determined using an Olympus EPOCH 600 ultrasonic tester. Equations 1, 2, and 3 were utilized to calculate Poisson's ratio (ν), elastic modulus (E), and shear modulus (G) [14].

$$\nu = \frac{1 - 2\left(\frac{V_T}{V_L}\right)^2}{2 - 2\left(\frac{V_T}{V_L}\right)^2} \quad \dots (1)$$

$$E = V_L^2 \cdot \frac{\rho \cdot (1 + \nu) \cdot (1 - 2\nu)}{(1 - \nu)} \quad \dots (2)$$

$$G = V_T^2 \cdot \rho \quad \dots (3)$$

Where V_L is the longitudinal wave velocity and V_T is transverse wave velocity.

Samples measuring $10 \times 10 \times 3 \text{ mm}^3$ were mounted on a conducting polymer, then ground and polished using $0.05 \text{ }\mu\text{m}$ colloidal silica. These samples were analysed for electron backscatter diffraction (EBSD) using a scanning electron microscope (SEM) (FEI Scios II dual beam FIB-FESEM) operating at 20 kV, with a 15 mm working distance, and a 70° tilt angle. The scan area was $100 \times 100 \text{ }\mu\text{m}^2$, with a step size of $0.15 \text{ }\mu\text{m}$. The collected data was post-processed using TSL-OIM v8 software to examine phase fractions, microstructure, and residual strain within the material. Flat tensile samples with dimensions of 15 mm gauge length, 5 mm width, and 2 mm thickness were cut using electrical discharge machining (EDM). The gauge length sections were mechanically ground to achieve a smooth surface. Uniaxial tensile tests were performed at room temperature on PD1 samples using an Instron 5982 universal testing machine with a 100 kN capacity, at a strain rate of 0.001 s^{-1} . Yield strength (YS), ultimate tensile strength (UTS), and total plastic elongation were derived from the load-elongation data, with reported values representing the average of two tests to ensure consistency. The magnetic properties at room temperature were evaluated under an applied magnetic field of ± 0.5 Tesla.

3. RESULTS & DISCUSSION

The EBSD-derived micrographs of the PD1 sample are depicted in Figure 1. In Figure 1(a), the phase map reveals a predominance of the face-centered cubic (FCC) phase, represented in red, which constitutes 79.8% of the total microstructure. The green regions correspond to the body-centered cubic (BCC_B2) phase, accounting for 20.2%. The microstructure exhibits both banded and globular morphologies of the B2 phase. The banded morphology likely developed during hot rolling due to the high aluminum content,

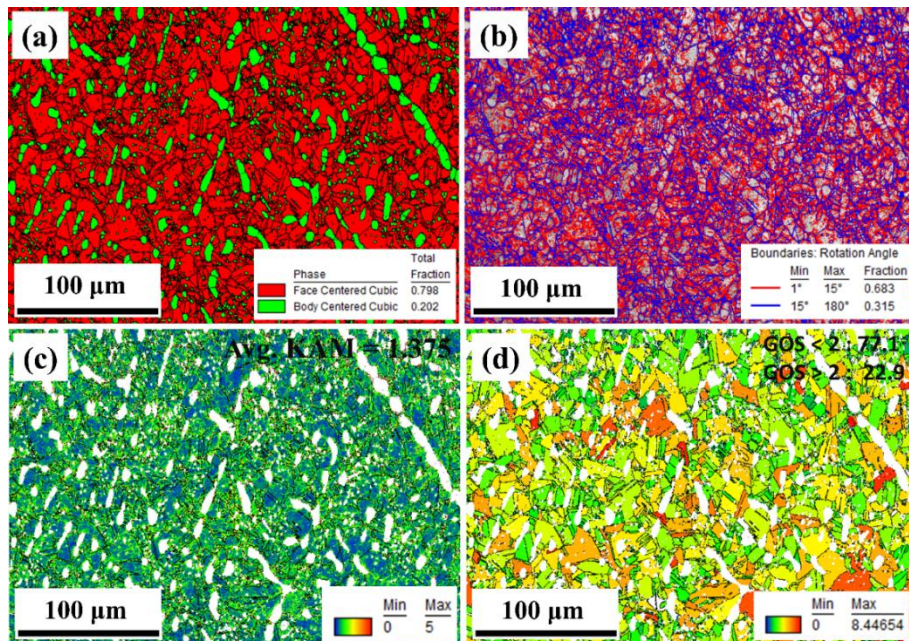


Figure 1: EBSD-derived micrographs of PD1 showing (a) Phase map, (b) Image quality map with superimposed grain boundaries (1–15° representing low angle grain boundaries, 15–180° representing high angle grain boundaries), (c) Kernel average misorientation (KAM) map of austenite (blue indicating low strain, red indicating maximum strain), and (d) Grain orientation spread (GOS) map of austenite.

which stabilizes the B2 phase. The globular B2 particles are thought to have precipitated during the same hot rolling process, particularly at recrystallized grain boundaries [7]. The higher processing temperatures contributed to the coarsening of these precipitates. Austenite grains display noticeable twin formation. Additionally, a bimodal grain size distribution is observed, with grain sizes ranging from 413 nm to 24 μm. Specifically, only 2% of grains are below 1 μm, 78.65% fall within the 1–12.7 μm range, and 19.35% grains are in the range from 15.79 to 24.93 μm. The average austenite grain size is calculated to be 9.7 ± 5.7 μm. For the B2 phase, only 3.4% of grains are below 1 μm, 44.5% fall within the 1–5 μm range, and the remaining 52.1% are between 7 and 15.2 μm. The average grain size for the B2 phase is 5.8 ± 3.6 μm. Figure 1(b) presents the image quality (IQ) map of the PD1 sample, with superimposed grain boundaries to highlight

the microstructural features. The grain boundaries are categorized into low-angle grain boundaries (LAGBs), characterized by misorientations between 1° and 15°, are shown in red and high-angle grain boundaries (HAGBs) based on their misorientation angles higher than 15°, i.e. 15° to 180°. LAGBs constitute 68.3% of the total boundary fraction. This significant proportion of LAGBs indicates a substantial degree of substructure formation, which is likely the result of thermomechanical processing. During hot rolling, the material undergoes continuous deformation combined with elevated temperatures, promoting the rearrangement of dislocations into LAGBs. This process helps to reduce the internal energy of the material, contributing to the observed high fraction of LAGBs. On the other hand, HAGBs, represented in blue, account for 31.5% of the total boundary fraction. The presence of HAGBs is attributed

to dynamic recrystallization, a process where the accumulated strain energy during deformation leads to the nucleation of new grains. These newly formed grains exhibit higher misorientation angles relative to the parent grains, resulting in the formation of HAGBs. The lower fraction of HAGBs suggests that dynamic recrystallization was limited during hot rolling treatment. Fig. 1(c) presents the Kernel Average Misorientation (KAM) map for the austenitic (FCC) phase, where KAM values are depicted on a colour scale ranging from blue (low) to red (high), corresponding to regions of minimal to significant local misorientation, respectively. The average KAM value for the austenite phase was calculated to be 1.375° . KAM reflects the average misorientation of a given point relative to its neighbouring points, making it particularly sensitive to variations in dislocation density and local lattice distortions. Higher KAM values, observed as red or yellow regions, indicate areas of elevated dislocation density and stored strain energy within the grain structure [15]. In the KAM map, it is evident that regions surrounding the B2 phase, especially at the interface between B2 and austenite, exhibit higher KAM values. This suggests a significant degree of lattice incompatibility between the two phases, likely due to differences in their crystallographic structures and mechanical behaviour. The central areas of the austenite grains, shown in blue, are relatively strain-free, indicating minimal dislocation activity or lattice distortions in these regions. In contrast, the areas near the grain boundaries of the austenite phase show a moderate level of strain distribution, as evidenced by the intermediate colour gradations. Figure 1(d) displays the grain orientation spread (GOS) map of the austenite phase. GOS represents the average misorientation of all points within a grain relative to the grain's mean orientation, serving as a key indicator of the level of plastic deformation each grain has undergone. The map uses a color gradient, with green

representing low GOS values and red indicating high GOS values, to illustrate the degree of deformation within the grains. A GOS value of $\leq 2^\circ$ is typically used to distinguish between recrystallized and deformed grains [16]. In this map, 77.1% of the grains fall within the recrystallized category, characterized by low GOS values, indicating minimal internal strain and uniform orientation within those grains. Conversely, 22.9% of the grains show higher GOS values, indicative of non-recrystallized regions where significant plastic deformation has occurred. The GOS map reveals a considerable variation in deformation across the microstructure, with some regions exhibiting GOS values as high as 8.44° . This suggests that the deformation is heterogeneous, with certain areas experiencing much higher levels of strain, potentially due to localized stress concentrations or differences in grain orientation and boundary conditions during thermomechanical processing. The geometrically necessary dislocation density was calculated at $1.80 \times 10^{14}/\text{m}^2$.

Figures 2(a) and 2(b) depict the orientation distribution function (ODF), from EBSD data, of the B2 phase and austenite phase in the PD1 sample. ODF sections of sample PD 1 (Figure 2 (a)) show rotated cube texture components for the B2 phase of $\langle 001 \rangle \parallel \text{ND}$ fibre, $(001) [\bar{1}\bar{1}0]$ in positions 1 ($\varphi^2 = 0^\circ$), 4 ($\varphi^2 = 45^\circ$) and 6 ($\varphi^2 = 65^\circ$) having texture intensity of 5.2R, 5.1R and 5.1R, respectively. In addition, another rotated cube texture component of $(010) [101]$ of intensity 5.2R is also found in $\varphi^2 = 0^\circ$ section. Further at position 3 ($\varphi^2 = 45^\circ$) α -fibre component of $(113) [\bar{1}\bar{1}0]$ with an intensity of 6.7 R is also found. In BCC materials, rotated cube components have excellent stability due to their smaller Taylor factor which indicates low strain energy [17]. It forms by rotating the cube components by 45° from the rolling direction. Austenite texture in PD1 sample (Figure 2(b)) mainly shows the "S" component with maximum intensity of 3.22 R

at position 8, “W” ($\{001\} [100]$) with intensity of 2.3 R at position 1, Brass component with intensity of 2.3R at position 2, “G/B” ($\{110\} [115]$) type component with intensity of 1.6R at position 7, “Copper” ($\{112\} [111]$) component with intensity of 1.6R at position 6. The deformation texture of FCC materials is often characterized by the presence of Brass ($\{110\} \langle 112 \rangle$), Copper ($\{112\} \langle 111 \rangle$), S ($\{123\}$), and Goss ($\{110\} \langle 001 \rangle$) texture components and in recrystallization texture Cube ($\{100\} \langle 001 \rangle$), Goss ($\{110\}$), and Brass ($\{110\}$) [18]. The formation of an “S” type texture with major intensity, as indicated in the texture analysis, suggests the presence of deformed austenite grains within the microstructure.

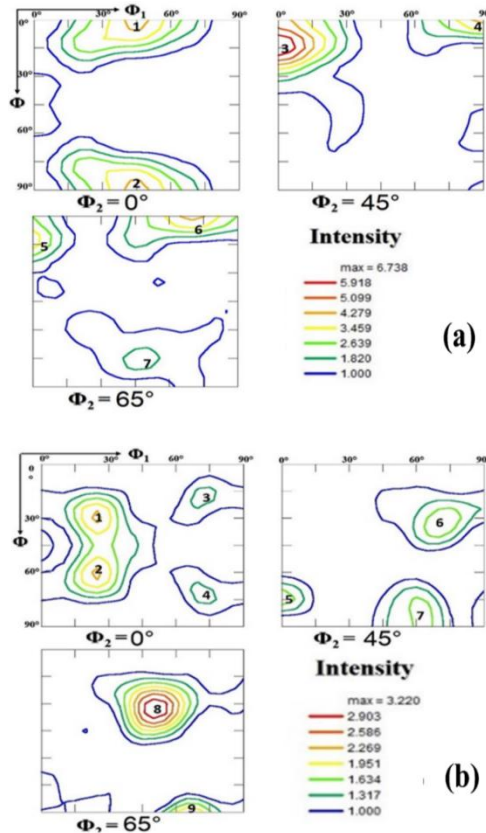


Figure 2: $\phi^2 = 0^\circ$, 45° and 65° Sections of Orientation Distribution Functions (ODFs) for (a) BCC_B2 and (b) Austenite Phases in PD1 Sample

Tensile testing results showed that PD1 has high yield strength of 1138 MPa, an ultimate tensile strength of 1296 MPa, and a plastic elongation of 16.7%. The elastic modulus of PD1 sample is measured to be 161 GPa lower than conventional steels due to the presence of aluminum, which reduces the elastic modulus by decreasing the lattice energy of the Fe-Al solid solution [19]. The magnetic behaviour of PD1 is shown in Fig. 3. The magnetic properties of PD1 were evaluated at room temperature using a vibrating sample magnetometer with an applied field of ± 5 kOe. PD1 exhibits a saturation magnetization of ~ 4.65 emu/g, retentivity of ~ 0.28 emu/g, and coercivity of ~ 11.35 Gauss, respectively. The presence of a significant amount of the B2 phase, which is ferromagnetic, contributes to these magnetic properties. This is likely influenced by the rotated cube texture observed in the B2 phase, which is known to be favourable for magnetic performance in materials, akin to those used in silicon steel for electrical applications [20]. The presence of the austenite phase, being non-magnetic, does not contribute to the overall magnetic behaviour, as its paramagnetic nature results in minimal interaction with the applied magnetic field [21],

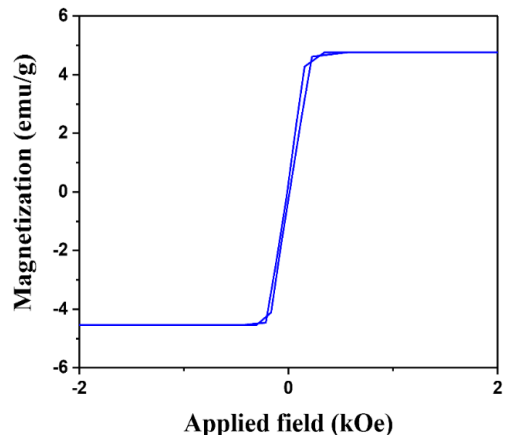


Figure 3: Room Temperature M vs. H Hysteresis Loops under ± 0.5 T of PD1

4. CONCLUSIONS

Based on the above results and discussions, the following conclusions were made:

1. The microstructural analysis of the PD1 sample reveals a predominant FCC phase of 80% with a bimodal grain size distribution and significant B2 phase presence of 20%, characterized by banded and globular morphologies, which are influenced by hot rolling and the high aluminum content.
2. The predominance of low-angle grain boundaries in the PD1 sample indicates substantial substructure formation due to thermomechanical processing, while the limited presence of high-angle grain boundaries suggests restricted dynamic recrystallization during hot rolling.
3. KAM map of the austenitic (FCC) phase, revealing that higher KAM values, particularly near the B2 phase interfaces, indicate significant lattice incompatibility and elevated dislocation density, while central regions of the austenite grains are relatively strain-free with minimal dislocation activity.
4. GOS map of the austenite phase, where 77.1% of grains are classified as recrystallized with low GOS values, indicating minimal internal strain, while 22.9% of grains exhibit higher GOS values, reflecting significant plastic deformation and heterogeneous strain distribution across the microstructure.
5. ODF of the B2 and austenite phases in the PD1 sample, showing the B2 phase with rotated cube texture components and an α -fiber component, while the austenite phase primarily exhibits an "S" texture component with significant intensity, suggesting the presence of deformed austenite grains within the microstructure.
6. The PD1 sample exhibits a high yield strength of 1138 MPa, ultimate tensile strength of 1296 MPa, and a plastic

elongation of 16.7%, with a lower elastic modulus of 161 GPa.

7. The magnetic properties, characterized by a saturation magnetization of 4.65 emu/g, retentivity of 0.28 emu/g, and coercivity of 11.35 Gauss, are significantly influenced by the ferromagnetic B2 phase with a favourable rotated cube texture, while the non-magnetic austenite phase has minimal impact on the overall magnetic behaviour.

5. AUTHOR CONTRIBUTIONS

Rajavarapu Pavan Kumar: conceptualization, methodology, experimentation, data analysis, data curation, original draft. N.C. Santhi Srinivas: conceptualization, data curation, supervision, and reviewing and editing the manuscript. R. Manna: funding acquisition, conceptualization, data curation, supervision, and reviewing and editing the manuscript.

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DATA AVAILABILITY

All data presented in this study are available upon request through email to the corresponding author.

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Development of Online Property Prediction Models for Flat Rolled Products

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ABSTRACT: Hot rolling and cold rolling are crucial processes in steel manufacturing, each with significant impact on the final product's mechanical properties. In hot rolling, continuously cast slabs are heated above their recrystallization temperature and rolled into thin sheets or coils. Whereas the Cold Rolled Close Annealed (CRCA) steel coils are processed in the inter-critical annealing range post cold rolling to achieve an optimum combination of strength and formability. The mechanical properties of these HR and CRCA steel coils - UTS, YS, and %El - are significantly influenced by grade composition and process parameters at each stage. Key parameters such as composition, temperatures, and dimensional changes throughout the manufacturing stages determine the final mechanical properties. This mandates testing for every coil for their mechanical properties for maintaining stringent quality control. It requires multiple steps of sample collection, preparation and testing which involves huge time and effort. Moreover, there is a significant time delay of 20–30 hours between sampling and testing, which delays decision making in case of quality deviations. To mitigate this issue, fully automated online property prediction models were developed using machine learning techniques to predict the mechanical properties of all the flat rolled coils processed at hot rolling (HR) and continuous annealing lines (CAL) without any time delay. Hot rolling, cold rolling and annealing parameters along with composition were selected as inputs for the models. Gradient boosting technique was deployed to develop the models using Python language. The HR property prediction model achieved an R^2 of 0.96 for UTS, 0.92 for YS and 0.85 for %EL whereas the CAL property prediction model achieved an R^2 of 0.99 for UTS, 0.98 for YS and 0.96 for %EL. Subsequently, the models were deployed on-line by interfacing through hot and cold rolling plant automation systems to predict the properties of all the HR and CRCA coils on a real time basis in a fully automated manner, yielding an average accuracy of ~98% for UTS, ~97% for YS, and ~95% for %El. An online dashboard and mailing system was created to monitor and automatically report the model performance to the concerned. Post deployment, the model helped in improving the process yield through reduced sampling and also enabled quick quality clearances and faster corrective action at the operators' in case of any deviation or deterioration in properties. Thus, by leveraging advanced machine learning techniques, both hot rolling and cold rolling processes have been optimized for improved efficiency in predicting mechanical properties, thus enhancing overall quality control and decision-making in steel manufacturing.

Keywords: Hot Rolling, Continuous Annealing Line, Property Prediction Model, Machine Learning, Gradient Boosting.

1. INTRODUCTION

The hot-rolled steel plates or coils are widely used in various industrial

applications such as construction engineering, machinery and container manufacturing, ship building, bridge construction and related

industries given their excellent mechanical properties and weldability. Different hot rolled steel grades correspond to different elemental compositions and processing parameters and are often produced on an industrial scale through the thermomechanical controlled processing (TMCP) technique to improve the microstructure and mechanical properties of hot rolled steel by controlling the rolling and cooling parameters in the rolling mill. On the other hand, new generation steels like IF (Interstitial-Free) and AHSS (advanced high strength steels) are widely used for automotive and structural applications. They offer unique combination of low weight, high strength and optimised formability, which allows automakers to use less material, greatly reducing a vehicle's weight. Conventionally, these steel grades are produced through Steelmaking → Hot rolling → Cold rolling → Continuous Annealing route. The mechanical properties of these flat rolled coils (UTS, YS and %El) are very important in determining the end-application of the material and must be achieved in close tolerances as per the customer specifications. The final mechanical properties depend on several parameters such as chemical composition of steel, hot and cold rolling parameters and temperatures along with annealing temperature, annealing time, and initial grain size.

The relation between the parameters and mechanical properties is highly nonlinear and requires complex numerical models for accurate estimation. Therefore, routine tensile testing is often carried out for determination of mechanical properties (UTS, YS & %EL) of hot rolled (HR) and cold rolled and continuous annealed (CRCA) coils for ensuring compliance to customer specifications. However, it requires multiple steps of sample collection, preparation, testing and reporting which involves huge time and effort and often leads to over-sampling. Occasionally, due to sampling or measurement system errors, abnormal properties get

reported, which requires resampling and re-testing, again adding to the overhead costs.

Mechanical property prediction is a very important tool for the steel manufacturers because it helps to avoid quality problems and increase productivity. However, prediction of yield strength, tensile strength and elongation of steel after hot rolling, cold rolling and continuous annealing through analytical methods is a difficult task because the relation between mechanical properties and process parameters like hot rolling temperatures, %reduction, annealing time, annealing temperature and alloying elements of steel is highly nonlinear. Moreover, analytical models mostly depend on experimental constants, which are hard to obtain for industrial processes due to the wide range of the process parameters. The relation between the parameters and mechanical properties is highly nonlinear and requires complex numerical models for their estimation. These relations have to be known by steel manufacturers to avoid quality problems and increase the productivity. In such complex scenarios, data based prediction models are quite helpful in predicting the desired parameters. These models can be developed quite quickly from the historical data and are computationally inexpensive to deploy.

Machine learning deals with the studies of the design of algorithms that can learn on its own after training on an initial dataset. Typical machine learning tasks are concept learning, function learning or “predictive modeling”, clustering and finding predictive patterns. The ultimate goal is to improve the learning in such a way that it becomes automatic, so that manual intervention is not required. In the present work, data analytics and machine learning based predictive algorithms have been used to develop online mechanical property prediction models for hot rolling (HR) and continuous annealing lines (CAL) at JSW Steel Ltd. Vijayanagar Works.

2. LITERATURE REVIEW

As the hot rolling followed by annealing process is a complex and dynamic nonlinearity system, it is extremely difficult to express the relationships mathematically. Various aspects of hot and cold rolling followed by continuous annealing processing have been explored in great detail by numerous researchers. The effects of process parameters and grade composition on final mechanical properties of the processed steel coils have been duly investigated.

Noppon *et al.* have established empirical relations using MLR for prediction of UTS, YS and %EL as a function of chemical compositions and rolling parameters for low carbon steel grades. Seven thousand sets of data consisting of mechanical properties, chemical compositions, and rolling parameters of industrial hot-rolled coils were analysed using multiple regression. This was to establish empirical formulas to predict mechanical properties of steel as a function of chemical compositions and rolling parameters [1]. Xu *et al.* have developed a convolutional neural network (CNN)-based method for predicting the mechanical properties of hot rolled steel using chemical composition and process parameters. They have concluded that the TS is more affected by the change of carbon content and the YS is more affected by the finish rolling and coiling temperatures [2]. Saravanakumar *et al.* have developed a mechanical properties prediction model for hot rolled coils of IS1079 Gr. D steel having 0.12% max C, 0.5% max. Mn, 0.04% max. S and 0.04% max. P [3]. Mohanty *et al.* have postulated that the rolling process is complex and final mechanical properties of steel depend on many parameters, it is almost impossible to develop an accurate first principle based mathematical model. They have developed artificial neural network based model to predict the mechanical properties of hot rolled steel strip for IF steel grades. The developed model is capable of capturing

various metallurgical phenomena during rolling [4]. Patel *et al.* have reported the impact of composition and processing parameters on properties of HSLA steel with approx. 0.07% carbon and varying Mn levels along with different micro alloying elements. Good toughness can be achieved through grain refinement (the Hall-Petch relationship) and a reduction of second phase micro constituent. A reduction in the latter also improves the cold formability [5].

Kuang *et al.* have given a brief overview on the effect of continuous annealing parameters on the mechanical properties and microstructures of a cold rolled dual phase steel through Gleeble simulations. They have reported that soaking between 760 and 820°C for more than 80 s, rapid cooling at the rate of more than 30°C/s from the quenching temperature between 620 and 680°C, and overaging at less than 300°C are beneficial for the mechanical properties of DP steels [6]. Kong *et al.* have conducted annealing experiments in the laboratory based on the actual industrial production process in order to investigate the effects of continuous annealing process parameters on the microstructure and mechanical properties of DP steel quantitatively. They have found that the effect of the intercritical temperature, the slow cooling temperature, the over-aging temperature, and the strip speed have a significant effect on the microstructure and mechanical properties of DP steel [7]. Ayres *et al.* have studied the effect of intercritical annealing on the mechanical properties of dual-phase steel. They have reported that the volume fraction and grain size of martensite increase with increasing soak temperature, higher soak temperatures also led to tempered martensite in the final microstructure. Increasing the soak temperature led to an increase in martensite grain size and a decrease in ferrite grain size. The best combination of strength and ductility was achieved at the highest soak temperatures, but resulted in poor BH performance [8].

Qian Xie *et al.* postulated that numerous machine learning algorithms exist, such as multilinear regression, support vector machine, decision trees, boosting trees etc., deep neural network (DNN) have gained prominence among the lot, in the recent past. This is primarily due to the advantages they offer in comparison to the other algorithms, such as mapping of highly complex nonlinear data, ability to handle large datasets, tolerance for data structure and flexible learning ability [9]. Chibani and Coudart have provided a detailed methodology for building machine learning and artificial intelligence based prediction systems. They have reported that post data collection, feature extraction is an important step for proper model development. The authors have postulated that different types of decision tree-based learners such as Random Forest (RF) and Gradient Boosting Decision Tree (GBDT) are useful for both regression as well as classification based predictions and have suggested usage of cross-validation techniques to evaluate the prediction models [10]. Traditionally, mechanical property determination is carried out by destructive testing, which is costly,

time consuming and inefficient. Mukhopadhyay *et al.* emphasised the fact that during conventional testing a sample is cut and a typical tensile test is performed on a servo-hydraulic machine which usually takes 24 hrs for the test samples to be ready for dispatch which is of a significant delay that involves the processing of a slab that exits from the furnace which in turn results in high inventory, delayed customer delivery, and high lock-in capital [11].

3. METHODOLOGY

3.1 Data Mining and Input Parameters

For development of property prediction models, the composition, rolling temperatures, dimensions of the coils and process parameters at HR, CR and continuous annealing stages were considered as input parameters. This data was taken for all the coils processed at HSM & CAL for the past 2 years. After collecting all the recorded data, filters were applied for all the parameters to neglect any erratic values which adversely affect model accuracy. The classification of input parameters for property prediction models is shown schematically in Figure 1.

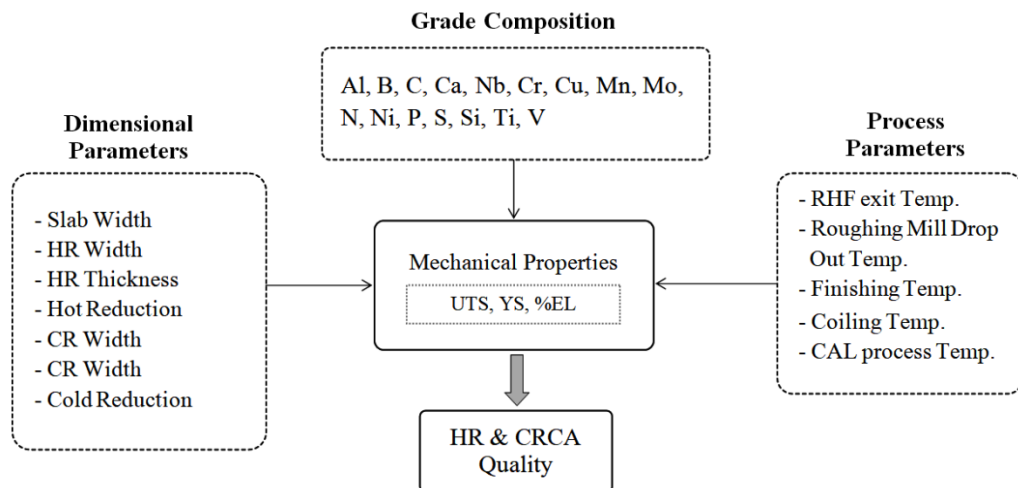


Figure 1: Parameters Affecting Properties of HR & CRCA Coils

3.2 Feature Selection

Feature selection is an important technique for eliminating redundant or insignificant variables from model building. The relative importance of input parameters on the final predicted output was estimated through their respective regression coefficients after normalization of the variables range. The relative importance of all input parameters

for predicted output mechanical properties for CAL process are shown in figure 2.

Sn & Ca were found to be the common insignificant variables for all the 3 properties, hence were not considered for final model development. Additional dimensionality/variable reduction was not required/considered as the number of variables were not too high to adversely affect model performance.

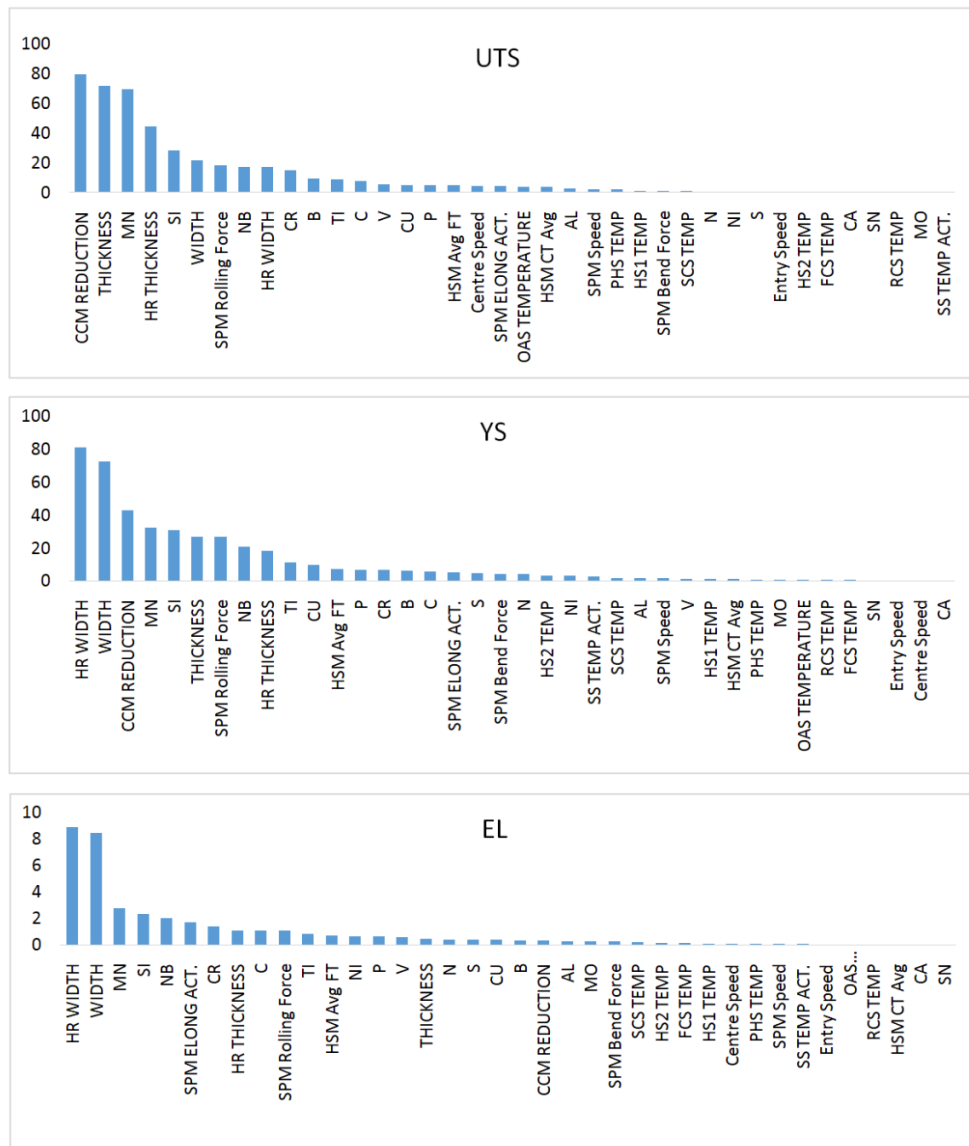


Figure 2: Relative Importance Plots of Different Input Parameters for CRCA Coils

3.3 Model Development based on Gradient Boosting

The use of advanced machine learning algorithm involves mathematical processing of the data using the machine learning techniques. In this study, an ensemble learning based algorithm was implemented for predictions.

Ensemble models are the algorithms which combine various predictions and give a final prediction based on the majority thereby reducing the bias, variances and improved accuracy. Also referred to as meta-algorithms, these can be sub-divided based on the way the learning takes place, such as bagging, which has parallel learning or boosting, which has sequential learning.

Bagging involves the generation of base learners in sequence to generalise their dependency which results in reduction of error. Mathematically, the M different decision trees can be trained using the data, which are randomly selected with the replacement, which infers to the fact that M different trees are used to reduce the variance by creating data subsets for training the base learners, which uses averaging and can be represented as a function as shown in equation 1.

$$\hat{f}(x) = \frac{1}{M} \sum_{m=1}^M f_m(x) \quad \dots (1)$$

These are generally applied in conglomeration with decision trees than linearized models. The examples for these models include Decision trees and Random Forest.

Boosting on the other strata can convert weak learners to strong learners by fitting a bunch of weak learners, which are usually small decision trees to a weighted version of the data and just like any ensemble technique, the weighted majority vote is taken as the prediction. Since the present model incorporates the boosting (specifically gradient boosting) algorithm, the mathematical interpretation is as follows.

Consider Y_i to be the dependent variable which is a function of the vector of all predictor variables (X_i). Since the predictor cannot fully describe the outcome, there is a bias function which is the error (e) as denoted by equation 2.

$$Y_1 = F_1(x_i) + e_{1i} \quad \dots (2)$$

In boosting, the weak learners are converted into strong learners and the second iteration (model) will be trained with the error term. The corrected second model is given below (equation 3),

$$Y_1 - F_1(x_i) = e_{1i} = h_1(x_i) + e_{2i} \quad \dots (3)$$

From equations 1 & 2,

$$F_2(x_i) = F_1(x_i) + h_1(x_i) \quad \dots (4)$$

After fitting the model for the m^{th} boosting iteration step,

$$F_m(x_i) = F_{m-1}(x_i) + h_{m-1}(x_i) \quad \dots (5)$$

Where, $h_{m-1}(x_i)$ is a weak learner which, on training, becomes a part of a stronger tree. The residual error is expressed as loss function $L[Y, F_m(x)]$ which signifies the difference in actual and predicted value and the ultimate aim is to reduce this loss. This happens by taking the derivative of this loss function concerning the predictor value.

The gradient (γ_{im}) is defined as:

$$\gamma_{im} = - \left\{ \frac{\partial L[y_i, F_{m-1}(x_i)]}{\partial F_{m-1}(x_i)} \right\} \quad \dots (6)$$

Where i is the index for observations, which will have one gradient value. Therefore the weak learner $h_m(x)$ is fit by computing the γ [m]

$$\gamma_m = \arg \gamma \min$$

$$\sum_{i=1}^m L[y_i, F_{m-1}(x_i) + \gamma \cdot F_m(x_i)] \quad \dots (7)$$

The solution becomes,

$$\gamma_m = \frac{\sum_{i=1}^n h_m(x_i)[y_i - F_{m-1}(x_i)]}{\sum_{i=1}^n h_m(x_i)^2} \quad \dots (8)$$

The final equation that gives the prediction can be generalised and is updated with

$$F_m(x) = F_{m-1}(x) + \gamma m h_m(x) \dots (9)$$

Inferring from equation (9), $F_m(x)$ is the final value of the prediction obtained. Using this bagging technique, the model was developed using gradient boosting technique. Gradient boosting can be performed using a number of tools like Matlab, Python, R etc. In the present work, objective was to develop and implement an online prediction model. Therefore, Python was selected as it can communicate to the production databases, can create dynamic web pages as well as also be used to send automated e-mails by using suitable libraries.

The model development approach is shown in figure 3. After model development, the predicted values were stored back into the central database using Python libraries.

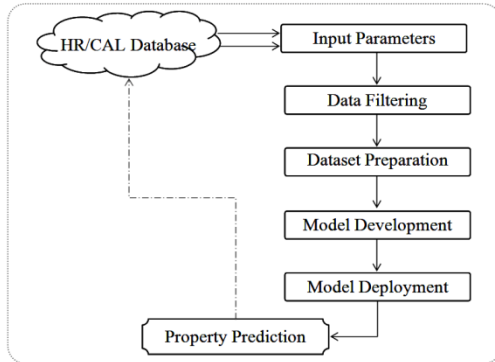


Figure 3: Prediction Model Development Approach

3.4 Performance Evaluation of Model

The performance criteria of a regression-based data analytics model can be interpreted using several ways, one of which includes a coefficient of determination (R^2) as listed in equation 10.

$$R = \frac{\sum_{i=1}^n (C_{pi(act)} - C'_{p(act)}) (C_{pi(pred)} - C'_{p(pred)})}{\sqrt{\sum_{i=1}^n (C_{pi(act)} - C'_{p(act)})^2 \sum_{i=1}^n (C_{pi(pred)} - C'_{p(pred)})^2}} \dots (10)$$

where, $C_{p(pred)}$ and $C_{p(act)}$ represent the mean of the actual and predicted values.

The accuracies of the model were checked in two phases - one during the model building phase to arrive at the right algorithm and second after deployment in the production scenario for real-time checking of the performance. The coefficients of determination (R^2) for the predicted output from the model were calculated using the sklearn Python library and are listed in table 1.

Table 1: Coefficient of Determination for Predicted Values

Output Parameters	Coefficient of Determination (R^2)	
	HR Model	CAL Model
UTS	0.96	0.99
YS	0.92	0.98
% Elongation	0.85	0.96

3.5 Model Validation

The model predicted values were compared with the actual tested values for >500 HR and CRCA coils as shown in figure 4. The average prediction accuracies corresponding to different mechanical properties are listed in table 2.

It is evident that the models provide fairly accurate predictions based on input parameters.

Table 2: Accuracy % for Predicted Values

Parameters	Average Prediction Accuracy (%)
UTS	97–98%
YS	95–96%
% Elongation	94–95%

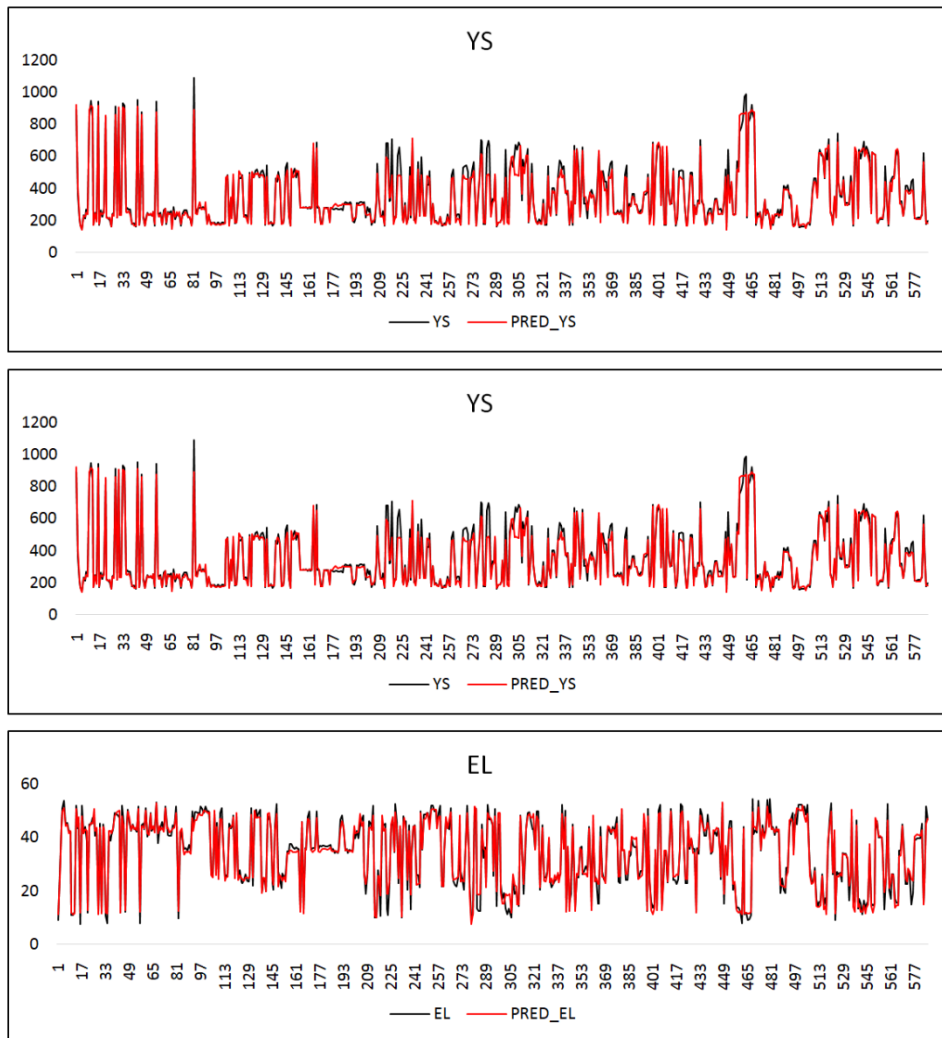


Figure 4: Comparison of Model Predictions with Actual Tested Values for CRCA Coils of Different Grades

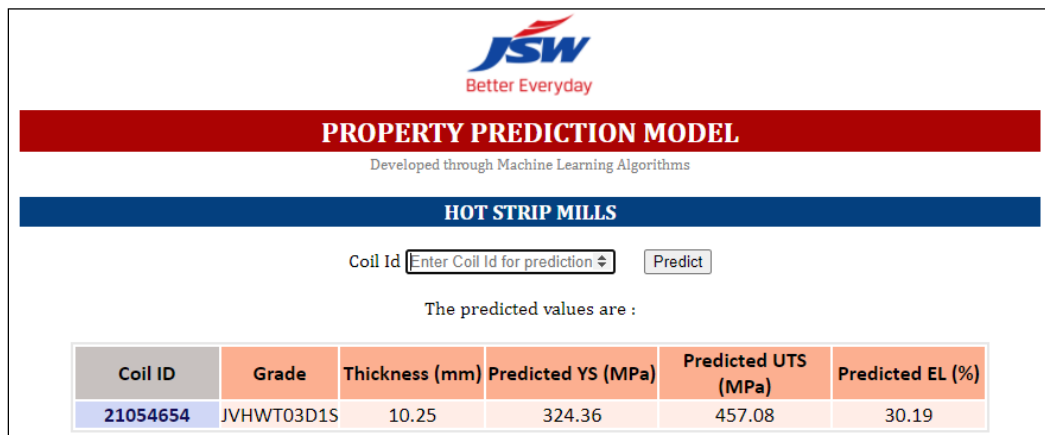
4. PLANT SCALE IMPLEMENTATION

The prediction model was deployed in the plant scale operation through user input web-based prediction system and automated prediction & mail notification system.

4.1 Web-based On-demand Prediction System

A web-based prediction system for delivering instantaneous on-demand predictions was

deployed using HTML as GUI frontend and Python & SQL at the backend for predictions. The interface has provisions of accepting manual input from the user in the form of Coil Id and giving predictions as shown in figure 5. This prediction system can be accessed anywhere within the JSW Vijayanagar LAN using a web browser through the URL (uniform resource locator) link even without an internet connection.



PROPERTY PREDICTION MODEL
Developed through Machine Learning Algorithms

HOT STRIP MILLS

Coil Id

The predicted values are :

Coil ID	Grade	Thickness (mm)	Predicted YS (MPa)	Predicted UTS (MPa)	Predicted EL (%)
21054654	JVHWT03D1S	10.25	324.36	457.08	30.19

Figure 5: User Entry Based On-demand Prediction System Interface

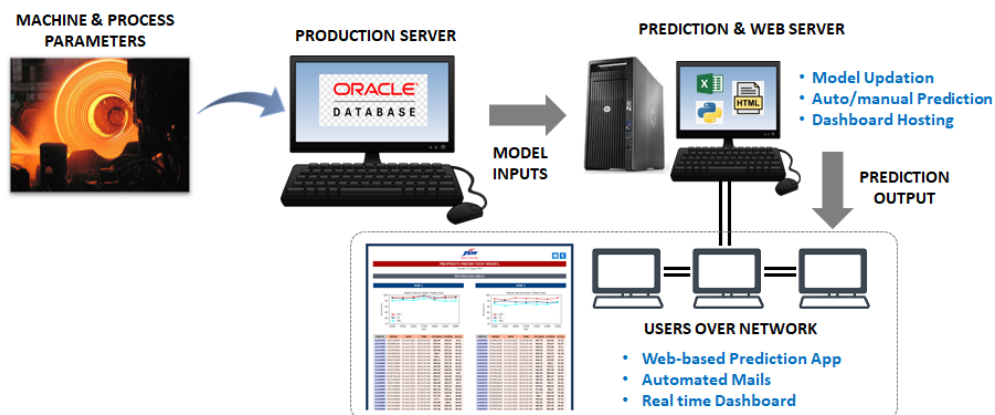


Figure 6: Automated Prediction and Reporting System

4.2 Automated Prediction and Reporting System

An automated prediction system was deployed, which can fetch the input parameters from the production server and can deliver automated timed predictions as per the defined schedule as shown in figure 6. The predicted values of UTS, YS and %EL were updated on a web-based dashboard which gets auto-updated every 15 minutes and can be accessed anywhere over the local intranet to track the predicted properties and monitor model performance. An automated mailing system was developed using Python to send daily emails for the predicted values and model performance to HSM and CRM

quality control team and concerned authorities.

4.3 Model Accuracy Assessment

The prediction accuracy after model deployment was continuously monitored through online dashboards wherein the actual tested and predicted values were compared and the closeness of predictions was measured in form of percentage for each coil. This was calculated for all the coils rolled in a single day where tested values were available and then the average was taken to obtain the day-wise average model accuracy for UTS, YS and %EL. The average model accuracy weekly trend is shown in figure 7

which shows an average accuracy of ~98% for UTS, ~97% for YS and ~95% for %EL for hot rolled coils. Similar accuracy trends were achieved for CRCA coils also.

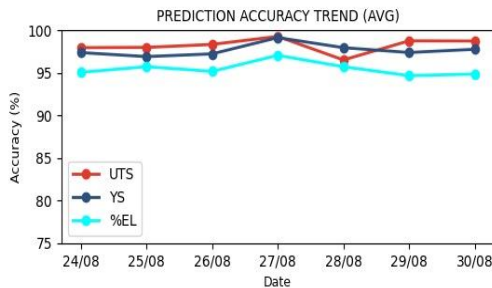


Figure 7: Model Accuracy Weekly Trend for HR coils

5. CONCLUSIONS

1. A machine learning model was developed using gradient boosting algorithm for the prediction of hot rolled and cold rolled & annealed coils mechanical properties.
2. The final deployed models were developed using 36 input process variables. The dataset was split into 70:20:10 ratio for model training, testing and validation.
3. The models can predict hot rolled and CRCA coil properties with ~95% accuracy.
4. The models were interfaced with HR-SPTS and CRM-2 MES systems for online deployment to provide real-time predictions without any manual intervention.
5. A reporting system was created through automated real-time dashboards and daily emails to report the predictions done by the model along with the accuracy trends.
6. Post-deployment in the plant, the model can help in reducing the sampling frequency leading to savings of consumables, man-hours and maintenance cost of the testing equipment.

ACKNOWLEDGEMENTS

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Prediction of Microstructure and Mechanical Properties Considering DRX, SRX and MRX during Hot Rolling Process

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ABSTRACT: Determination of microstructure and mechanical properties using conventional experimental methods is time and resource consuming; therefore, different mathematical models were developed to predict these properties. However, it was observed that in these studies, predicted results slightly deviated from experimental results. Therefore, in this paper, a mathematical model was developed that predicts microstructure and mechanical properties of three different grades of steel with large, medium and small grain sizes. To predict microstructure and mechanical properties dynamic recrystallization (DRX), static recrystallization (SRX) and metadynamics recrystallization (MRX) during hot rolling process were considered. Different sets of strain, strain rate and temperature were consider to calculate Zener-Holloman parameter, activation energy, and critical strain for SRX, DRX and MRX. To calculate Zener-Holloman parameter and activation energy Arrhenius equation was used. It was found that strain, strain rate and temperature significantly affected microstructure and mechanical properties prediction. It was also observed that after considering above all parameters prediction capability of model was improved. This developed model was further used to predict the microstructure and mechanical properties of hot rolled mill.

Keywords: DRX, SRX, MRX, Microstructure Prediction, Arrhenius Equation.

1. INTRODUCTION

With the application of new technology and equipment, the modern steel industry focuses on the customers' stringent quality demands. Excellent mechanical properties and simultaneously cost effective production technology are the key issues for successful steel companies. It is critical to control process parameters and figure out the most economical compositions to meet customers' requirement. Off line/on-line computer modelling is an appropriate tool for optimizing alloy design and adjusting process parameters. A through-process and metallurgical model enables to control the rolling condition parameters in an integrated manner [1].

In the past decades, a number of models was developed to simulate the hot rolling process. Saito *et al.* [2,3] proposed the first integrated model for prediction of microstructure evolution and mechanical properties of hot strip in the early 1980s. Thereafter other integrated models were presented by Esaka *et al.* [4] in 1986, Suehiro *et al.* [5] in 1987, Brimacombe *et al.* [6] in 1988, Choquet *et al.* [7] and Hodgson and Gibbs [8] in 1990. Recently some off line/on-line systems for predicting microstructure and properties of hot rolled strip have been developed and applied in the large steel companies, such as VAI-Q strip system at Voest Alpine, METMODEL at British Steel, STRIPCAM at ThyssenKrupp etc. The benefits of these

systems concern the further understanding of the physical metallurgical process during hot rolling, controlling the process parameters to achieve the desired mechanical properties and reducing the number of sampling tests. The models could thus also be adopted for engineering studies and developing new steel grades.

In the hot strip rolling process, temperature is not only the important influential parameter to control strip size accuracy and load distribution in the stands, but also one of the most critical parameters to the microstructural evolution and the mechanical properties of final products. Among all process parameters, the strip properties mainly depend upon temperature [9, 10]. In order to correctly model the microstructural evolution and predict the mechanical properties of final products, it is essential to know the accurate temperature variation in the whole length direction at different stages. However, to our knowledge, a through-process and physically based metallurgical model has not been published in the literature until now, especially, no detailed thermal and elongation models. Most of thermal model relied on the FEM [9]. A simple, fast, empirically based on-line prediction of temperature has never been published. Although a prediction system of microstructure and mechanical properties

was definitely applied, the temperature variation model did not present the details necessary for commercial application. Elongation is a basic index for customers, thus only tensile strength and yield strength prediction are not sufficient. However, some groups predicted the elongation by neural network, but compared with a neural network model for elongation of hot rolled strip, the present physically based model for elongation has advantages, because of thoroughly tracing the sources of “problems” in the setup.

In this report, based on the local metallurgical models and process models, a through-model is developed, and it is combined with the actual 1780 mm hot rolling production line of Anshan Iron and Steel Group Corporation in China. The set-up of this line is schematically shown in **Figure 1**.

The model is utilized to simulate the temperature variation and the properties distribution along the whole strip length as shown in **Figure 2** and to evaluate the effect of various process parameters in the analysis. This through-model is characterized by simple, fast and convenient on-line/off-line prediction of mechanical properties. To support the development of the model, validation and application of the model are carried out.

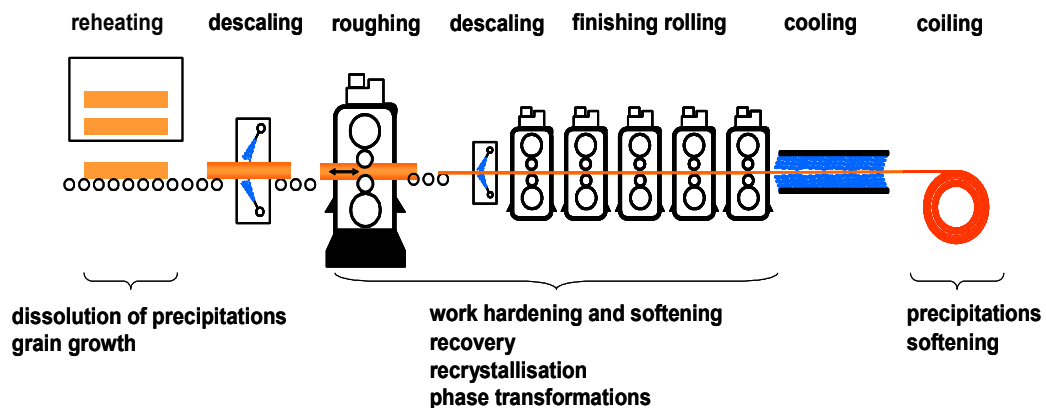


Figure 1: Different Phenomenon Observed at Various Location of Hot Rolling Mills

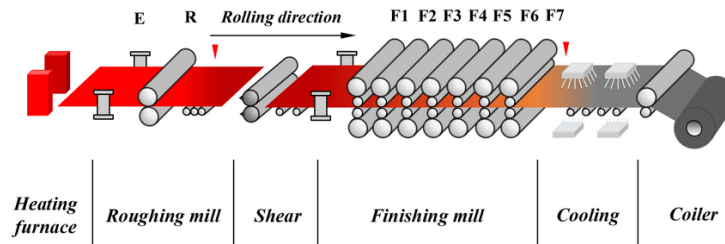


Figure 2: Process Involved in the Hot Rolling Mills

Table 1: Chemical Composition of as Received Materials

<i>G_{rade}</i>	<i>C</i>	<i>Mn</i>	<i>S</i>	<i>Ni</i>	<i>P</i>	<i>Al</i>	<i>Nb</i>	<i>N</i>
Micro-alloy	0.082	0.84	0.005	—	0.013	0.036	0.028	0.0036
HTR14A	0.076	1.59	0.004	0.008	0.016	0.041	0.021	0.0039
HLNT8A	0.047	1.51	0.002	0.15	0.008	0.027	0.058	0.0045

2. EXPERIMENTATION

2.1 Material Used

The material used in this study was different grade of steel, chemistry of the material are given in Table 1 in as received condition.

2.2 Compression Test

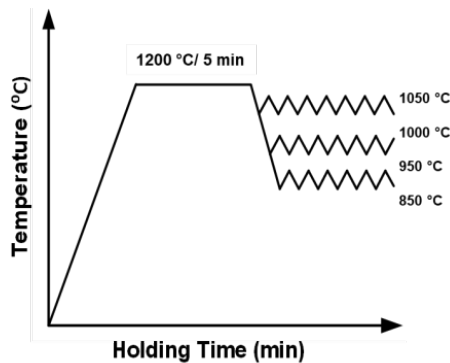
A hot compression test is a common experimental technique used in materials science and metallurgy to study the deformation behaviour of materials at high temperatures and under high strain rates. In a hot compression test, a small specimen of the material is subjected to a constant load and then compressed to a specified strain at a specified temperature and strain rate. The deformation behaviour of the material is recorded and analysed to provide insights into its mechanical properties and behaviour.

The Gleeble-3800 is a commonly used instrument in materials science and metallurgy for performing high-temperature compression tests on metallic materials. The Gleeble-3800 uses a computer-controlled thermomechanical simulator to deform the material under controlled conditions of temperature, strain rate, and deformation mode. The Gleeble-3800 can be used to simulate a wide range of

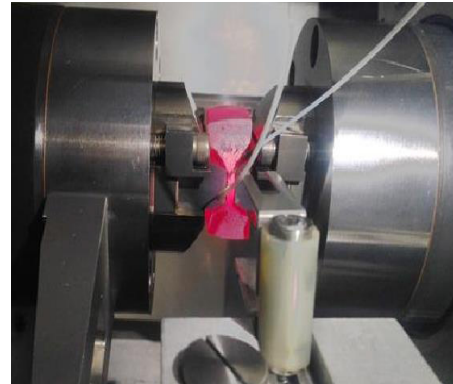
processing conditions, such as hot rolling, forging, and extrusion, and to investigate the mechanical behaviour of materials at high temperatures.

To perform a high-temperature compression test using the Gleeble-3800, the following steps can be taken:

- **Sample preparation:** A small cylindrical specimen of the material is machined to the required size and shape, and any necessary surface preparation is carried out.
- **Test set-up:** The specimen is loaded onto the compression testing machine, and the required temperature and strain rate are set.
- **Heating:** The specimen is heated to the desired temperature using a furnace or other heating method. The Gleeble-3800 can rapidly heat the specimen to the desired temperature using its resistance heating system.
- **Compression:** Once the specimen has reached the desired temperature, compression is applied to the specimen using a controlled load. The Gleeble-3800 uses a servo-hydraulic actuator to apply the load, and the deformation of the specimen is recorded using strain gauges.



(a) Process Cycle Used for Compression Test in Gleeble-3800



(b) Specimen during Deformation in Gleeble-3800

Figure 3

- **Cooling:** After the test is complete, the specimen is rapidly cooled using the Gleeble-3800's water cooling system.
- **Analysis:** The deformation behaviour of the material is recorded and analysed to provide insights into its mechanical properties and behaviour.

The Gleeble-3800 allows for a wide range of testing parameters, including temperature, strain rate, strain, and deformation mode (such as uniaxial compression, torsion, or bending) as shown in **Figure 3**. The instrument can also simulate different processing conditions, such as hot rolling or forging, by varying the deformation mode and the direction of loading.

The results of high-temperature compression tests using the Gleeble-3800 can be used to find out flow behaviour of materials, activation energy and zener-hollomon parameter.

2.3 Through-Model of Hot Strip Rolling

This through-model consists not only of local models describing microstructure evolution of hot strip from reheating to accelerated cooling and final structure-properties, but also of process models precisely predicting the temperature distribution along the length

of a hot strip. In order to predict the final mechanical properties, it is necessary to know the temperature variation of the strip from reheating to coiling, as well as strain and strain rate during hot rolling. After temperature, strain and strain rate have been achieved, the microstructure evolution in the hot strip is calculated, and finally the mechanical properties can be predicted. The construction of the local models and the through-model is shown in **Figure 4**.

2.4 Thermal Model

Figure 4 exhibits the local complex heat transmission process during hot rolling. Based on this process, an average temperature evolution model along the strip length is established.

As shown in **Figure 4**, the temperature change of hot strips is caused by air cooling, water cooling including roll cooling water and spraying water between passes, deformation heat, friction heat and heat transmission by roll contact. The model for each process has been described recently. In order to save computer time and improve computer efficiency, an empirical formula is employed to calculate the temperature change caused by each process.

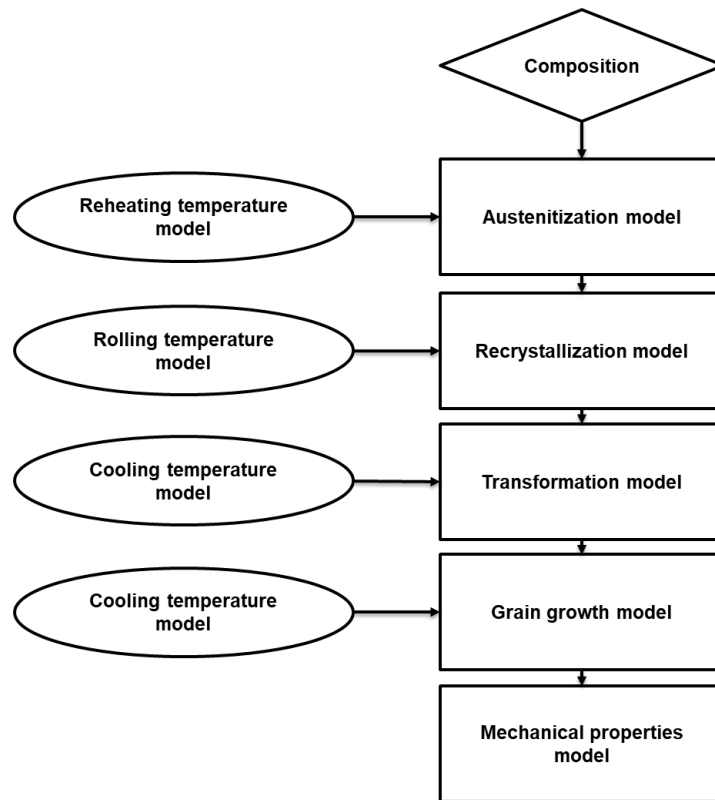


Figure 4: Schematic Diagram for Different Steps in Hot Roll Mills

The temperature difference within the strip between entrance and exit of a pass is the total sum of air cooling, water cooling, heat contact, heat generation by deformation and friction. The strip temperature in each pass is calculated repeatedly according to the five processes from the beginning to the end of hot rolling. In this temperature model, the acceleration rate of the strip in the finishing train must be included because it is used to ensure the uniform temperature distribution along the strip length. A self-learning algorithm is also employed in this integrated model in order to guarantee the accuracy of temperature prediction. If the temperature difference between the calculated and measured temperatures at roughing exit (RT2), finishing exit (FT7) and coiling position (CT) is larger than the permitted value, the self-learning process works until the temperature deviation is acceptable.

During accelerated cooling, the strip on the run-out-table is cooled by cooling water when passing open banks, and cooled by air between banks or when passing closed banks. So the temperature change of the hot strip during accelerated cooling is mainly caused by side water cooling and laminar water cooling. The air cooling model for accelerated cooling is the same as that of hot rolling, and the water cooling model is similar to that of hot rolling, but the heat transmission coefficient in accelerated cooling is modified and the specific heat is different because here the equivalent specific heat is considered as phase transformation latent heat.

It is worth noting that the time which head, middle and tail of the strip need for passing through the run-out-table is different. So the cooling rate of each point along the strip length is different, which has great influence

on the microstructure after ferrite transformation.

The temperature drop in the strip after coiling is dominantly caused by radiation to the atmosphere, which is modelled based on finite element method. By recording the temperature curve at different locations, the cooling time of different positions can be obtained. The temperature distribution varies along the strip length because cooling conditions are different at the core and the outer surface of the coiler. For strips with different coiling temperature and thickness, their temperature can be predicted at any time after coiling.

2.5 Reheating and Grain Growth Model

The ferrite grains begin to grow at the beginning of the reheating stage. When the temperature reaches the austenitization temperature, ferrite starts to transform into austenite (e.g., $\alpha \rightarrow \gamma$) after austenitization completed, austenite grains grow and this process continues until the slab exits from the reheating furnace.

The developed model predicts austenite grain size evolution of slabs during reheating. As described above, an accurate model should predict ferrite grain growth, $\alpha \rightarrow \gamma$ phase transformation and austenite grain growth in this process. However, it is sufficient that this model can predict austenite grain growth because the primary grain size of austenite in the reheating furnace is mainly controlled by grain growth of austenite. Computer simulations on various integrated models show that the final microstructure is hardly influenced by the initial grain size. Thus zero or an arbitrary value is assumed as the initial grain size just after the $\alpha \rightarrow \gamma$ phase transformation.

The grain growth model of austenite during reheating is given as:

$$d_1^n - d_0^n = k_1 * \exp\left(\frac{-Q}{RT}\right) * t$$

where d_1^n is the grain size of austenite (μm), d_0 is the initial grain size (μm) immediately after the α phase transformation, Q is the active activation energy (J/mol) for grain growth, R is the gas constant (J/mol K), T is the temperature (K) and, t is the time (s) for grain growth, and n and k_1 ($\mu\text{m}^n/\text{s}$) are constants.

2.6 Recrystallization Models

As shown in figure 2, the strips in zone 3 are deformed in a high temperature region (e.g., above austenite start transformation temperature A_{r3}). During this period, continuous deformation causes work hardening and dynamic recovery. Meanwhile dynamic recrystallization may occur if the strain is higher than the critical strain ε_c . Otherwise, only work hardening and dynamic recovery happen. After that static recrystallization occurs in the strip while passing the inter-stand zone. If dynamic recrystallization happens during deformation, the process taking place in the inter-stand section is called meta-dynamic recrystallization because it is quite different from static recrystallization.

$$\varepsilon_p = A_1(d_o)^{0.3}Z^q$$

Above 1000 °C and with $d_o = 277 \mu\text{m}$

$$\begin{aligned} Z_1 &= \varepsilon \exp\left(\frac{238000}{RT}\right) A_1 \\ &= 6.2 \times 10^{-4}q \\ &= 0.22 \end{aligned}$$

Below 1000 °C and with $d_o = 26 \mu\text{m}$

$$\begin{aligned} Z_2 &= \varepsilon \exp\left(\frac{330000}{RT}\right) A_1 \\ &= 1.3 \times 10^{-4}q \\ &= 0.2 \end{aligned}$$

The developed rolling model describes austenite recrystallization and grain growth behaviour in multi-pass hot deformation. Nuclei of recrystallization have already existed when the actual strain is higher than the critical strain ε_c , but they must be formed after hot deformation when the strain is

lower than the critical strain ε_c . The critical strain ε_c is calculated as in equation:

$$\varepsilon_c = 5.6 \times 10^{-4} d_0^{0.3} Z^{0.17}$$

Where d_0 is the initial grain size (gm) of austenite before recrystallization, and $Z = \exp(300000)$ is the Zener-Hollomon parameter. The dynamic recrystallization starts if the strain is higher than the critical strain and then meta-dynamic recrystallization occurs in the next inter-pass. If the strain is lower than the critical strain, static recrystallization happens in the next inter-stand zone. For meta-dynamic recrystallization, the recrystallized grain size is described as:

$$d_{MDRX} = 2.6 \times 10^4 Z^{-0.23}$$

For static recrystallization the recrystallized grain size is expressed as:

$$d_{SRX} = 343 \varepsilon^{-0.5} d_0^{0.4} \exp\left(\frac{-45000}{RT}\right)$$

The grain growth of austenite starts after recrystallization is finished. This grain growth process is predicted by

$$d^7 = d_{SRX}^7 + 1.5 \times 10^{27} (t_{ip} - 4.32 t_{0.5}) \exp\left(\frac{-40000}{RT}\right)$$

The recrystallized fraction at a given pass is expressed by Avrami equation:

$$X = 1 - \exp\left[-0.693 \left(\frac{t}{t_{0.5}}\right)^q\right]$$

Where is the time (s) for 50% softening. For static recrystallization, $t_{0.5}$ is calculated as:

$$t_{0.5}^{SRX} = 2.3 \times 10^{-15} \varepsilon^{-2.5} d_0^2 \exp\left(\frac{230000}{RT}\right)$$

For meta-recrystallization, $t_{0.5}$ is specified as:

$$t_{0.5}^{MDRX} = 1.1 Z^{-0.8} \exp\left(\frac{23000}{RT}\right)$$

Fraction is calculated as,

$$X = 1 - \exp\left[-0.693 \left(\frac{t}{t_{0.5}}\right)^q\right]$$

$q = 1$ for static recrystallization and $q = 1.5$ for meta-dynamic recrystallization.

With decreasing rolling temperature, recrystallization speed slows down. As the rolling speed becomes faster and faster in finish rolling, recrystallization cannot occur completely during last finish rolling inter pass. In order to consider the influence of residual work hardening on the recrystallization in the next stand and the phase transformation of austenite during accelerated cooling on run-out table, residual strain for partial recrystallization is calculated as following:

$$\varepsilon_r = (1 - X)\varepsilon$$

Where ε_r is the residual strain and X is the recrystallized fraction. The strain in the next stand includes the deformation strain at the present stand and the residual strain at the last stand. For partial recrystallization, the grain size at the entrance of the next stand is calculated from equation

$$d = X^{4/3} * d_{rex} + (1 - X) * d_0$$

Where d_{rex} is the recrystallized grain size (μm), and d_0 is the initial grain size (μm) of austenite before deformation.

The modelled recrystallized austenite grain size and residual strain are the input parameters for the phase transformation model during the accelerated cooling.

2.7 Model for Austenite Decomposition during Accelerated Cooling

The strip temperature decreases from FT7 to CT on the run-out-table during the accelerated cooling. Austenite decomposes into different products depending on the cooling rates. The maximum average cooling rate is up to 150 K/s for the thin strip such as 1.45 mm thickness in Anshan hot rolling mill. The products of the phase transformation are mainly ferrite and pearlite. Moreover, experiments have been conducted in order to detect the products of austenite decom-

position. The results show that in low carbon steel, austenite transforms into ferrite and pearlite and there is no bainite and martensite found.

The developed model describes the austenite phase transformation behaviour of hot strips during the accelerated cooling on the run-out-table. Austenite starts to transform into ferrite when the temperature is lower than Ar_3 . Meanwhile the carbon concentration in the residual austenite phase increases because carbon atoms diffuse from newly formed ferrite into austenite at the interface. The transformation from austenite to ferrite ($\gamma \rightarrow \alpha$) finishes when the carbon concentration in the retained austenite reaches the extrapolated A_{cm} line, then the transformation from austenite to pearlite ($\gamma \rightarrow P$) starts and it will cease when all austenite is exhausted.

Based on Schiel's additivity rule, the continuous cooling process must be divided into a series of isothermal processes in order to predict the continuous phase transformation of hot strip on run-out-table during accelerated cooling. The volume fraction of newly formed phase is calculated by using isothermal transformation kinetics. The volume fraction of newly formed phase is predicted by equation,

$$X = 1 - \exp(-kt^n)$$

Where k is a rate constant depending on temperature and phase transformation mechanism, and n is a constant covering the

whole temperature range when only one transformation mechanism operates.

The modified rate parameter k proposed by Donnay *et al.* is adopted, which is expressed as:

$$k = P(1) * \exp \left\{ - \left(\frac{T - P(2)}{P(3)} \right)^{P(4)} \right\}$$

Where the parameters $P(1)$, $P(2)$, $P(3)$, and $P(4)$ are usually determined for each steel through the TTT diagram and experiments; they are summarized in Table 3. Ae_3 is equilibrium transformation temperature (K), Ae_1 is $\gamma \rightarrow P$ equilibrium transformation temperature (K) and d_r is the effective austenite grain size (μm), and C and Mn are the contents (wt %) of carbon and manganese, respectively. Equilibrium transformation temperatures (Ae_3 and Ae_1) are calculated by phase diagram. Austenite effective grain size is described as:

$$d_r = \frac{d_{r0}}{(1 + 0.5\varepsilon_r)}$$

Where d_{r0} is the austenite grain size (μm) immediately before phase transformation, and ε_r is the residual strain of the strip after the last finishing stand.

The start transformation temperature Ar_3 of austenite during continuous cooling is calculated based on Ae_3 and the cooling rate. Ar_3 is given as:

$$Ar_3 = Ae_3 - AV_c^n$$

Where V_c the cooling rate (K/s), A and n are constants

Table 2: Parameters $P(1)$, $P(2)$, $P(3)$ and $P(4)$

	$P(1)$	$P(2)$	$P(3)$	$P(4)$
$\gamma \rightarrow \alpha$	$\frac{2}{\{d_r (C + \frac{Mn}{6})\}}$	$Ae_3 - 175 + \frac{60}{d_r^{0.02}} - 0.7C$	80	3
$\gamma \rightarrow P$	$\frac{13}{d_r}$	$Ae_3 - 175 + \frac{27.8}{d_r^{0.02}} - 22C$	47	2.2

2.8 Grain Growth Model after Coiling

In an accurate through model, the grain growth model after coiling should be established. The coiling temperature of hot strip for low carbon steel is about 6000C. After coiling, the strip will spend a long time to cool down from CT to room temperature. During this process, ferrite grains will grow slowly in the high temperature region. The grain growth model of ferrite is similar to equation (3), but the parameters in this model are different. It is formulated as,

$$d_1^n - d_0^n = k_1 \times \exp\left(\frac{-Q}{RT}\right) \times t$$

where d is the grain size (μm) after growth, d_0 is the initial ferrite grain size (μm), n , k ($\mu\text{m}^n/\text{s}$) are constants, Q_{gg} is the activation energy (J/mol) for grain growth, R is a gas

constant (J/mol K), t is the time (s) for grain growth and the constants are determined as $k = 6 \times 10^8$; $n = 3.5$ and Q_{gg} is 160 kJ/mol, respectively.

2.9 Structure-Properties Model

The present research has been combined with data from the literature to develop a structure-properties model [22]. For low carbon steel, the predominant microstructural component is ferrite and a few amount of pearlite. The microstructure after austenite (γ) transformation can be predicted using the transformation model described above. Based on these models, a mechanical properties model is established considering chemical composition, grain diameter of ferrite and volume fraction of ferrite. Besides these parameters, FT7 and CT are also considered in this model. In our experiments, it has been found that although

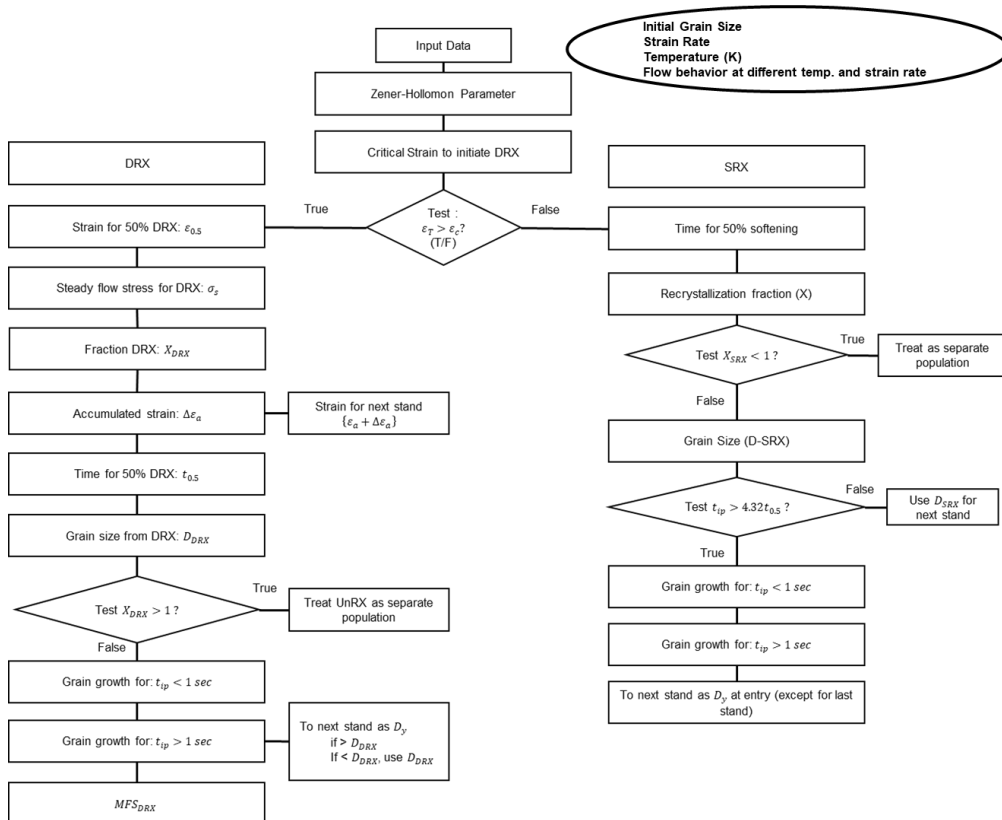


Figure 5: Flow Chart for Grain Size Prediction

the composition, grain size and volume of ferrite are the same, the mechanical properties can differ because of different morphology of ferrite and pearlite. Experiments show that FT7 and CT have an influence on the morphology of ferrite and pearlite. Therefore, these two key parameters have been included in the properties model and the predicted accuracy has been improved.

The structure-properties model describes the relationship between mechanical properties and microstructure of the strip. The mechanical properties include tensile strength, yield strength and elongation. The tensile strength, (MPa), is presented as follows

$$TS = 1006.8 + 72.85Si + 12.86Mn + 4.17d_F^{-0.5} - 31.11X_f - 112.28 \ln(FT7) - 16.15 \ln(CT) + 12.65 \ln(FT7 - CT)$$

where d_F is the ferrite grain size (μm), FT7 and CT are the last finishing rolling exit temperature and coiling temperature (K), respectively, and X_f is the ferrite fraction, and Si and Mn are the contents (wt%) of silicon and manganese, respectively. The yield strength, YS (MPa) is described as:

$$YS = 12826.2 + 10.33Si + 17.98Mn + 13.28d_F^{-0.5} - 114.63X_f - 398.8 \ln(FT7) - 3167.36 \ln(CT) - 348.49 \ln(FT7 - CT) - 13.13 \ln(H)$$

The elongation is calculated as,

$$\delta = -1779.92 - 0.57Si - 2.89Mn - 9.87 \ln(H) + 2.01d_F^{-0.5} + 99.89 \ln(FT7) + 386.81 \ln(CT) + 40.15 \ln(FT7 - CT)$$

3. RESULT & DISCUSSION

In conclusion, the choice of steel grade will have a significant impact on the thinning distribution in cross members, and the specific requirements of the application, such as

strength, toughness, formability, and cost, will dictate the best choice for a given application.

3.1 Flow Behaviour of Materials

The flow behaviour of steel, or how it deforms under stress, can be significantly affected by temperature and strain rate. Understanding how steel behaves at different temperatures and strain rates is crucial for selecting appropriate processing conditions, predicting the material's mechanical properties, and designing reliable structures.

At low temperatures, steel is typically more brittle and less ductile, meaning it is more likely to fracture than deform plastically. As temperature increases, steel becomes more ductile and easier to deform, but at very high temperatures, it may become too soft and lose its load-carrying capacity.

The strain rate also has a significant impact on the flow behaviour of steel. At high strain rates, steel is less likely to deform plastically and more likely to fracture, whereas at lower strain rates, it is more ductile and able to undergo significant plastic deformation before failure.

To determine the flow behaviour of steel at different temperatures and strain rates, hot compression tests can be performed. By controlling the temperature and strain rate during the test, the deformation behaviour of the steel can be studied.

The results of hot compression tests can be plotted as stress-strain curves, which show the relationship between the applied stress and the resulting strain. The slope of the stress-strain curve, or the material's modulus of elasticity, indicates the steel's resistance to deformation. At high temperatures, the slope of the stress-strain curve decreases, indicating that the steel is becoming more ductile and easier to deform. At higher strain rates, the slope of the stress-strain curve is steeper, indicating that the steel is becoming more brittle and less ductile.

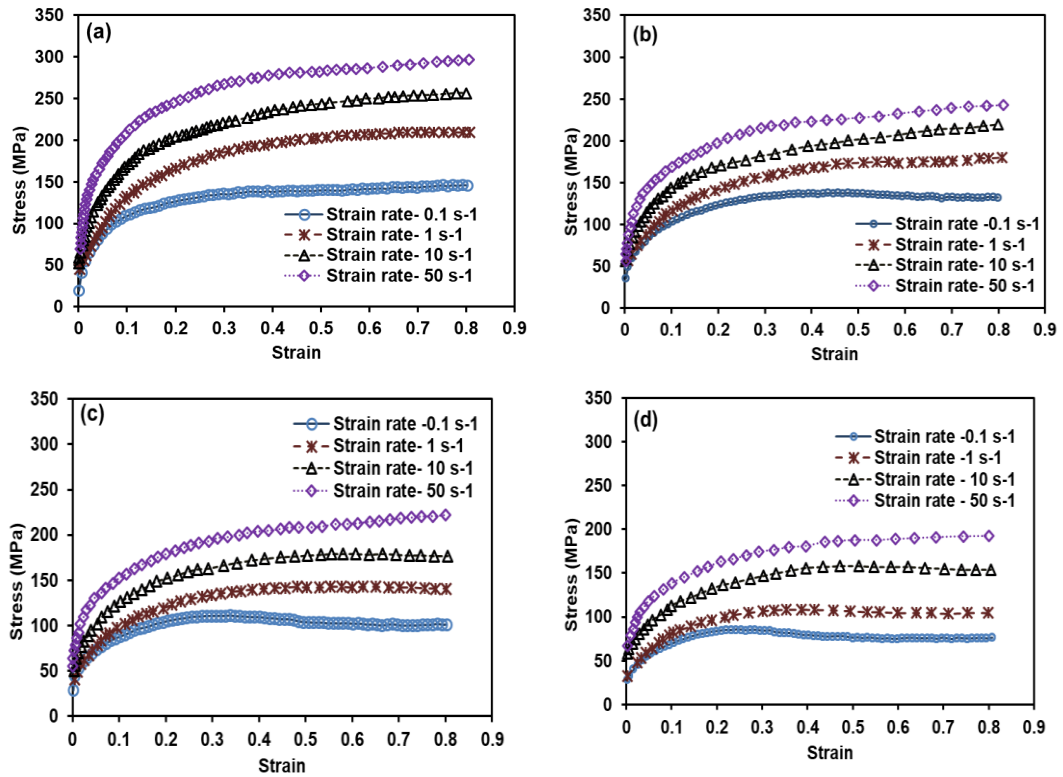


Figure 6: Flow Curve (true stress vs true strain) at Different Strain Rates 0.1/s, 1/s, 10/s & 50/s and at Different Temperature (a) 850°C (b) 900°C (c) 950°C (d) 1000°C

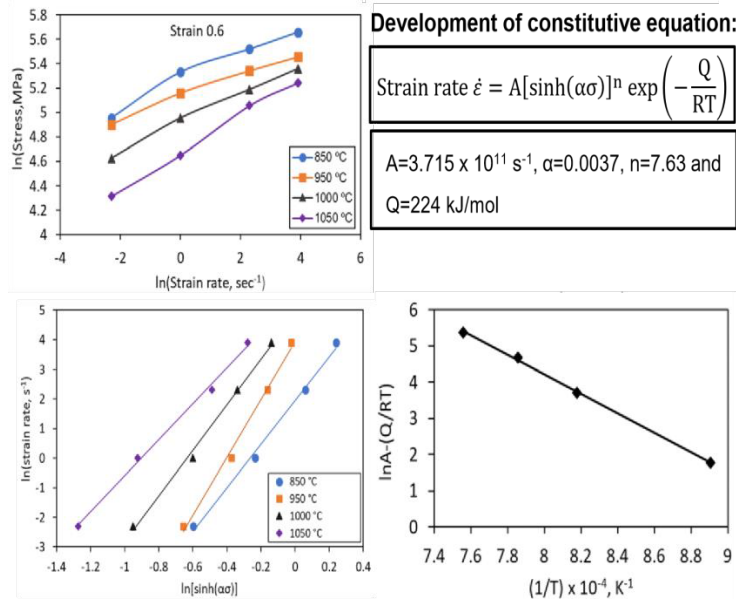


Figure 7: Plot for Activation Energy Calculation (a) $\ln(\text{stress})$ vs $\ln(\text{strain rate})$ at Different Temperature and Strain (b) $\ln(\text{strain rate})$ vs $\ln[\sinh(\alpha\sigma)]$ at Different Temperature (c) Activation Energy vs Temperature

In addition to stress-strain curves, hot compression tests can also provide information on other material properties, such as yield strength, ultimate strength, and strain hardening. This information can be used to develop material models that can predict the behaviour of steel under different processing conditions and loading scenarios.

3.2 Activation Energy

Activation energy of hot deformation is a term used in materials science and metallurgy to describe the energy required to initiate and drive the plastic deformation of a material at high temperatures. When a material is deformed, its atoms or molecules must be moved from their original positions, which requires energy. The activation energy is the minimum amount of energy required to start this process, and it is typically measured in units of joules per mole (J/mol).

At high temperatures, materials are more ductile and easier to deform, and the activation energy required for plastic deformation decreases. This is because the thermal energy of the material increases, which helps to overcome the energy barriers that prevent atoms from moving. As a result, materials can be deformed more easily at high temperatures, which makes hot deformation an important processing technique for many materials.

The activation energy of hot deformation can be determined experimentally by measuring the deformation behaviour of a material over a range of temperatures and strain rates, and then using this data to calculate the activation energy. This information is useful for understanding the deformation behaviour of materials, and for optimizing processing conditions for manufacturing and fabrication.

3.3 Zener-Hollomon Parameters

Zener-Hollomon parameters are used to quantify the dynamic recrystallization behaviour of metals during hot working

processes. These parameters can be calculated by analysing the flow stress data obtained from hot compression tests. The parameters include Zener-Hollomon parameter (Z), strain rate sensitivity exponent (m), and activation energy for hot deformation (Q). The Zener-Hollomon parameter is related to the strain rate and temperature, while the strain rate sensitivity exponent indicates the rate of change in flow stress with respect to the strain rate. The activation energy for hot deformation describes the energy required for dislocation motion and is related to the temperature. These parameters are critical in understanding and optimizing hot working processes to achieve the desired microstructure and mechanical properties of the final product.

$$Z = \dot{\epsilon} \times \exp\left(\frac{Q}{RT}\right)$$

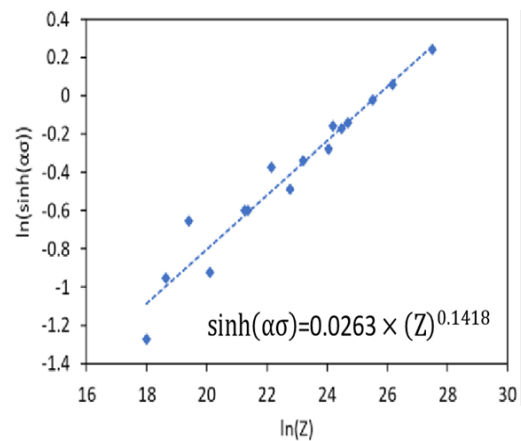


Figure 8: Variation of Zener-Hollomon Parameter with Hyperbolic Sin of Stress

3.4 Comparison between the Calculated and Measured Grain Size

Model grain size predictions and experimental grain size measurements are often compared to evaluate the accuracy and effectiveness of models used to predict grain size during hot rolling of low carbon steels.

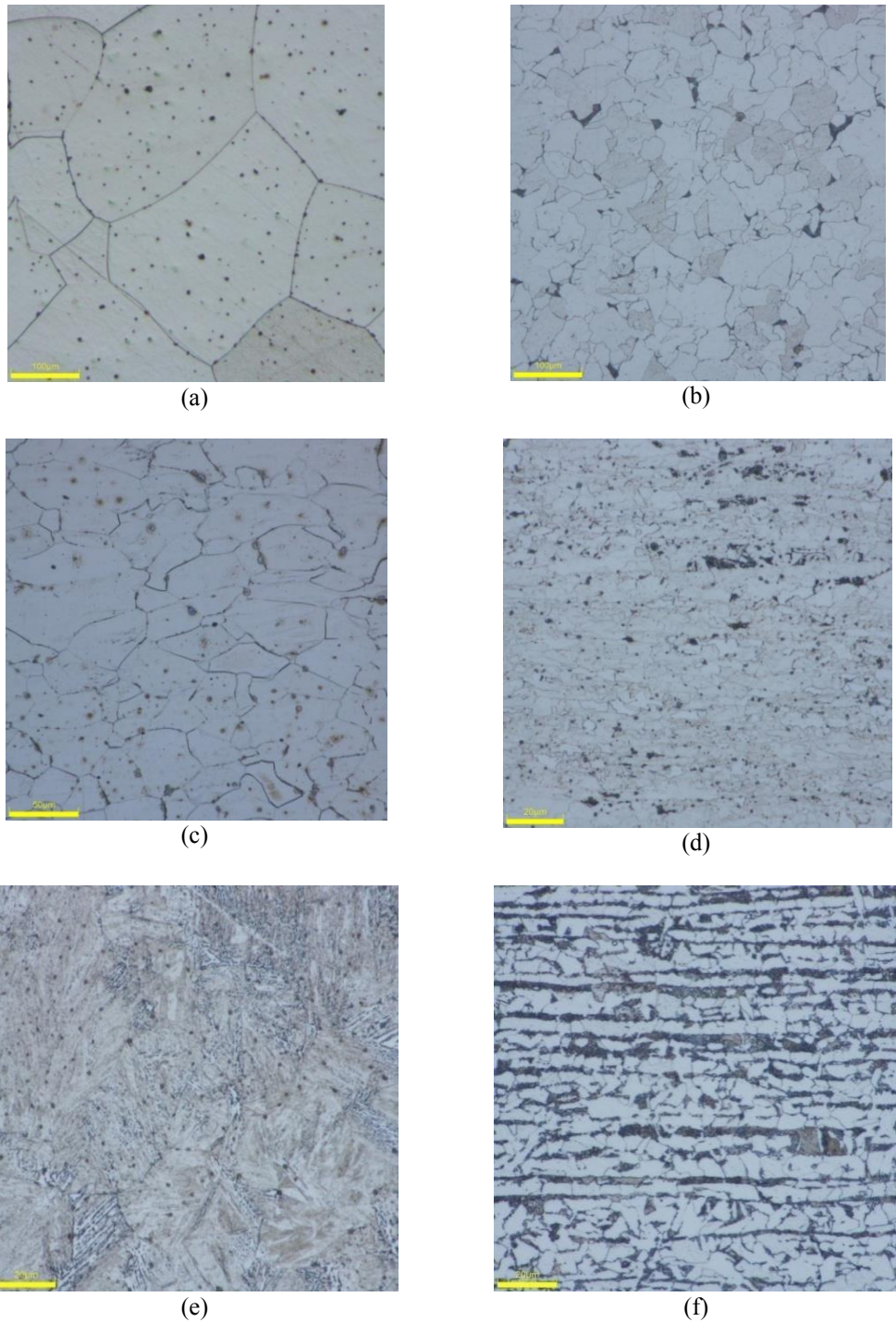


Figure 9: Microstructure (grain size) of Transfer Bar and Rolled Sheet after Laminar Cooling for Different Grade of Steel (a) & (b) Silicon Grade of Steel (c) & (d) IF Steel (e) & (f) Low Carbon Steel

Table 3: Comparison of Measured Grain Size and Calculated Grain Size

<i>S. No.</i>	<i>Measured</i>		<i>Predicted</i>		<i>Validation</i>	
	<i>Initial Grain Size (μm)</i>	<i>Final Grain Size (μm)</i>	<i>Initial Grain Size (μm)</i>	<i>Final Grain Size (μm)</i>	<i>Error (%)</i>	<i>Accuracy (%)</i>
1.	248.77	20.13	248.77	23.52	16.84	83.16
2.	49.68	5.02	49.68	4.78	9.51	90.49
3.	102.4	14.2	102.4	15.55	5.34	94.66

Hot rolling of low carbon steels typically involves the recrystallization and grain growth of the steel, which can result in changes in grain size and microstructure. Several models have been developed to predict the grain size during hot rolling, including analytical, empirical, and numerical models.

To compare the model grain size predictions with the experimental grain size, several measures can be used. One common measure is the mean grain size, which is the average size of all the grains in a sample. Other measures include the standard deviation of the grain size distribution, the coefficient of variation, and the fraction of large and small grains in the sample.

Typically, the comparison is made by calculating the difference between the predicted and experimental grain size, often expressed as a percentage. A low percentage difference indicates good agreement between the predicted and experimental grain sizes, while a high percentage difference indicates poor agreement.

In general, the accuracy of the model grain size predictions depends on the model's assumptions, the quality and quantity of the input data, and the complexity of the process being modelled. Empirical and numerical models tend to provide better predictions than analytical models, which are more limited in their ability to account for the complex physics of the process.

In practice, experimental measurements of grain size are essential to validate and refine the predictive models and to ensure that the models are appropriate for the specific steel

being rolled and the processing conditions used. By comparing the model predictions with experimental measurements, it is possible to improve the accuracy of the models and to optimize the hot rolling process for different types of low carbon steels.

4. CONCLUSION

A through-process and physically metallurgical model is presented for prediction of microstructure and mechanical properties of hot strips. This through-model includes six modules, which are thermal history and deformation module, reheating module, rolling recrystallization module, phase transformation module in continuous cooling, grain growth module after coiling and mechanical properties module, respectively.

For the thermal module, empirically based models of air cooling, water-cooling, heat transmission by roll contact, heat generation by deformation and heat generation by friction are developed. The effect of various process parameters such as rolling speed, reduction rate in each pass and interfacial heat transfer coefficients are considered in the model. A self-learning method is adopted and the accuracy for rolling temperature prediction is improved remarkably.

In the mechanical properties module, not only the normal composition, grain diameter and volume fraction of ferrite are considered, but also the process parameters such as the finishing exit temperature (FT7) and coiling temperature (CT) are covered in order to quantitatively evaluate the influence of ferrite and pearlite morphology on mechanical properties.

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APPENDIX

This part of report content all the equation used for prediction of grain size.

Application	Equation	Definitions
Test for DRX	$\varepsilon_p = A_1(d_o)^{0.3}Z^q$ Above 1000 °C and with $d_o = 277 \mu\text{m}$ $Z_1 = \dot{\varepsilon} \exp\left(\frac{238000}{RT}\right) A_1 = 6.2 \times 10^{-4}q = 0.22$ Below 1000 °C and with $d_o = 26 \mu\text{m}$ $Z_2 = \dot{\varepsilon} \exp\left(\frac{330000}{RT}\right) A_1 = 1.3 \times 10^{-4}q = 0.2$	ε_p = peak strain d_o = austenite grain size going into stand (μm) T = temperature (K) Z = Zener-Hollomon parameter (/s) R = universal gas constant (J/mol/K) $\dot{\varepsilon}$ = Strain rate during pass
Strain at 50% DRX	$\varepsilon_{0.5} = 1.144 \times 10^{-5} d_o^{0.28} (\dot{\varepsilon})^{0.05} \exp\left(\frac{53388}{RT}\right)$	
Fraction from DRX	$X_{\text{DRX}} = 1 - \exp\left[\frac{(\varepsilon_T - \varepsilon_c)}{\varepsilon_{0.5}}\right]$	X_{DRX} = Fraction recrystallized from DRX ε_T = total strain of pass (including redundant strain) ε_c = critical strain for DRX = $0.8\varepsilon_p$
Accumulated strain and strain for next stand	$\Delta\varepsilon_a = K_{\text{acc}}(1 - X_{\text{DRX}})\varepsilon_{n-1}$ $\varepsilon_{n+1} = \varepsilon_n + \Delta\varepsilon_a$	$\Delta\varepsilon_a$ = accumulated strain for stand n K_{acc} = constant 0.5 to 1 ε_{n-1} = strain from previous stand ε_{n+1} = strain for next stand
Time for 50% DRX	$t_{0.5} = 0.4 \left\{ \dot{\varepsilon} \exp\left(\frac{238000}{RT}\right) \right\}^{-0.8} \left\{ \exp\left(\frac{240000}{RT}\right) \right\}$	$t_{0.5}$ = time for 50 % DRX (s)
Grain size from DRX	$d_{\text{DRX}} = 2.6 \times 10^4 \left\{ \dot{\varepsilon} \exp\left(\frac{238000}{RT}\right) \right\}^{-0.23}$	d_{DRX} = grain size from DRX (μm)
Grain growth after DRX at $t_{ip} < 1$	$d^2 = d_{\text{DRX}}^2 + 1.2 \times 10^7 (t_{ip} - 2.65t_{0.5}) \exp\left(\frac{-113000}{RT}\right)$	d = grain size after t_{ip} (μm)
Grain growth after DRX at $t_{ip} > 1$	$d^7 = d_{\text{DRX}}^7 + 8.2 \times 10^{25} \{(t_{ip} - 1) - 2.65t_{0.5}\} \exp\left(\frac{-40000}{RT}\right)$	
Critical strain for DRX	$\varepsilon_c = 5.6 \times 10^{-4} d_o^{0.3} Z^{0.17}$	ε_c = critical strain for DRX
Zener-Hollomon Parameter	$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right)$	Z = Zener-Hollomon parameter Q = Activation energy

<i>Application</i>	<i>Equation</i>	<i>Definitions</i>
Fractional softening	$X = 1 - \exp \left[-0.693 \left(\frac{t}{t_{0.5}} \right)^q \right]$	X = fraction softening
Accumulated strain at pass n	$\varepsilon_a = \varepsilon_n + (1 - X)\varepsilon_{n-1}$	
Recrystallized grain size	$\text{if } \varepsilon_a < \varepsilon_c$ $d_{SRX} = 343\varepsilon^{-0.5}d_o^{0.4}\exp\left(\frac{-45000}{RT}\right)$ $\text{if } \varepsilon_a > \varepsilon_c$ $d_{MDRX} = 2.6 \times 10^4 Z^{-0.23}$	
Time for 50% recrystallization	$\text{if } \varepsilon_a < \varepsilon_c$ $t_{0.5}^{SRX} = 2.3 \times 10^{-15} \varepsilon^{-2.5} d_o^2 \exp\left(\frac{230000}{RT}\right)$ $\text{if } \varepsilon_a > \varepsilon_c$ $t_{0.5}^{MDRX} = 1.1 Z^{-0.8} \exp\left(\frac{23000}{RT}\right)$	
Grain growth	SRX $d^7 = d_{SRX}^7 + 1.5 \times 10^{27} (t_{ip} - 4.32t_{0.5}) \exp\left(\frac{-40000}{RT}\right)$ If $t_{ip} > 1$ MDRX $d^7 = d_{MDRX}^7 + 8.2 \times 10^{25} (t_{ip} - 2.62t_{0.5}) \exp\left(\frac{-40000}{RT}\right)$ SRX $d^2 = d_{SRX}^2 + 4.0 \times 10^7 (t_{ip} - 4.32t_{0.5}) \exp\left(\frac{-113000}{RT}\right)$ If $t_{ip} > 1$ MDRX $d^2 = d_{MDRX}^2 + 1.2 \times 10^7 (t_{ip} - 2.65t_{0.5}) \exp\left(\frac{-113000}{RT}\right)$	

Failures of Hot Rolled Flat Steel Product by Undesirable Metallurgical Constituents (δ/γ) Interaction and Casting Defects

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ABSTRACT: This investigation was carried out in form of case study on a failure of whole heat of the hot rolled plate of AISI 309S Stainless steel. Other than the routine break downs and mechanical maintenance issues, the loss of production due to complete heat off was affected on production efficiency and increased cost of production due to undesirable metallurgical complexity between delta ferrite (δ) and high temperature austenite (γ) formation. The expensive steels of high chromium and high nickel are specifically used in high temperature, pressure and chemical environments like furnace burners, fluidized bed furnaces, petroleum refineries, power generation units and thermal processing equipment etc. When it losses the production and quality, there will be tremendous demand to design alloy composition and process parameters for successful casting and rolling operations to the finishing flat products. However, the flat products are their own importance over long products due to high surface to volume ratio that demands large quantity of steel requirement (i.e. MT). Therefore, the failures and reasons were investigated by using structural and metallographic analysis. Main reasons found that enrichment of the delta ferrite formation in the slab cast structure may be increased by improper of chemical composition and casting parameters. It may be acting as resistance to hot deformation by suppressing desirable metallurgical constituent of austenite fraction and also increased grain boundary strength. The un-decomposed delta ferrite boundaries were observed as elongated in the rolling direction. They may be initiated cracking and void formation by increasing interaction between δ/γ phase boundaries under high temperature and high pressure rolling. Micro-structural cracking might be converted into macro-scale crack that is observed at different locations on the finished plates. Moreover, the uneven distribution of pressure and temperature effect at different positions on the surface of the steel plate was also noticed by randomly defected surface morphology. Therefore, the plate also contained shrinkage porosity defects at different places that might be accelerated shearing component by connecting cracks and voids growth during hot-rolling. The characterisation results were discussed for directionally elongated delta ferrite boundaries and shrinkage porosity voids and localised shearing/cracking regions in the production of the advanced stainless steel grades which are superior for oxidation resistance and retention of high strength and ductility.

Keywords: Flat Products, Stainless Steel Plates, Delta Ferrite, Austenite, Rolling, Defects.

1. INTRODUCTION

From several decades, the plate and sheet products have been widely employed for the engineering components, basic structural application and protective surfaces including furnace burners, fluidized bed furnaces, petroleum refineries, power generation units, thermal processing equipment, metallic bridge construction industry, nuclear plants, welded pipes for off-shore and on-shore oil and gas industries and shipbuilding workshops [1–3]. However, the engineering applications are frequently subjected to mechanical and thermal stress and strain effects. They will be inevitably led to the plate surface deterioration and reduction of service life due to release of energy during the stress-strain inducement either gradually or catastrophically that could give rise to an instantaneous high-pressure deformation in macro- and micro-structures [4, 5]. Thus, a statistical and dynamical stresses when originating in the engineering and service applications could be resulted extreme damage to the structural components and coupled with a violent expansion in the metallurgical constituents like ferrite and austenite microstructures in the steels and stainless steel plate and sheet materials [1, 4].

Macro and microscopically, many research experiments and modern numerical simulations have being used to investigate and predict the high pressure deformation failures of the plates and sheets products. In addition, metallographic studies have being used as an effective method for analysis and observation of the microstructure change which can determine the involved mechanical, process and operational failures. Liu *et al.* [6] observed characteristics of fracture in HSLA steel plates and suggested that crack propagation was occurred by the coalescence of microscopic voids. Geffroy *et al.* [7] observed fracture morphology in a high purity ferritic-pearlitic DH36 steel plate under the explosion loads and showed results of fracture by inducement of shear-ductile interruptions.

However, many studies are discussed fracture mechanisms and material failures due to crack propagation and shear-ductile distortions in the steels and alloy steel plates. This is mainly focused on the macroscopic scale and mechanical failures, but they are connected with the microscopic damage mechanisms in the structural components of the plate materials. Since, the research and understanding of the damage mechanism of structural and engineering steel products are still far from enough in the industrial production scale. Therefore, further research must be devoted to these areas and keeping attention on case studies of the stainless steel materials and rolled plate products from the industrial production. In this study, typically a failed stainless steel plate of AISI 309S austenitic grade material was selected for case investigation. The hot rolling process dynamics and poor response of the mechanical deformation during plate making process were interpreted undertaking macroscopic and microscopic studies by using various characterization methods. Their results are correlated with microstructures and their morphological changes and then found relationship between macroscopic failures connected with microscopic defects. In this case study, theoretical concepts, analytical reports for prediction and prevention of plate failures and to improve deformation ability of AISI 309S materials during conversion of slab to plate and sheet metals under hot rolling process are also thoroughly discussed.

2. MATERIAL AND METHOD

A failed stainless steel plate of AISI 309S austenitic grade materials was selected for this case study, which contains chemical composition as given in Table. 1. The first six elements are mainly to be considered for grade conformation and the remaining elements contribution should be as low as possible. But, their solubility is unavoidable due to effect of scrap melting in the secondary steel making route as shown in Table 1.

Table 1: Chemical Composition of AISI 309S Austenitic Stainless Steel Plate Material

<i>Elements</i>	<i>%C</i>	<i>%Mn</i>	<i>%Si</i>	<i>%S</i>	<i>P%</i>	<i>%Cr</i>	<i>%Ni</i>	<i>%Cu</i>	<i>%Mo</i>	<i>N(ppm)</i>
Range	0.050	1.60	0.52	0.007	0.039	22.15	12.15	0.12	0.06	389
Std. range	0.08	2.00	0.75	0.030	0.045	22–24	12–15	–	–	–

<i>Elements</i>	<i>%Co</i>	<i>%Ti</i>	<i>%Al</i>	<i>Ni_{eq}</i> <i>(WRC)</i>	<i>Cr_{eq}</i> <i>(WRC)</i>	<i>Sigma</i> <i>Phase</i>	<i>Ferrite No.</i> <i>(WRC)</i>	<i>Hardness</i>
Range	0.23	0.005	0.006	14.70	22.21	1.231	8.20	170–180

The hot rolling process was applied to plate making from the slab castings which is semi-finished raw material casted by continuous casting technique in the steel plant production and too large volumes. Before processing of the slab castings, the quality department was estimated following parameters of Nickel (Ni_{eq}) and Chromium equivalent (Cr_{eq}), sigma phase and ferrite number as shown in Table 1 according to the WRC-1992 suggested calculations [8]. The AISI 309S stainless steel slabs were subjected to the hot rolling process by reducing slab thickness under the temperature range from 950–1250°C. The plates produced by hot rolling process were subjected to solution annealing treatment in the range of 1000–1150°C followed by rapid water quenching technique. Many samples for failure analysis were collected from two different regions like cracked and non-cracked portions from five locations throughout the length of the stainless steel plate. For this case study, the samples were analysed by using ferritoscope, microscope and hardness testers following standard (Std.) laboratory practices.

3. RESULTS

Initially, collected cracked and non-cracked samples of the hot rolled plate are shown to highlight their surface morphology and distinguish cracks formation as shown in Figure 1. While, the sample hardness measurements are also shown to differentiate cracked and non-cracked regional strengths

in terms of hardness of the plate material. The hardness is found to be higher for non-cracked samples when compared with the cracked plate sample. Hardness values range is specified in the bottom of the each sample photograph as shown in Figure 1.

In continuation, inclusions rating are presented of the same samples after proper metal-graphic preparation but without chemical etching. One can see the cracked and non-cracked samples morphologies and presented inclusions rating as shown in Figure 2. Micrographs of the cracked samples are shown one from centre (Figure 2a) and the other one taken near to the surface region (Figure 2b). Those cracks are in macro-scale they are named as cracked plate samples but macro-cracks are not identified in another sample that named as non-cracked samples as shown in Figure 2(c&d). However, major inclusions like oxides, sulphides, silicates and aluminates have not been found in both the samples according to the national and international standards used in major steel industries [2, 3].

For micro-structural analysis, the samples collected from both the sides as called surface and thickness of the stainless steel plate were polished for metallographic finishing. Both the samples were chemically etched to reveal their parental austenitic microstructure with aqueous reagent of 75ml HCl and 25 ml HNO_3 as shown in Figure 3. The micro-structural results are revealed two different features as shown in Figure 3 (a–d). But, the austenitic grains are clearly



Figure 1: Macro Surface of the Cracked and Non-cracked Samples of the Failed AISI 309S Austenitic Stainless Steel Plates

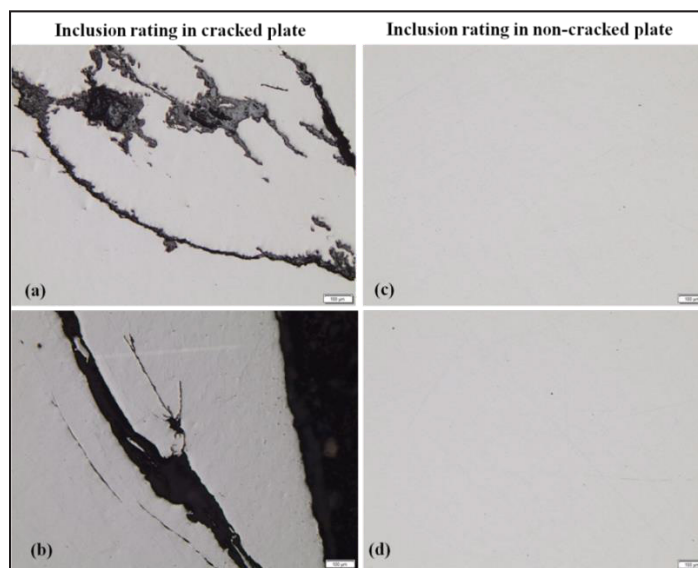


Figure 2: Micrographs of Cracked and Non-cracked Plates of AISI 309S Austenitic Stainless Steels

revealing in the surface side of both the samples as shown in Figure 3(a&c). In addition, the microstructures are also revealing a secondary phase in the black colour contrast to both the cracked samples, which are elongated into a specific direction. Similar features one can observe in the non-cracked samples but the results have morphologically different in the surface and

thickness side. The secondary phase which is undesired has quantitatively higher fraction in case of the cracked sample (Figure 3 a&b) when compared with the non-cracked samples as shown in Figure 3 (c&d). Thus, the microstructures of the thickness side samples are different in both the cases but very severe in case of the cracked samples as shown in Figure 3(b). The non-cracked

samples have different type of microstructure morphology than the cracked sample therefore the structure may be not cracked under extreme rolling temperature and pressure.

The micro-structural features are also studied at higher magnifications to reveal detailed information about micro-phases morphology and micro-cracks characteristics as shown in Figure 4 and Figure 5. The austenitic phase in the microstructure is very clearly resolved in the surface side samples of both the cracked and non-cracked as shown in Figure 4 (a&c). However, the secondary phase appears more elongated and quantitatively large fraction in the cracked sample when compare with the non-cracked samples. But, the secondary phase may not be appearing as crack morphology in the surface side when compared with thickness side samples as shown in Figure 4 (a&b). The micro-cracks characteristics are very sharp and moreover straight line morphology in the thickness side

of the cracked samples (Figure 4 b&d) compared with the cracks presented in the non-cracked samples (Figure 4 c&d). If quantified, the length of the cracks has greater than $100\mu\text{m}$ in the cracked sample and less than $100\mu\text{m}$ in the non-cracked samples. One can also observe that the cracks are propagating along the austenitic grain boundaries as shown in Figure 4(d).

The nature of the cracks one can clearly observe and understandable from the results of Figure 5. At higher magnification, the micro-cracks structure looks like a secondary metallurgical phase according to their morphology in the austenitic matrix. Because, the secondary phase morphology appears quite different contrast and lied specifically in the austenitic grain boundaries. It means that the secondary phase might be retained as non-decomposed delta ferrite due to improper reheating and roughing mill reductions in the hot rolling

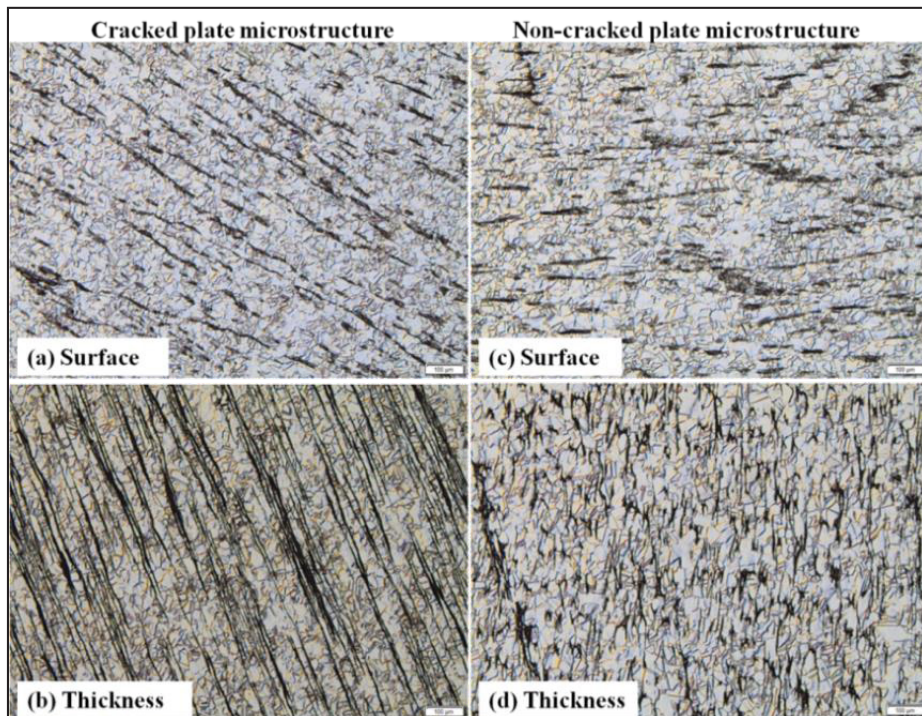


Figure 3: Microstructures of Surface and Thickness Side of Cracked and Non-cracked Plates of AISI 309S Steels

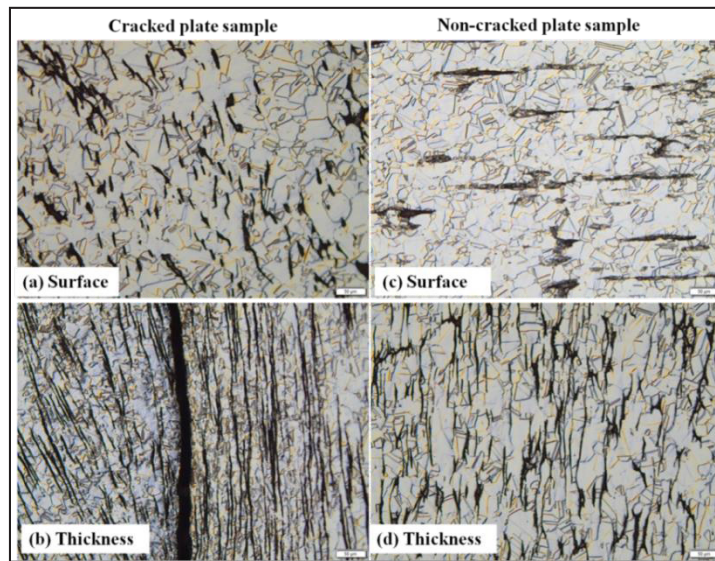


Figure 4: Micro-cracks Structure in the Surface and Thickness Side of the Cracked and Non-cracked Plates

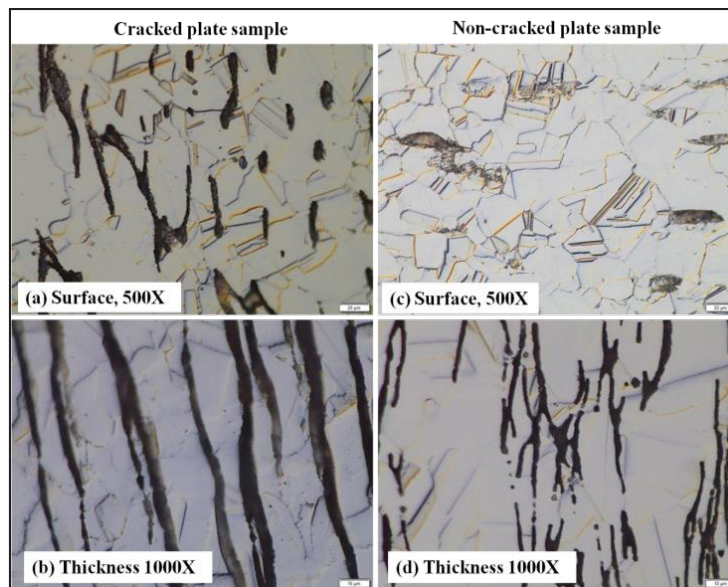


Figure 5: Microstructures of the Surface and Thickness Side of the Cracked and Non-cracked Plates

process of the plate. This observation can conform as retained delta-ferrite due to a type of secondary phase formation around an austenitic grain boundary in the surface side samples and following directionality along the austenitic grain boundaries in the

thickness side samples Figure 5 (a&b). The elongated delta-ferrite phase may be separated in the surface microstructure (Figure 5 a&c) due to high spreading ratio of the plate surface rolling but the same elongated delta ferrite phase is consolidated and sintered into

the directional delta ferrite in case of the thickness side surface (Figure 5 b&d) due to enhanced compressive forces during hot rolling process of the AISI 309S austenitic stainless steel plate.

However, if the secondary phase conclude as a delta ferrite concentration in the revealed austenitic matrix from the above results. The plate material must be thoroughly analysed to find reasons to form such a large amount of delta ferrite in the AISI 309S austenitic stainless steels. In further analysis, the microstructural defects were searched for land marks to formation of excess delta ferrite during solidification irregularities and also revealed solidification shrinkage marks in many places across the plate material as shown in Figure 6(a). The secondary phase of the delta ferrite is quantified as shown in Figure 6(b) and found as formed in the range of 12–15% in the AISI 309S austenitic phase

based on the surface side micro-structural results of plate. The excess range of delta ferrite must be differentiated the deformation behaviour of the austenite from the delta-ferrite phase that leads separation of two different phases.

For confirmation of the delta ferrite formation by other direct methods, the ferritoscopic instrument was used and results are shown in Table. 2 including the plate surface region and the thickness side surface material region. The advanced ferritoscope instrument can easily determine ferrite properties like ferrite number, percent of ferrite and martensite details by direct measurements using principles of magnetic resonances more accurately on the polished surfaces of stainless steel samples which contains both ferrite and austenite phases. The ferrite fractions are varying from surface to thickness side as shown in Table 2.

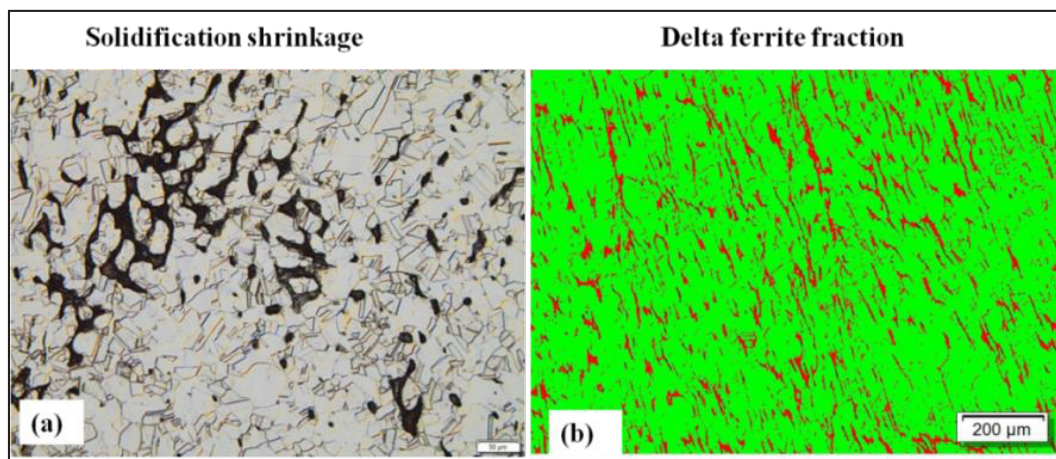


Figure 6: Micrographs of Solidification Shrinkage Marks and Delta Ferrite Distribution in AISI 309S Austenitic Stainless Steels Plates

Table 2: Ferritscope Analysis of the Failed AISI 309S Austenitic Stainless Steel Plates

<i>Ferritscope Readings on Top Surface</i>			<i>Ferritscope Readings on Thickness Surface</i>		
<i>Ferrite No.</i>	<i>%Ferrite</i>	<i>%Martensite</i>	<i>Ferrite No.</i>	<i>%Ferrite</i>	<i>%Martensite</i>
2–3	3–4	5–6.5	3.8–5.5	5.5–6.5	8–11

4. DISCUSSION

From the above analysis and interpretations, the AISI 309S stainless steels are known to be fully austenite phase in the microstructure of the plate material. The plate products have been produced by secondary steel making following continuous slab casting and hot rolling processes. But the plate materials production was failed during the hot rolling deformation due to cracking of the plates. Initially, one is assumed about cracking of plates due to increasing inclusions content therefore samples were collected from cracked and non-cracked locations and studied inclusion rating as shown in Figure 2. But, no inclusions were found in both the cracked and non-cracked plate samples. Therefore, it is concluded that inclusion rating and their contribution may not be reason to failure of the plate material production. In continuation, the micro-structural analysis was carried out to understand either effect of grain size variation or carbide precipitation. Unexpectedly, the plate microstructure shows plenty of the micro-cracks in both samples of surface and thickness side portion. The surface side where the material was widely spread due to malleability shows broken cracks, while the thickness side material where the material was reduced section due to compressibility shows continuous cracks aligned parallelly to each other in the austenite phase (Figure 3 & Figure 4). This may be considered as effect of high surface to volume ratio in some high alloy stainless steels. A reason to form cracks has been investigated by resolving their microstructures at very high magnification as shown in Figure 5. One can understand that the cracked regions are not very deep in depth and separated from the matrix. This means that it may be a secondary matrix which is forming from the process of alloy designing, melting and casting. Moreover, solidification shrinkage defects are also found in austenitic phase (Figure 6a). The secondary phase is increasing

the grain boundary strength by aligning into single form which looks like a crack at lower magnification. However, the secondary phase is also determined as delta ferrite as shown in Figure 6(b) [9]. Due to increasing the grain boundary strength of the material, the hot rolling process used for slab to plate making may be cracking plate under high temperature and high pressure conditions. The temperature and pressure may be uneven due to ferrite and austenite matrixes across widely spreading surface area during the hot rolling deformation [10]. Certain amount of delta ferrite phase may not be decomposed during reheating and roughing rolling process due to formation of excess amount during continuous casting of the slabs. For the conformation, direct measurements were carried out as reported in Table 2. By this case study, the alloy composition is redesigned and delta ferrite formation controlled by melting and casting processes to reduce the cracking of the plate production.

5. CONCLUSIONS

The AISI 309S plate material was failed during hot rolling process. The cracked and non-cracked regions of the plate material were investigated. The cracking is observed taking place along the grain boundaries. The austenitic grain boundaries contain returned delta ferrite and undecomposed even after large thickness reduction by hot rolling process. The delta ferrite fraction is measured being in the range of 12–15% by phase analysis. The ferrite content is also measured direct method using ferritscope instrument suitable for austenitic steels.

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Advanced Hot Rolled Steel Sheet for Hot Forming Application

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ABSTRACT: Axle housing are critical components for automotive vehicles. These components are manufactured through induction heating of hot rolled (HR) steel to 800°C–900°C, followed by hot forming and air cooling. Key requirements of HR steel for the application are (i) steel to retain its strength in hot formed (HF) parts, and (ii) Impact property guarantee in as rolled and HF condition at sub-zero temperatures. Attaining very high strength (UTS>600 MPa), along with impact toughness guarantee at –20°C and –40°C is technically challenging for thickness range of 12–16 mm. Also, controlling the significant strength drop due to precipitate coarsening at HF part is difficult. Accordingly, appropriate alloy design and processing strategy needs to be adopted to develop these grades.

Plant trial was undertaken with a V micro alloyed chemistry with some Nb and Ti in composition. In developed HF grade, high strength after hot forming was retained primarily through refinement of ferrite (polygonal/bainitic) grains/plates, and precipitation strengthening. Some level of dislocation strengthening was also utilized to get the required strength in final axle housing part. Grain growth at high temperature processing (both during hot rolling and hot forming) were controlled by having very small amount of TiN precipitates. Suitable coiling strategy is used to partially suppress precipitates at HR coil, resulting in better low temperature toughness at –20°C and –40°C. Suppressed precipitates were utilised during hot forming step to retain the property in final component through precipitation hardening. Hot rolled HF grade is successfully developed at Tata Steel Ltd. (India) for automotive customers.

Keywords: First Keyword, Second Keyword, Third Keyword.

1. INTRODUCTION

Axle housing for heavy commercial vehicles is an important automotive component with a function to transfer the power from the engine to the wheels while supporting the weight of the vehicle. The axle housing provides the mounting point for suspension system, which absorbs shock and keep the wheels in contact with the road. Usually, the axle housing is manufactured through induction heating and hot forming the hot rolled (HR) steel of 12–16 mm

thickness. The hot forming temperature usually ranges from 800°C to 900°C. After hot forming, the formed component is air cooled to room temperature to reduce thermal stress. Typical axle housing component is shown in figure 1[14].



Figure 1: Hot Formed Axle Housing Component[14]

As a primary functional requirement, the HR steel sheet for hot formed axel housing application must retain its original strength and toughness along with good weldability after hot forming. Literature suggests Vanadium (V) based microalloying concept with Nitrogen (N) is as preferred choice for hot forming and normalising application due to following advantages [1, 2, 5, 6, 7, 10, 11, 15]:

1. Vanadium shows highest solubility among other microalloying elements which ensures better precipitation hardening efficiency. Majority of microalloy remains in solution prior to finish rolling leading to reduced finishing mill (FM) roll force. Most of the precipitation hardening occurs at run out table (ROT) and after coiling. This makes the precipitation hardening more predictable for relatively large range of V addition.
2. Minimum precipitation during casting and solidification improves hot ductility and reduces edge crack/edge burst defect during casting, which could get translated to final HR coil.
3. V microalloyed steels are compatible with high finish rolling temperature due to recrystallized controlled rolling (RCR) strategy. This results in reduced internal stresses and improved shape after banking, making the HR sheet more suitable for laser or plasma cutting application. Blanking for axel housing component is usually done through plasma torch which make it extremely critical for HR sheet to have flat surface after blanking.
4. If sufficient N is available in steel, V based microalloyed steel shows linear effect in chemistry-strength model.
5. With optimized hot rolling processing condition, refined ferrite microstructure and precipitation control, improved toughness, and weldability like Nb microalloyed design can be achieved. [2]

6. Dissolution and reprecipitation of vanadium microalloy precipitates during normalising thermal cycle is plays an important role to retain property in final part. [12–15]

Thermomechanical behavior during hot rolling of V microalloyed steel is shown in figure 2 [7]. The first stage of rolling (in roughing mill) promotes RCR of austenite (γ). As per the precipitation kinetics of VN or V[C, N] during finish hot rolling described in literature [7], strain induced precipitation of V microalloyed precipitates may occur during finish rolling which acts a nucleation site for ferrite [12]. This leads to very fine ferrite grain size due to higher ferrite nucleation rate. Also, the VN or V[C, N] that precipitates at the austenite grain boundaries restricts austenite grain growth. Literature also suggests that additions of small amount of Ti, which forms TiN, inhibits recrystallized austenite grain growth through Zener pinning. This improves strength and toughness after RCR rolling.

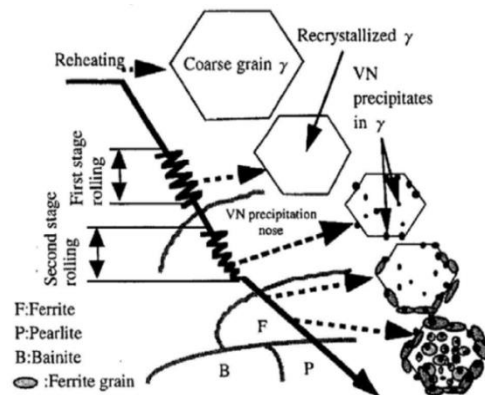


Figure 2: Austenite Recrystallisation, VN precipitation and austenite to ferrite phase transformation during hot rolling of thick section V microalloyed steel [7]

The microstructure and precipitation evolution of V and N microalloyed steel, subjected to hot forming + air cooling condition is explained in Figure 3 [15]. The thermal cycle for Axel housing manufacturing is like

normalising heat treatment condition, where substantial strength drop due to microstructure and precipitation coarsening limits the TMCP rolling + Accelerated cooling (ACC) strategy, that is used in case of Nb microalloyed design. At higher austenitising temperature, size, volume fraction and distribution of microalloying precipitates gets affected which leads to significant strength drop. For normalising application, V-N microalloying strategy is an effective method of strengthening specifically for thicker sections. Due to higher thermodynamic stability of V-N based precipitates, some undissolved VN remains in austenite matrix [15]. These precipitates restrict growth of austenite at normalising temperature. During air cooling, dissolved V microalloy precipitates get reprecipitated and provide precipitation strengthening. The undissolved V[C, N] bring on intragranular ferrite nucleation and refines the ferrite grains [11]. The refined ferrite grains as shown in Figure 3[c] leads to improvement in toughness at normalized condition. Nevertheless, an increased precipitation hardening in as rolled HR condition, with large volume fraction of second phase (pearlite) causes toughness drop at sub zero temperatures. [1, 3, 5, 13]

2. MATERIAL AND PROCEDURE

Chemical composition of 450HF steel grade is given in Table 1. It is a peritectic C and vanadium microalloyed design, with some amount of Nb and Ti present in the composition. Slabs of given composition range were industrially cast to 230mm thickness in continuous casting machine, and hot rolled in industrial Hot Strip Mill (HSM) to final coil thickness ranging from 11–16 mm. Detailed HSM parameter set up along with metallurgical changes occurring during industrial rolling of 450HF grade is shown in Figure 4.

Hot rolling trial was taken at three different coiling temperatures (CT) ranging from 550–620°C. Accordingly, HR coils processed at different CT to be referred as **Steel A** – coiled at 550°C, **Steel B** – coiled at 580°C and **Steel C** – coiled at 620°C.

Standard metallographic procedure was used for polishing the samples. Samples were etched with 2% Nital to reveal the Microstructures. Leica optical microscope, FEG-scanning electron microscope, Zeiss SUPRA-25 with EDS were used to observe the microstructure. A 200 keV transmission electron microscope (TEM) was used to study the microalloy precipitates.

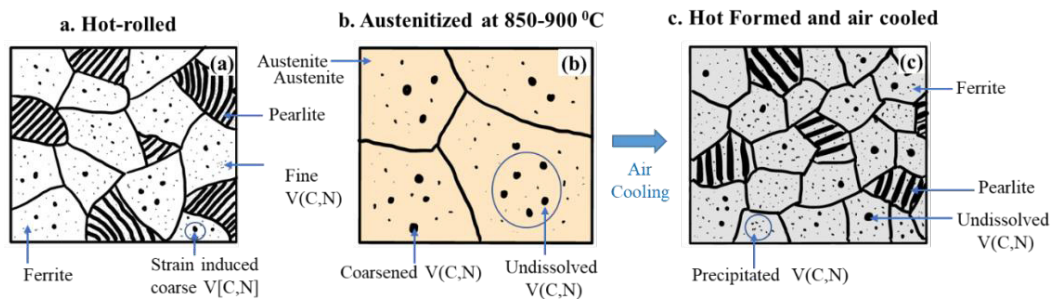


Figure 3: Microstructure and Precipitation Evolution of V and N Microalloyed Steel Subjected to Hot Forming + Air Cooling Condition [15]

Table 1: Chemical Composition (in wt%)

Steel Grade	C	Mn	S	P	Si	Al	N, ppm	V+Nb+Ti	Ca, ppm
450HF	0.07–0.11	1.4–1.6	<0.005	<0.025	0.2–0.5	0.02–0.06	60–120	0.25 max	10–30

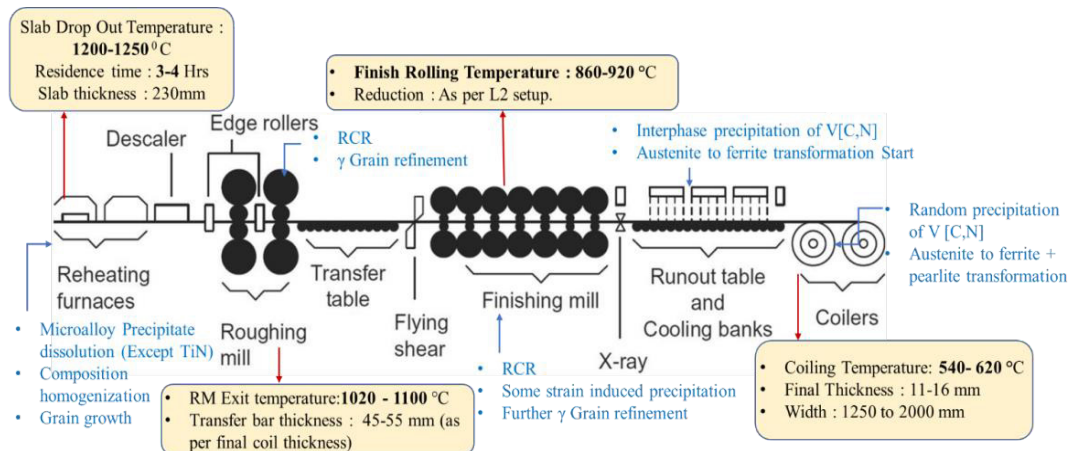


Figure 4: Hot Rolling Mill Parameter Setup along with Stage Wise Metallurgical Phenomenon for the Rolling of V-Microalloyed Alloyed 450 HF Grade

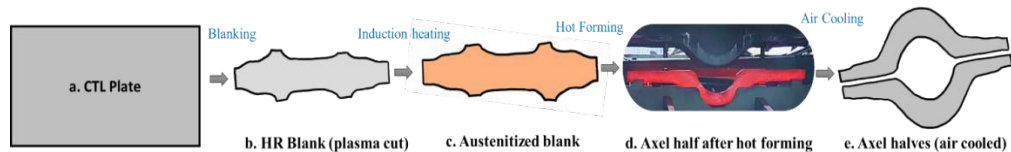


Figure 5: Process to Manufacture Hot Formed Axle Halves

Hot rolled coils were sized to Cut to Length (CTL) plates, followed by plasma cutting to make blanks (Figure 5a) at automotive customer facility. HR blanks were induction heated from room temperature to austenitising temperature with a heating rate of $\sim 10^\circ\text{C}/\text{Sec}$. Austenitising temperature was varied from 800–900°C to study the effect of hot forming temperature. Heated blanks were hot formed to axle halves in an industrial hot forming machine having an induction heater. It was followed by air cooling the hot formed axle half to room temperature at a cooling rate of $\sim 1^\circ\text{C}/\text{sec}$.

3. RESULT AND DISCUSSION

As rolled microstructures of HR coil samples processed at different coiling temperatures are shown in figure 6. The transition from mostly bainitic ferrite type microstructure at low CT 550°C, to increase in fraction of

polygonal ferrite at higher CT [620°C] is evident from microstructure analysis. Very limited precipitate volume in Steel A is due to inferior thermal activation energy for precipitation at lower CT (Figure 5b). In case of Steel C, due to increased thermal activation energy at higher CT, higher volume fraction of precipitates is visible. These precipitates are mostly carbides and carbonitrides of V. In Steel B, the precipitation is still shallow compared to Steel C, with marginally higher amount of polygonal ferrite as compared to Steel A. The average grain size of Steel A is very fine ($\sim 4 \mu\text{m}$) compared to average grain size ($\sim 10 \mu\text{m}$) of Steel C.

Grain growth at high temperature (both during hot rolling and hot forming) may also been prevented by having very small amount of Ti in chemistry. Ti forms stable TiN precipitates during casting and remains undissolved during reheating, and thermal heat treatment cycle.

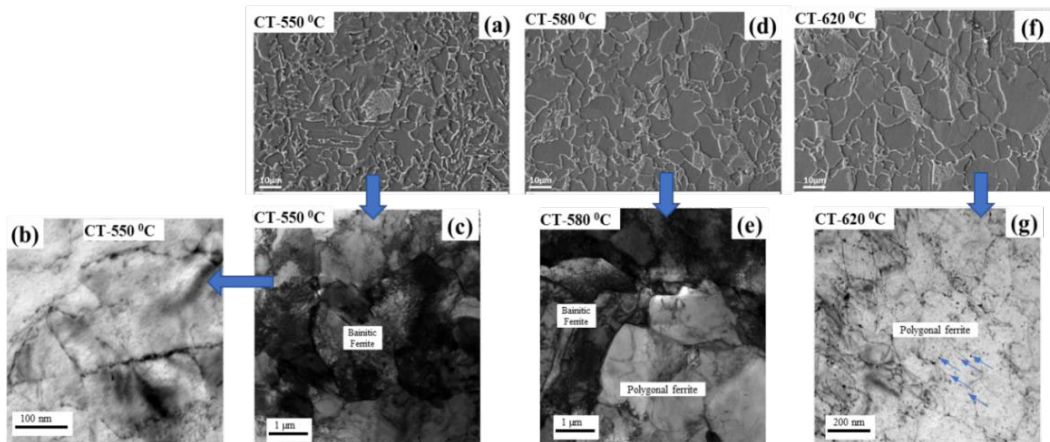


Figure 6: As rolled coil microstructure of 450 HF grade processed at different Coiling Temperatures (CT): (a) SEM image Steel A with acicular/bainitic ferrite microstructure (b) TEM image of Steel A showing limited precipitation due to reduced CT (c) TEM image Steel A showing bainitic ferrite and some polygonal ferrite + dislocations (d) SEM image of Steel B (e) TEM image Steel B showing bainitic ferrite and increased polygonal ferrite (f) SEM of Steel C with mostly polygonal ferrite microstructure (g) TEM of Steel C showing higher volume fraction of precipitates.

Automotive axel component manufacturer requires minimum YS of 500 MPa, UTS of 600 MPa and CVN of 35J at -20°C in as rolled HR condition for selected hot forming grade. Also, the minimum YS and UTS requirement after hot forming at 850°C is 450 MPa and 580 MPa respectively. The said requirement is challenging to achieve due to following metallurgical reasons:

1. Increasing the strength of as rolled HR coil through conventional strengthening mechanism such as precipitation strengthening, solid solution strengthening, and higher pearlite content through C addition may lead to drop in CVN value at sub-zero temperature (-20°C and -40°C) [5].
2. Retaining the strength of steel after hot forming, which is comparable to normalising thermal cycle is difficult. The conventional strengthening through high C addition and pearlitic microstructure, with Nb only microalloyed design is invalid due rapid precipitation coarsening, and insufficient grain size refinement [1,11,13]. As a result, strength drop of >120 MPa from HR

coil to hot formed component is expected if strengthening and processing is done through conventional method.

3. Steel for such stringent property requirement requires tailoring the microstructure that gives improved strength and toughness combination in as rolled condition, while being resistant to major strength drop after hot forming.

Mechanical properties and Charpy V Notch (CVN) test results for samples coiled at different temperatures are shown in figure 7 and figure 8 respectively. Relatively high YS (588 MPa) and UTS (693) MPa of Steel C is attributed to increased precipitation strengthening through $\text{V}[\text{C}, \text{N}]$ precipitates [11]. As a result, steel coiled at higher temperature (Steel C) showed the least CVN value for given test temperature (CVN of 54J and 23J at -20°C and -40°C respectively).

The higher YS to UTS ratio (~ 0.85) of Steel C is due to reduced mobile dislocations, and increased precipitation hardening [Figure 6 f, g] [11]. Conversely, Steel A showed and improved combination of strength and CVN value even at sub-zero temperatures. The

improved strength (UTS 693 MPa) and toughness combination (CVN of 178J and 103J at -20°C and -40°C respectively) in Steel A was obtained through acicular/bainitic ferrite type microstructure. It showed high degree of misorientation, along with very fine grain size ($\sim 4\ \mu$) and higher dislocation density[11][Figure 6 a, b, c]. Also, reduced precipitation strengthening in Steel A results in improved toughness [5], specially at sub zero temperatures. The V remained in solution during low temperature coiling can be utilised for precipitation strengthening during austenitising and air-cooling step of

hot forming. Precipitation of V[C, N] during hot forming thermal cycle can also compensate for strength drop due to dislocation annihilation and precipitation coarsening in final component. This phenomenon can reduce the overall strength drop from HR coil to hot formed axel part. Steel B shows similar mechanical property and impact property as Steel A sample with marginally reduced strength and toughness combination. The rationale remains the same as that for Steel A coil, with reduced precipitation strengthening and bainitic ferrite microstructure (Figure 6 d, e).

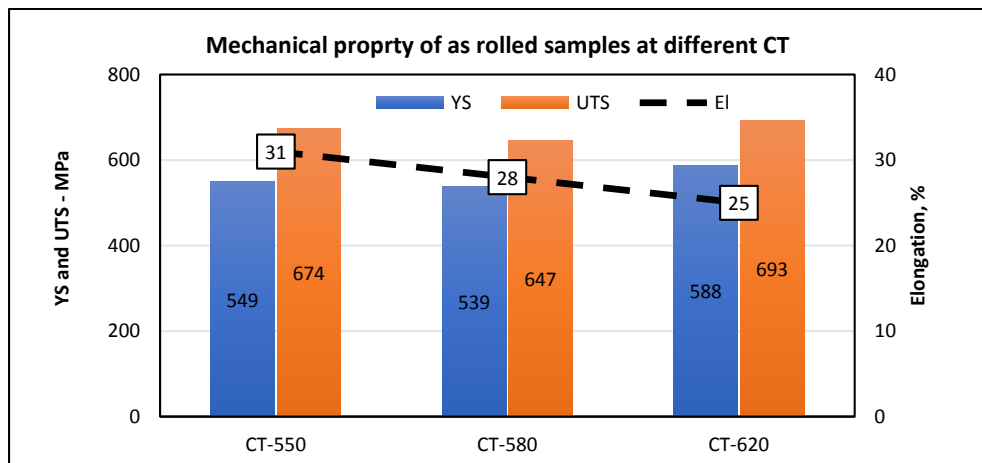


Figure 7: Mechanical Properties of as Rolled (HR) Samples at Different Coiling Temperatures

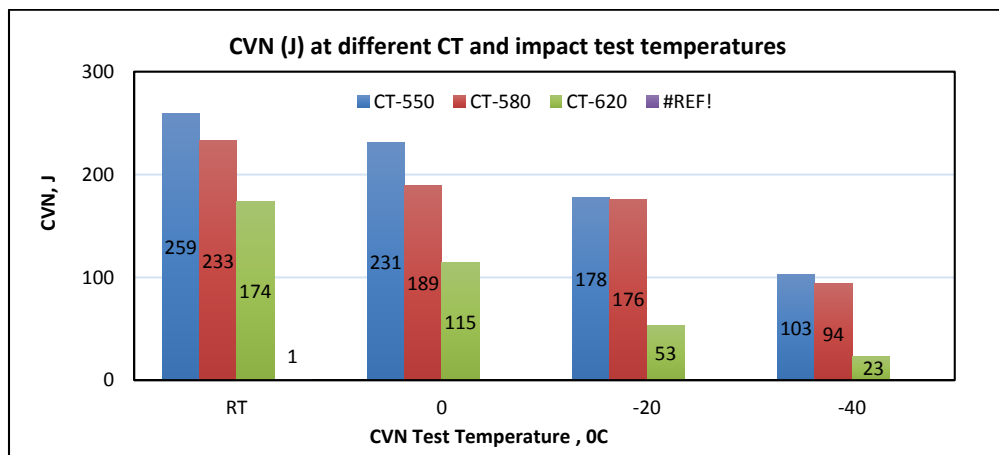


Figure 8: Charpy V Notch (CVN) Impact Test Values at Different Impact Test Temperatures, for Samples Coiled at Different CT

Based on the as rolled HR coil property, Steel A was tried at automotive customer facility to manufacture hot formed axel housing parts. The processing at customer end was as per Figure 5. Austenization temperature during hot forming was varied from 800–900°C to study the effect of hot forming temperature. Mechanical property and CVN impact test results of hot formed part is plotted in figure 9. Mechanical property in HF component is comfortably meeting the automotive customers requirement of YS ≥ 450 MPa and UTS ≥ 580 MPa at 800°C and 850°C. Also, the CVN value is well above the minimum specified requirement of 35J @ –20°C at given hot forming temperature.

Strength decreased with increase in hot forming temperature in the range of 800°C to 900°C. Level of precipitation coarsening and fraction of dislocation annihilation at given hot forming temperature can cause this strength drop. It is also important to consider that heating rate in an industrial induction heating is much higher compared to oil bath type heating. Accordingly, significant annihilation of dislocations in initial ferrite/bainitic ferrite phase might not happen if the hot forming temperature is kept low ($\leq 850^\circ\text{C}$).

To understand the amount of austenite fraction at given hot forming temperatures, transformation temperature was measured from the dilation vs temperature curves during heating and cooling (figure 10). Heating rate was kept at 10°C/sec, and cooling rate at 1°C/sec to simulate the industrial induction heating and air-cooling condition. At 800°C, the microstructure had a very low level ($\sim 14\%$) of austenite content and remaining phase as ferrite. Accordingly, the level of precipitation coarsening, grain growth and dislocation annihilation will be low. Therefore, the strength in low temperature austenization is higher (YS 554 MPa, UTS 654 MPa) compared to high temperature austenization at 900°C (YS 477 MPa, UTS 565 MPa). When the forming temperature was raised to 850°C, austenite content increased to $\sim 46\%$. At 900°C, the microstructure was completely austenitic as marked in figure 10. Relatively larger precipitation and grain size coarsening, along with higher dislocation annihilation would lead to significant strength drop as seen in case of 900°C hot formed sample. Increase in CVN values in samples formed at higher temperatures can be attributed to reduced precipitation hardening, with adequate grain size refinement during air cooling [9, 11, 15].

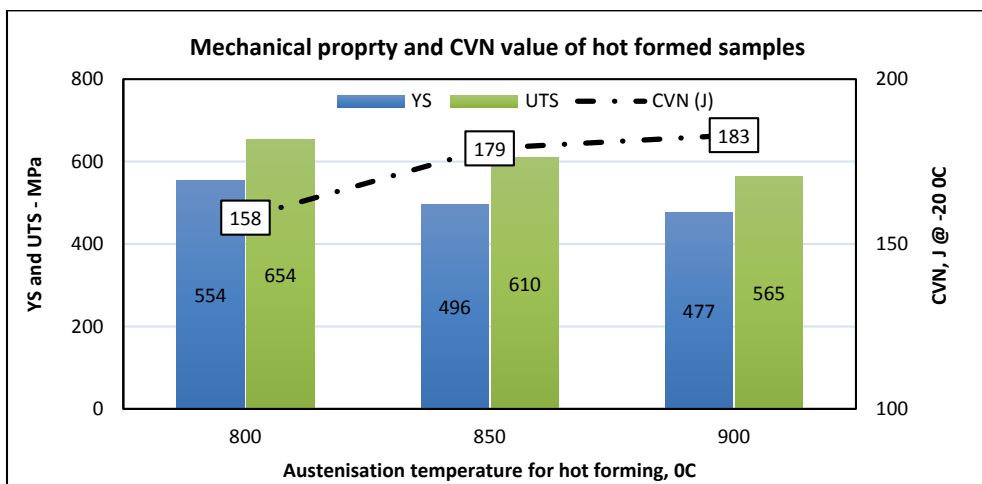


Figure 9: Mechanical Property CVN Impact Test Values at Different Hot Forming Temperatures

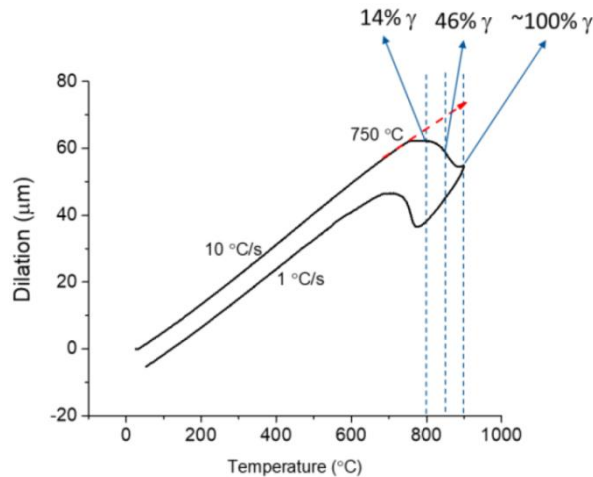


Figure 10: Transformation temperatures measured from the dilation vs temperature curves during heating (10°C/s) and cooling (1°C/s). Amount of austenite phase at selected austenization temperatures are marked on the curve.

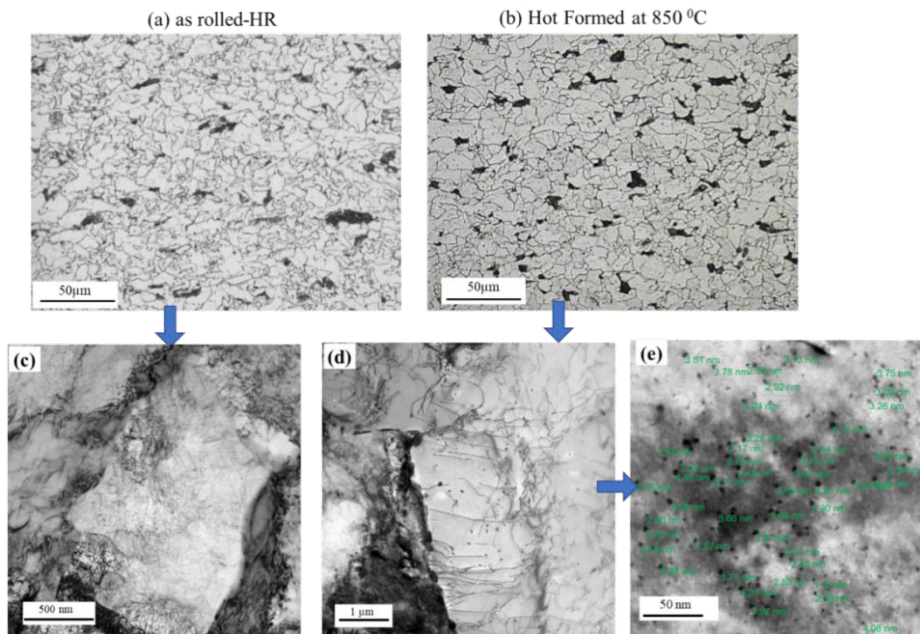


Figure 11: Microstructure of as Rolled HR and Hot Formed Samples

For better dimension control in final part, and to reduce forming force in the forging die, austenization temperature was finalised as 850°C. The minimum required mechanical properties were comfortably met in hot formed part at selected austenization temperature.

Microstructure comparison of as rolled vs hot formed samples at 850°C is illustrated in figure 11. Acicular ferrite/bainitic ferrite type microstructure (figure 11a) can be seen in as rolled condition, which was also illustrated in Figure 6 (Steel A). The level of acicularity of ferrite grains are reduced in hot formed

condition due to slow cooling rate from hot forming temperature (figure 11b). Any significant grain coarsening in hot formed sample is not evident as can be seen in figure 11b. Addition of some Ti in composition to form some fine TiN may have added to restriction of grain coarsening.

As explained earlier, due to higher heating rate, dislocation annihilation seems to be partial even at 850°C, as can be seen in figure 11(d). This may provide an additional strength in hot formed condition through dislocation strengthening. Precipitation is not very clear in as rolled condition (figure 11 c), suggesting partial suppression of precipitation at low coiling temperature. TEM micrograph hot formed sample shows both finer precipitates of size (2–5 nm), and few coarser precipitates of size ~15 nm (figure 11e). To sum up, the strength dropped in hot formed part due to grain coarsening, some precipitates coarsening, and dislocation annihilation may get balanced through very fine precipitation of new V[C, N] precipitates.

4. CONCLUSION

- Hot formed 450 HF grade was successfully developed and validated through industrial hot forming at automotive customer facility. Strength at hot formed condition were YS of 496 MPa, UTS of 610 MPa and CVN value of 179J at –20°C. The hot formed property comfortably meets the stringent customer requirement.
- The strength drops as the austenization temperature increases from 800°C to 900°C. Precipitation and grain coarsening, with dislocation annihilation at higher hot forming temperature may have caused this strength drop.
- In developed 450 HF grade, high strength after hot forming was retained primarily through refinement of ferrite (polygonal/bainitic) grains/plates, and precipitation

strengthening. Some level of dislocation strengthening was also utilized to get the required HF strength.

- Suitable coiling strategy is used to partially suppress precipitates at HR coil, resulting in better low temperature toughness at –20°C and –40°C. Suppressed precipitates were utilised during hot forming step to retain the property in final component through precipitation hardening.

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Eliminating Edge Waviness Issue in High Strength Dual Phase Hot Rolled Grades for Cold Rolling at Hot Strip Mill Kalinganagar

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ABSTRACT: Newly developed hot rolled Dual Phase (DP) grades for further cold rolling were encountering severe shape issues post hot rolling. The shape issue was edge waviness on both edges of the hot rolled coil post coiling when they were opened for surface and shape inspection at the Coil Dividing Line (CDL). This was resulting in coil parting and led to poor coil weight for further cold rolling applications. (Approximately 30% of the coil length was affected). A scientific study was done to understand the microstructural changes being encountered by grade during hot rolling along with comprehensive study of the hot mill process parameters. An innovative yet cost effective approach to encounter this problem was thought of and trialled in various campaigns. Better than expected results were obtained and this resulted in full coils being dispatched to the end customer (Cold Rolling Mill) without any loss due to parting at HSM. The paper captures the journey of this team to overcome and eliminate this problem of shape.

Keywords: Hot Rolling Flat, Work Roll, Finishing Mill, Crown, Dead Flat Rolling Curve.

1. BACKGROUND

Tata Steel's Cold Rolling Mill (CRM) at Kalinganagar was facing issues of shape in Hot Rolled (HR) coils which led to concerns and reduced satisfaction.



Figure 1: A Coil with Edge Waviness

This was leading to increased scrap generations in the cold rolling mill. This was almost to the tune of 30% of the coil length especially in the head end of the HR coil.

A brainstorming session with all concerned was held and many root causes were identified through a Fish Bone diagram.

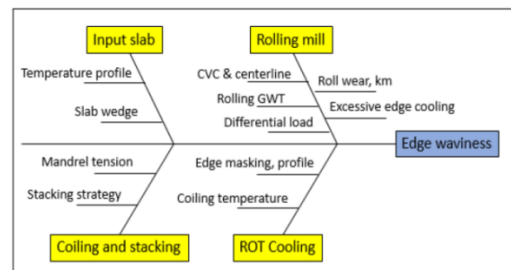


Figure 2: Fish Bone Diagram for Possible Causes of Edge Waviness

Literature reviews were also conducted to understand the phenomenon of edge waviness in hot rolled coils.

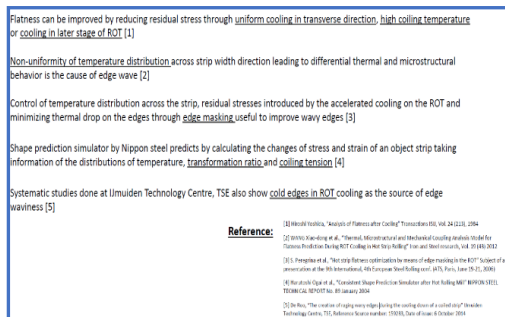


Figure 3: Literature Review

2. ROOT CAUSE IDENTIFICATION

Root cause investigation involved literature review and statistical analysis, leading to the formation of a cross-functional team. Gemba visits and data analysis pinpointed the issue and proposed essential corrective actions.

3. LITERATURE REVIEW

Extensive literature review was carried out.

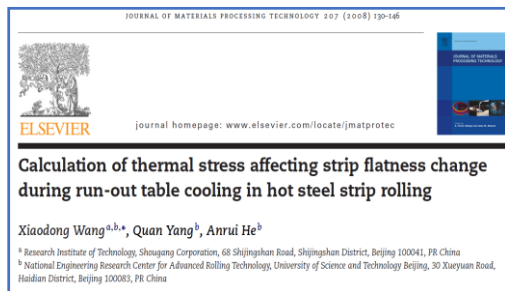


Figure 4: Paper Titled 'Calculation of Thermal Stress Affecting Strip Flatness Change during Run ...Out Table Colling in Hot Steel Strip Rolling

The paper mentioned that phase transformation of steel strip occurs during its cooling. This temperature drop within the strip edge region will make the strip edge develop flatness issues.

occurs in the strip edge region. It is reasonable to consider the phase transformation in steel strip during its cooling process. The strip with a higher rolling speed will have a higher cooling speed to be cooled to a certain coiling temperature, and then thermal stress increases more rapidly in it.

Temperature drop within strip edge region will make strip flatness develop to the trend of edge wave defect, and that has been proved by the actual strip flatness observations after cooling to ambient temperature. This viewpoint agrees well with the actual production condition.

To better control the final shape quality of hot rolled strip, one compensation control strategy named slight center wave rolling is proposed based on the conclusion (4) in this work. The main idea is that steel strip is rolled with slight center wave at the exit of the last stand of finishing mill to compensate the flatness change trend of edge wave occurring at cooling stage. This measurement has the advantages of small investment, easy implemented and convenience for troubleshooting, compared with the methods of realizing uniform transverse temperature distribution in strip such as water flow rate control along transverse direction and edge masking on the run-out table.

Figure 4: Literature Suggesting that Edge Waves are Mainly Developed Due to Cooling on the Edges of the Strip

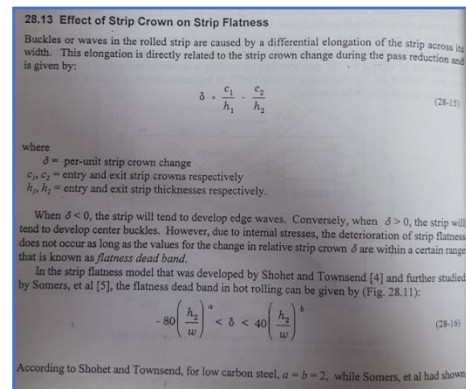


Figure 5: Paper Suggesting the Concept of Strip Crown on Strip Flatness

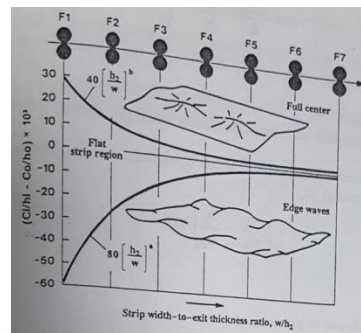


Figure 6: Concept of Centre Buckle and Edge Wavy and Strip Flatness Dead Band

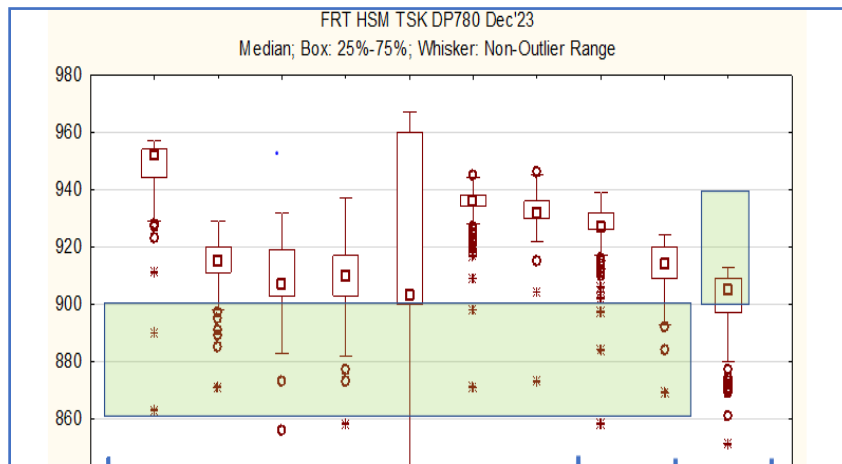


Figure 7: Finish Rolling Temperature [FRT] Box Plots Showing the Variation within the Length of the Coil

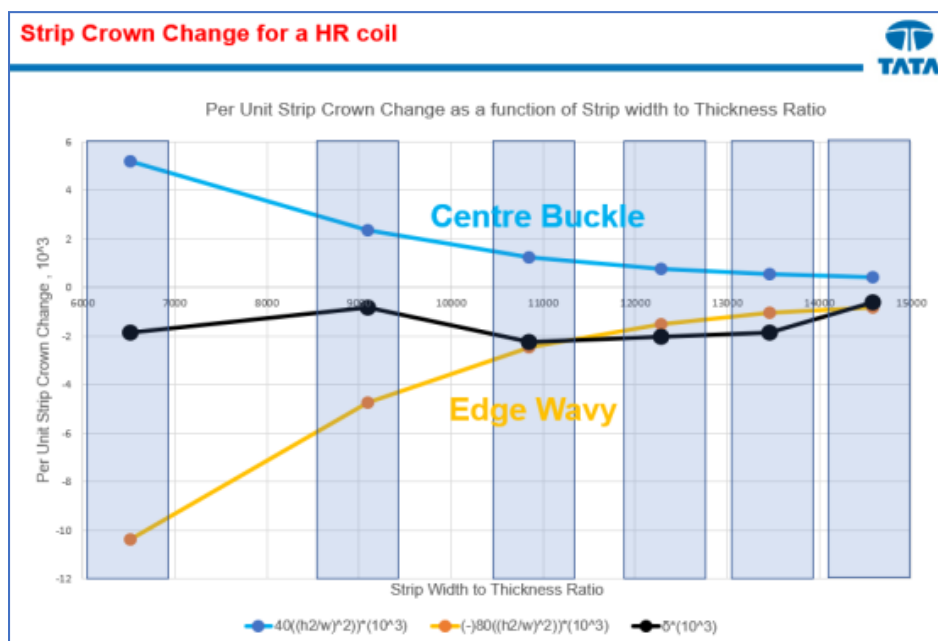


Figure 8: Calculation of Strip Crown Change for a HR Coil of HSM TSK

4. STATISTICAL ANALYSIS

It was also found that the temperature variation within the length of the coil has a very big impact on the shape of the coil. It was recommended that the temperature should be ensured within the range of the process charts.

5. TRIALS SUGGESTED

Based on the literature review and statistical analysis, it was suggested to take trials with the following actions.

1. Roll steel strip with slight centre wave at exit of the last stand of the finishing mill to compensate the flatness change

trend of edge wave occurring at the cooling stage.

2. Ensure minimum variation in Finish Rolling Temperature and Coiling Temperature.

6. RESULTS

The trials were conducted with the new process parameters.

Dead Flat coils were obtained at the end of Hot Rolling post cooling and ensured no rejections at the hot mill stage.

ACKNOWLEDGEMENT

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Addressing Double Edge Issue in Hot Rolled Coils

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ABSTRACT: *The phenomenon of split edge generation in hot rolled (HR) coils, particularly in thin gauge mill edge HR coils conforming to IS 11513 2017 CR3 grade, has been a persistent issue of hot strip mills. This study investigates the root cause of serrated or heavy edge cuts observed during subsequent cold rolling processing at downstream. Metallographic analysis did not reveal any material abnormalities. However, further inspection of the hot rolled edges uncovered a peculiar split edge or split edge defect, suspected to originate from the hot rolling process. Detailed examination suggested that these defects are linked to the concave or M-type profile of the slabs produced through Thin Slab Continuous Rolling (TSCR) route. The differential cooling rates and thermal contractions during the slab casting process at high-speed result in an uneven edge profile, leading to edge concavity. This concave profile, combined with potential guide misalignments and improper handling during hot rolling, exacerbates the formation of split edges.*

The study highlights that implementing liquid core reduction (LCR) during the slab casting process yields the best results in mitigating these defects. LCR helps in achieving a more uniform edge profile by reducing the core of the slab while it is still in a semi-solid state, minimizing the differential cooling effects. Despite attempts to mitigate the issue by adjusting the guide settings, the defects persisted. The study concludes that addressing the root cause in the TSCR process, through optimizing cooling rates, employing liquid core reduction, and ensuring uniform slab profiles, is crucial. Additionally, maintaining precise guide alignment and roll conditions during hot rolling is essential to minimize these edge defects and improve the overall quality of HR coils.

Keywords: Thin Slab Continuous Rolling (TSCR), Liquid Core Reduction (LCR), Split Edge.

1. INTRODUCTION

Steel manufacturing is a critical industry that plays a fundamental role in modern infrastructure and economic development. Steel, an alloy primarily composed of iron and carbon, is known for its strength, durability, and versatility, making it an essential material in construction, transportation, energy, and various other sectors. The production process, such as the one involving industrial heat is produced in a 200 MT Electric Arc Furnace (CONARC) and the final chemistry is adjusted in Ladle Furnace (LF)

station. The liquid metal is casted up to 1550 mm width and 65 mm thick slab up to a casting speed 6.35 mpm in a TSCR caster [1]. The TSCR process route followed is schematically represented in figure 1 is a combination of thin slab casting and direct rolling processes. The line slab (55 to 65 mm thick) is first descaled, sheared to desired length and then transported to a coke oven gas fired soaking tunnel furnace set between 1110 and 1150°C where it was soaked for 15–25 min. The slab is again descaled and hot-rolled using a 6-stand hot rolling mill to 1.5 to 25 mm thick coils.

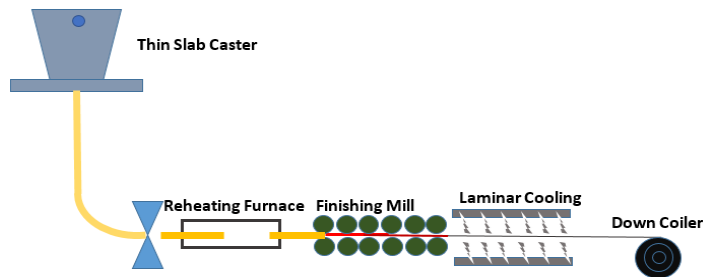


Figure 1: Schematic Layout of Thin Slab Casting and Direct Rolling Production Line

It is very advance manufacturing technology in the present iron and steel industry in terms of low production cost as compared to conventional mills. Today, it is very common to find plants having thin slab casting and direct rolling, producing high value-added steel products such as API grades, IF steels, dual phase steels as well as HSLA grades. Finish rolling temperature was approx. 880°C , drop down to coiling temperature of $\sim 540^{\circ}\text{C}$ by water cooling of top and bottom surfaces of strip by different cooling zones in 80 meters long run-out table, as shown in Figure 1. The HR strip is then coiled in the subsequent down coiler and cooled gradually in room temperature before dispatched to intended customers. The hot rolled strip coils are used for both direct and cold rolling applications, with approximately 70% of TSCR HR coils being supplied to cold rolling plants. The cold rolling process begins with pickling, where the HR coils are immersed in an acid bath, typically hydrochloric acid, to dissolve the scale. After pickling, the coils are rinsed and dried. The clean coils are then cold rolled to reduce thickness and enhance mechanical properties such as strength and surface finish. This is done at room temperature using Reversible or pickling line tandem cold rolling (PLTCM) mills, which consist of a series of rolls [2]. The coils are progressively reduced in thickness by 50–90%, depending on the final product requirements. Finally, the cold-rolled coils are processed for coating or cold rolled close annealed (CRCA) applications.

The objective of this paper is to highlight quality-related issues in hot rolled coils.

While surface defects such as slivers, rolled-in scale, and alumina streaks are commonly reported by researchers, coil edge-related defects are less frequently addressed [3]. Edge defects are a prevalent issue in hot rolled steel coils but are often not considered critical because they can be mitigated through edge trimming during direct applications of HR coils. However, many cold rolling mills are reluctant to incur the approximately 1.5% trimming loss associated with edge defects. Although PLTCM mills are equipped with built-in HR trimmers, some reversing mills lack HR trimmers and therefore process mill edge coils directly. Edge defects, especially double edge defects, are challenging to detect with standard surface inspection systems. When hot rolled coils with concave or double edges are directly fed into the cold rolling mill, they are prone to developing significant edge cracks, with depths ranging from 30 to 45 mm in the cold rolled coils. This paper focuses on the specific issue of double edge defects, exploring their impact on quality and productivity. Detecting double edge defects typically involves visual inspections. Author have tried to investigate the issue of double edge and its impact in quality and productive. Thorough study has proved that this edge defect originated at the casting of slab.

2. BACKGROUND

A complaint was raised regarding 7833 (metric ton) MT of standard grade IS 11513_CR3 material, consisting of 374 numbers of HR coils in sizes ranging from 2.15/2.5 (thickness, in mm) x 1020/1120/1225/1250

(width, in mm), supplied to a cold rolling customer for pre-painted galvanized (PPGI) application. The customer reported significant issues with edge cuts, which led to strip breakage during processing. This problem resulted in the rejection of a large portion of the material, causing operational disruptions and financial losses.

Table 1: Chemistry of the Grade
(in weight %)

<i>Element</i>	<i>C</i>	<i>Si</i>	<i>S</i>	<i>P</i>	<i>Mn</i>	<i>Al</i>	<i>N</i>
Min.	0.03	0	0	0	0.1	0.025	0
Max.	0.05	0.03	0.02	0.02	0.15	0.04	0.006

The finish rolling temperature (FT) and coiling temperature (CT) of the coils are in range of 865 to 895°C and 585 to 615°C respectively. The process involved at customer's end is taking hot rolled (HR) coils in mill edge condition, subjecting them to pickling, and then cold rolling (CR) at a reversing mill, reducing the thickness to 0.35 or 0.45 mm. After cold rolling, these coils underwent CR trimming and galvanizing. The customer processed 4867 MT of material, totaling 233 number coils. Out of these, 40 coils developed edge cuts of up to 35–40 mm, leading to strip breakage. The coils were intended to be reduced by 60–80% over 4–6 passes, but this reduction was not achieved because edge cuts began developing after just two passes. The majority of the edge cuts were observed on a single side, at about 2 meters from the inner dia. (ID)/outer dia. (OD). Some coils had multiple cuts in the cold rolled full hard (CRFH) coil, forcing the customer to slow down the rolling speed. This situation led to lower yield, higher scrap generation, and increased roll consumption. As a result, another 141 coils were held after pickling.

3. EXPERIMENTAL METHODS

The defect on the edges of the hot rolled coils were examined on the site by visual observation and images were taken for

record. Chemical composition of the failed component sample was analyzed by using Optical Emission Spectrometer from Applied Research Laboratories, model 3460 (Thermo-Scientific). The hot mounting, grinding, and polishing of samples were done by following the standard guidelines for metallography sample preparation for light optical or scanning electron microscope [4]. Microscopy examination was conducted in the OLYMPUS DSX1000 digital microscope. The hardness tests were performed in the semi-automatic Vickers microhardness testing machine of Omnitech (S-Auto 631) [5]. Scanning electron microscope (SEM) of JEOL, model IT500 was used for high magnification images of the fractured surfaces and inclusions features and detailed microstructural analysis. Energy dispersive spectroscopy (EDS) analysis of the defective region was conducted in the set-up detector supplied by Oxford Instruments equipped with Aztec software for inclusion analysis.

4. RESULTS AND DISCUSSION

During the field investigation, two HR mill edge coils were processed after thoroughly examining their HR edge condition. The first HR coil of size 2.15×1225 mm had a minor burr and double/split edge on the operator's side edge at the OD, while the drive's side edge was found to be in good condition. It is to be noted that, the coil two edges are acknowledged as drive side and operator side. After cold rolling, around 2 tons of material developed a saw-tooth pattern on the operator's side with a depth of 10 mm, while the drive's side edge remained unaffected. The second coil, also has the same size had no edge defects in its HR condition and did not develop any edge defects after cold rolling either.

Samples were drawn out for metallurgical investigation from the both damaged sides of the coil and also from the centre. This has been done to identify any material related abnormality.

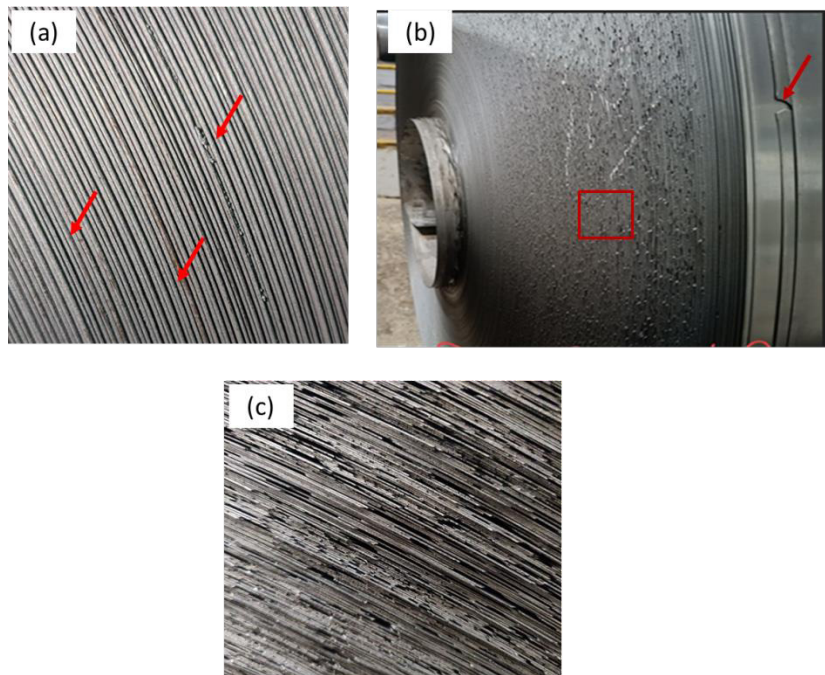


Figure 2: Image (a) shows the side view of the hot rolled coil having double edge defect (some are highlighted by arrow marks), image (b) is the side view of cold rolled coil & image (c) is the enlarged image of the enclosed box shown in image (b).

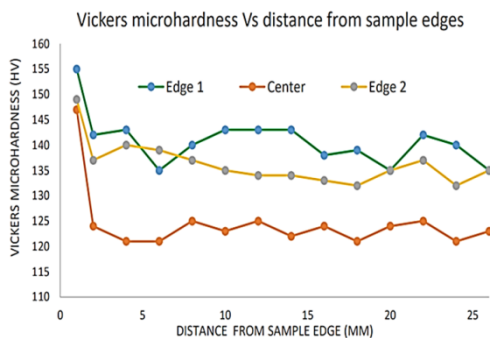


Figure 3: Hardness Profile of Samples Taken from Both the Sides (Edge 1 & Edge 2) of the Coil and from the Centre

The hardness profile showed the edges are having higher hardness as compared to the center. This was expected as the cooling of edges are faster than the center. Hardness is taken at the extreme edges of the samples as shown in the figure 3 to get understand the effect of cooling rate. Very fast cooling of edges can also lead to higher hardness consequently the brittleness of the edge. The

hardness values shows that there is no phase change phenomenon had occurred.

The cross verification of was also done by microstructural analysis. The samples are nital etched for microstrural analysis. Microstructure of the drawn three samples from taken from aforesaid locations are found to ferritic. Moreover, it has been observed that the ferritic grains are of fixed garin size as compared to the equiaxed garing at e center, as shown in Figure 4. It was also seen the at the edge are having cracks propagated towards the coil center width. This could be due to the presence of double slit of the edges. It ane be also physically visible as shown in Figure 5.

It is important to analysis of edge double slit region to look for presence of non-metallic inclusions (NMI). The SEM EDS mapping the region showed no evidence of NMI albeit iron and oxygen were observed at the site as shown in the Figure 6.

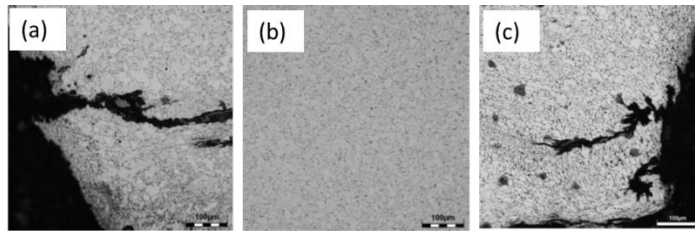


Figure 4: Microstructure of the Sample from Both the Sides (Edge 1 & Edge 2) of the Coil and from the Centre



Figure 5: Stereo Graphic Projection of the Double Slit Edge in Hot Rolled Coil

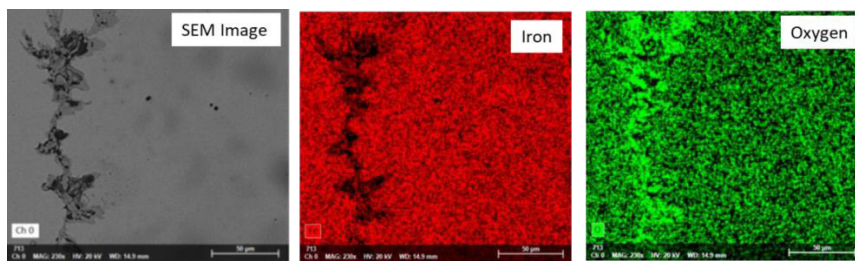


Figure 6: SEM EDS Mapping of the Edge Defect

The findings suggest that burrs and double edges present in the first HR coils can lead to significant saw -tooth defects during further processing, ultimately causing strip breakage. It emphasizes the need for thorough study and careful selection of HR coils before mill edge cold rolling to minimize the risk of edge defects.

The significance of edge shape in rolling processes and its impact on preventing edge cracking. Edge shape is a crucial parameter in managing tensile stresses at the edges of the material being rolled, which can lead to cracks if not properly controlled. The shape of the edge, whether convex or concave, evolves throughout the rolling process, with initial passes having the most significant effect. A square edge is often recommended to minimize edge cracking, as it can better

manage the tensile stresses compared to chamfered or rounded edges as shown in Figure (7). Convex profiles (barreled edges) are generally more resistant to cracking, while concave profiles (fish-tailed or double-barreled edges) are more prone to cracks. The transition between these shapes is influenced by factors like reduction percentages and rolling geometry [6]. The temperature and friction conditions during rolling play a critical role in determining the edge shape. Higher temperatures (with unheated rollers) tend to produce more convex profiles.

The slab profile in TSCR high-speed casters presents a significant challenge, primarily due to the non-uniform cooling rates at the edges. This uneven cooling can cause the slab to take on a concave shape, complicating

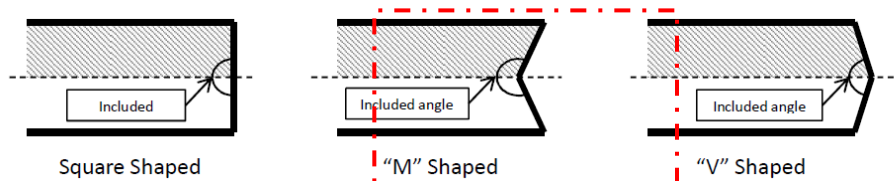


Figure 7: Schematic Representation of Shapes of Coil Edge Profiles

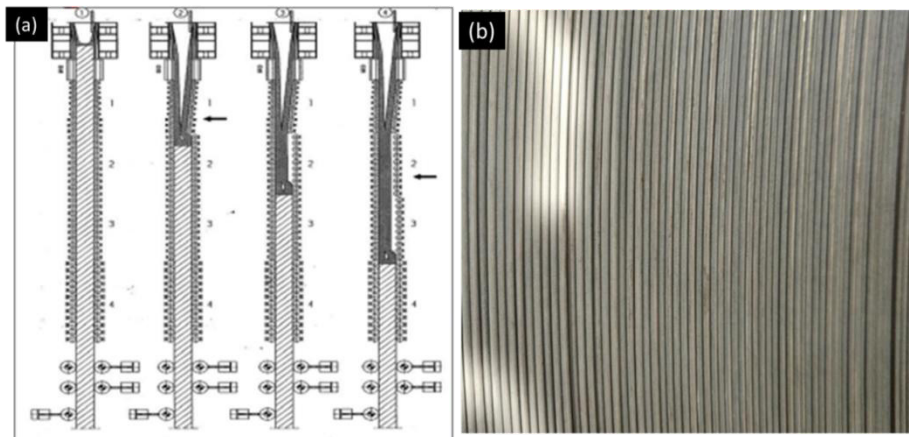


Figure 8: Above Image (a) Represents, Schematic Diagram of LCR in Subsequent Segments during the Casting Process & Image (b) Shows its Effect on the Edges of the Hot Rolled Coil

subsequent processing and potentially affecting the final product quality. It has been observed that the liquid core reduction (LCR) process yields the best results because, in this process, the semi-solid core is pressed from the loose side against the fixed side to reduce the thickness of the slab from 65 mm to 59 mm in subsequent segments. This pressing action causes the semi-solid material to flow towards both edges, creating significant pressure on them. As a result, the edges become convex shaped, which is the desired outcome for mill edge cold rolling applications.

In addition to the LCR process, several other initiatives were attempted, such as modifying the cooling curve and adjusting the guide settings, shown in Figure 8(a). However, none of these alternative approaches proved to be effective in achieving the desired results [7]. The LCR method, with its ability to ensure that material flows properly towards the edges, remains the most successful

technique for improving edge quality in the slab reduction process. The effect using LCR process during casting was found to be the most effective as it gave the convex edge curve with less include angle. Figure 8(b) shows the effect of LCR as convex shaped edges of the coil.

5. CONCLUSION

The double edge defect in hot rolled coils is a common issue in the TSCR route, significantly affecting product quality, yield and productivity, particularly for mill edge cold rollers. To address this defect, various strategies have been implemented, including adjustments to mold powder, casting speed, guide maintenance, alignment, and modifying the caster cooling curve from a hard to soft cycle. Among these, the introduction of the Liquid Core Reduction (LCR) process has shown great promise. The LCR process represents a significant advancement in

eliminating the double edge defect. This innovative approach not only enhances product quality but also improves operational efficiency, eliminating the need for the 48-hour holding time for visual inspection and reducing the risk of coil downgrading. Continued research and development in this area will likely lead to even more effective solutions, further optimizing the production process and reducing costs.

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Evaluating the Impact of Hot Rolling Production Scheduling on Strip Geometry Optimization in Steel Manufacturing

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ABSTRACT: *This paper explores the intricate challenges of scheduling within the hot rolling process in the steel industry, with the goal of developing an optimal rolling sequence that satisfies defined criteria while managing various constraints. We propose a practical and systematic approach to refining hot rolling production scheduling by examining distinct campaigns. One critical issue examined is the impact of a heightened thermal crown on the shape and strip profiles. In a “coffin” scheduling methodology, the initial rolling of narrow coils is employed to build up a thermal crown that enhances shape quality. However, this preliminary rolling phase may induce a slight central buckle, which is conventionally mitigated by the shape control system. As the process transitions to rolling wider coils, the edges often become wavy due to the increased thermal crown at the edges. To counteract this, the shape control system adjusts by increasing the bending force on the work rolls, which can inadvertently lead to both wavy edges and central buckling. This paper investigates strategies to minimize the duration and impact of the warm-up phase in coffin shape scheduling and seeks to achieve an optimal balance across the production campaign. We assess the implications of these adjustments on strip quality, aiming to enhance the overall efficiency and effectiveness of the hot rolling process.*

Keywords: Hot Rolling, Coffin Scheduling, Campaign, Warmup Phase, Thermal Crown Buckling.

1. INTRODUCTION

Intense competition in the industry compels metal forming technologists to continuously pursue the production of high-quality products. The demands for strip profile and flatness specifications are now more stringent than ever before. As a result, numerous techniques have been developed to enhance product quality, particularly in terms of flatness and thickness profile [1].

Strip crown is a parameter exhibiting the shape of strip cross-section, plays a vital role

among the performance indexes of strip flatness. Strip crown of rolled strips is generated by the 3-dimensional deformation of the strip during rolling, and it indicates the error between the thickness at the centre of the strip and at the reference point, which is approximately 40 mm apart from the edge called C40 value (figure 1), [2]. Strip crown can be estimated by the formula,

$$C40 = h_c - (h + h')/2$$

Where, h_c is the thickness at the centre of the strip, h and h' are the thickness at 40 mm on the left and right sides respectively.

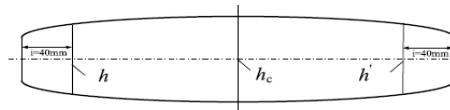


Figure 1: Cross Section View of a Hot Rolled Strip

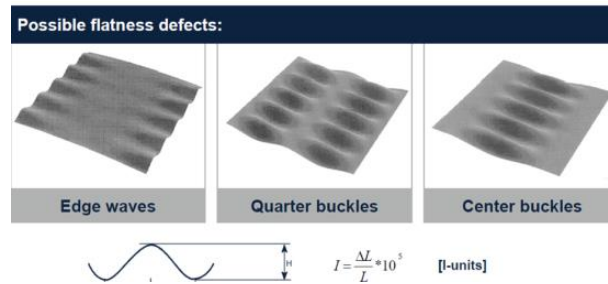


Figure 2: Types of Flatness Defect

Flatness deviations in strips often arise from the nonuniform elongation of the strip fibres along its length, caused by uneven stresses acting across the strip's width. When these internal stresses are not uniformly distributed and the strip's inherent latent forces are insufficient to counteract them, the quality of the strip deteriorates. This results in various forms such as strip camber, centre waves, edge waves, quarter buckles, edge buckles, and centre buckles (figure 2), [3], [4].

The hot strip mill (HSM) is one of the most important production lines in steel industry [5] are engineered to process various grades of material, each with distinct characteristics such as width, hardness, roughing temperature, finishing temperature, and coiling temperature. Maintaining product standards requires smooth transitions in these parameters because both the roughing mill and the finishing mill must adjust the load applied to each slab accordingly. During hot rolling, sets of slabs are transformed into strips, with the rolling schedule playing a crucial role in this process. A key consideration is the evolution of the roll profile due to mechanical wear and thermal expansion, which can directly impact the strip's profile. To optimize roll usage and ensure the quality of the strip, hot strip mills

typically employ a coffin-shaped rolling schedule. At the start of a new rolling schedule, the work roll temperature is initially below its optimal working temperature, leading to suboptimal performance. To address this, strips with greater thickness and lower surface quality are rolled first, serving to gradually heat the rolls. Once the rolls reach a stable working temperature, thinner steel strips with higher surface quality are then processed.

The transition in dimensions and hardness between successive coils must be gradual, especially in the warm-up and body sections. This requirement arises because the rollers must be precisely adjusted to manage any variations in dimensions and hardness at both the entry and exit of the mills. To address the complex challenge of scheduling in HSM, Chen, Lu, Ge, Yang, and Pan (2012) propose the use of hybrid evolutionary algorithms. These algorithms combine the strengths of genetic algorithms and extremal optimization to optimize the scheduling process in HSMs, ensuring efficient production and high-quality output [6].

Over time, as a certain cumulative length or weight of strips is rolled, the work rolls begin to deteriorate. This deterioration is marked

by the crown profile losing its shape due to significant wear and tear. To mitigate these effects and maintain consistent production quality, smooth transitions in strip thickness between adjacent strips are crucial. These transitions help in forming a parabolic shape during the rolling campaign and also require maintaining safe ratios of different gauge levels, as proposed by Quan-Ke Pan *et al.* [7].

2. PROBLEM STATEMENT

To effectively describe the production planning at the HSM of BSL, it is essential to first outline the production process of hot strips. Various grades of steel are initially cast into slabs at the caster, where they achieve a temperature of approximately 850°C. These slabs are then transported to the HSM slab yard, where they are stored in piles until needed. The slabs are subsequently charged into reheating furnaces according to customer demand. However, due to fluctuating demand, some slabs may remain in the yard for extended periods.

As the slabs cool down during transportation and storage, their temperature drops significantly from 850°C to about 20°C. To prepare them for rolling, these slabs must be reheated to the required rolling temperature. This is accomplished by charging the slabs into reheating furnaces, where they are heated to 1250°C. The reheating process at BSL is carried out in top-and-bottom-fired walking beam furnaces, which ensure uniform heating of the slabs.

BSL produces slabs that are 225 mm thick, 10 meters in length, and range from 950 mm to 1850 mm in width. From the moment a slab is charged into the reheating furnace until it is discharged, a minimum of three hours is required to bring the slab up to the rolling temperature.

This careful and meticulously managed process is central to the production planning at

BSL's HSM, ensuring that the slabs are consistently prepared to meet the stringent demands of hot strip rolling and customer specifications.

Due to the complexities of a fluctuating product mix, varying customer demands, and production limitations, it is difficult to adhere precisely to the intended coffin shape rolling schedule. Consequently, the actual rolling schedule often diverges from the ideal coffin shape. During the initial warm-up phase, slabs measuring between 1320 and 1280 mm are rolled to achieve the broader dimensions required for the campaign. The continuous processing of these similarly sized slabs generates a significant thermal crown on the work rolls, especially at the strip edges where friction occurs. This thermal crown can lead to edge waviness when the rolling process shifts to producing wider products. To correct this issue, the shape control system adjusts the bending forces to counteract the waviness and ensure the final strip profile meets the required specifications.

A critical aspect of hot strip mill operations is the evolution of the roll profile during rolling, which is influenced by mechanical wear and thermal expansion. These factors can have a direct impact on the strip profile, potentially affecting product quality. To optimize both the utilization of rolls and the quality of the produced strips, hot strip mills employ a "coffin-shaped" rolling schedule (figure 3) which is designed to manage the effects of thermal expansion and wear on the rolls. The coffin shape pattern is divided into two key sections:

Warm-Up Section - Rolling begins with narrow-width strips, gradually and swiftly transitioning to wider materials as the thermal crown of the roll's increases. This stage is crucial for warming up the rolls, ensuring they reach the desired thermal state before processing wider strips. The gradual increase in width helps to distribute thermal expansion evenly across the roll surface.

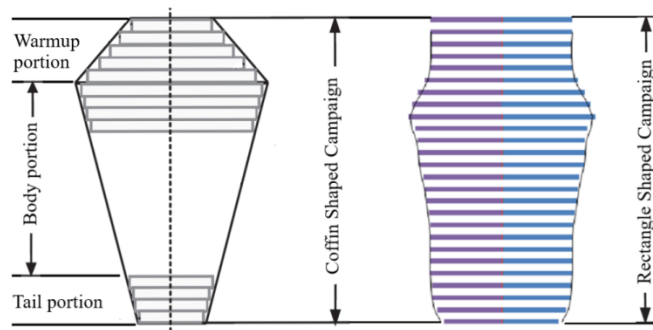


Figure 3: Actual Coffin Shape Rolling Pattern vs Plant Condition Rolling Pattern

Body Section—Once the thermal crown is stabilized, the rolling width is gradually narrowed. This tapering off in width is crucial for minimizing the risk of marks or grooves on the strip surface, which can result from uneven wear on the rolls. By carefully controlling the width in this phase, the mill can prolong the life of the rolls while maintaining high-quality strip profiles.

This coffin-shaped rolling schedule is an effective strategy for balancing the demands of roll wear and thermal expansion, ultimately contributing to the efficiency and quality of the hot strip mill operations. The importance of this approach is highlighted in the work of Pan and Yang (2009) [8], who discuss a method for addressing large-scale rolling batch scheduling problems in steel production, emphasizing the role of optimized rolling schedules in achieving superior strip quality and operational efficiency.

3. EXPERIMENTAL

To assess the impact of reaching the maximum width within a rolling campaign on the profile and flatness of the strips, we carefully selected 24 distinct campaigns for in-depth analysis. These campaigns, characterized by their coffin-shaped profiles during the charging process, were subjected to a rigorous examination within the finishing mill. We categorized the campaigns into three distinct groups based on the number of coils required

to achieve the wider segment of the charging profile: category 1: fewer than 20 coils, category 2: fewer than 30 coils, category 3: fewer than 40 coils.

For each campaign, we meticulously collected data on profile and flatness values, specifically focusing on coils rolled to a thickness of 4mm or less. For this study, a profile tolerance of 50 microns and a flatness threshold of 25 IU were established as upper limits. After standardization, we calculated the average profile and flatness values for each individual coil with a thickness of $\leq 4\text{mm}$ and correlated these averages with the respective category.

This comprehensive study provides critical insights into how the dynamics of coil width, particularly when approaching the maximum width, influence the final strip characteristics, with a particular focus on maintaining optimal profile and flatness within the defined tolerances.

4. RESULTS AND DISCUSSION

4.1 Zones of Poor Profile and Un-flatness within a Campaign

After analysing the dataset, it is evident that the profile quality of the strips tends to deteriorate as the rolling process progresses from the wider section of the campaign. The density map on top seems to be analysing the profile intensity as it correlates with the rolling schedule pattern shown below, figure

4. Areas of high density might correspond to the parts of the rolling schedule where the width is rapidly changing (either increasing or decreasing), causing more significant fluctuations in the profile intensity. The warm-up section and the body section could be particularly influential in these variations. This analysis can provide insights into how different phases of the rolling process impact the profile intensity, which in turn can affect the final quality of the strip. By understanding these patterns, adjustments can be made to the rolling schedule to minimize undesirable variations in profile intensity, thereby improving the overall quality of the finished product.

The figure 5 illustrates that flatness values—both symmetric and asymmetric—tend to deteriorate towards the end of the rolling campaign. This trend indicates that the

flatness of the strips is more significantly impacted by roll wear than by the coffin-shaped charging pattern. As the campaign progresses, the cumulative wear on the rolls becomes more pronounced, leading to a gradual decline in flatness quality. Unlike the profile values, which are influenced by the variations in width throughout the coffin-shaped rolling schedule, the flatness deterioration appears to be more directly tied to the physical condition of the rolls.

This suggests that while the coffin-shaped pattern helps manage profile deviations, it is less effective in controlling flatness issues that arise from roll wear. Consequently, roll maintenance and monitoring should be emphasized, especially in the latter stages of the campaign, to minimize flatness defects and ensure the overall quality of the strips.

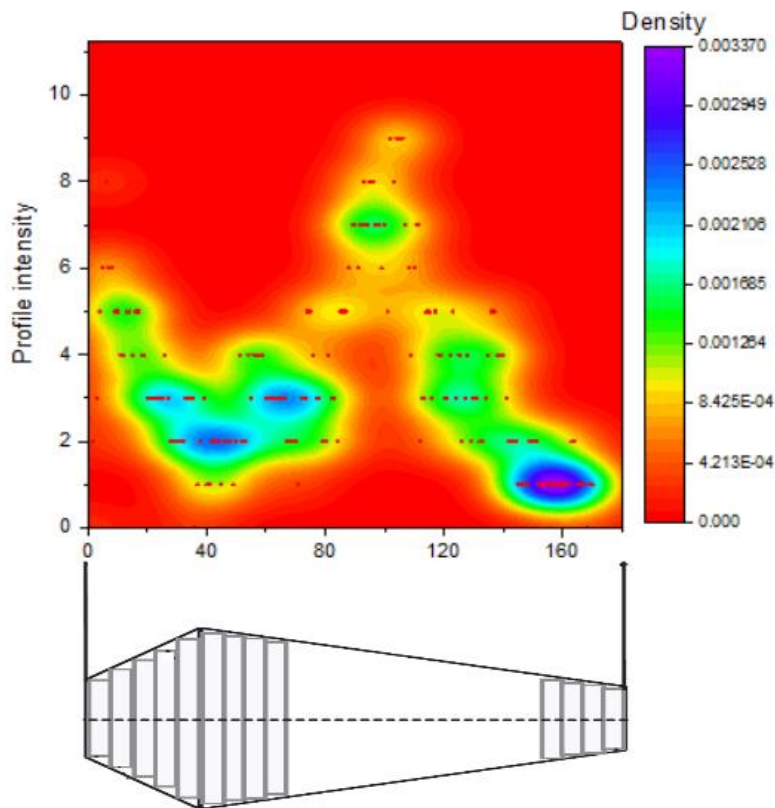


Figure 4: Density Plot of Average Positions for Bad Profile Corresponding to Rolling Schedule

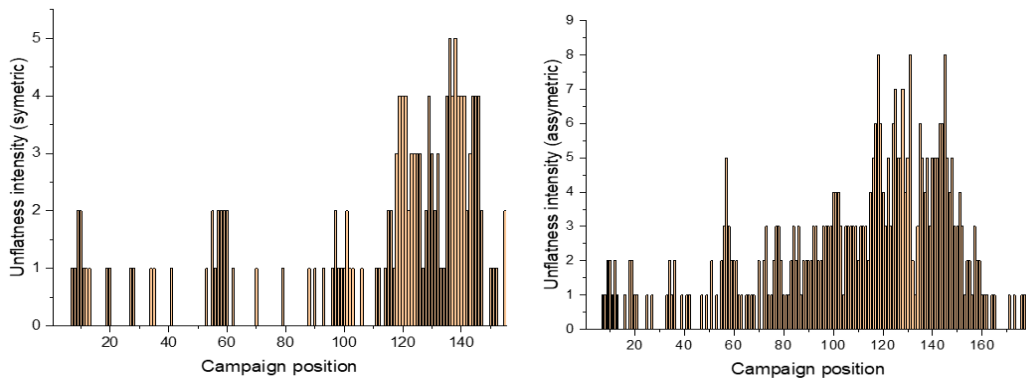


Figure 5: Average Positions for Un-flat Coils across 24 Campaigns

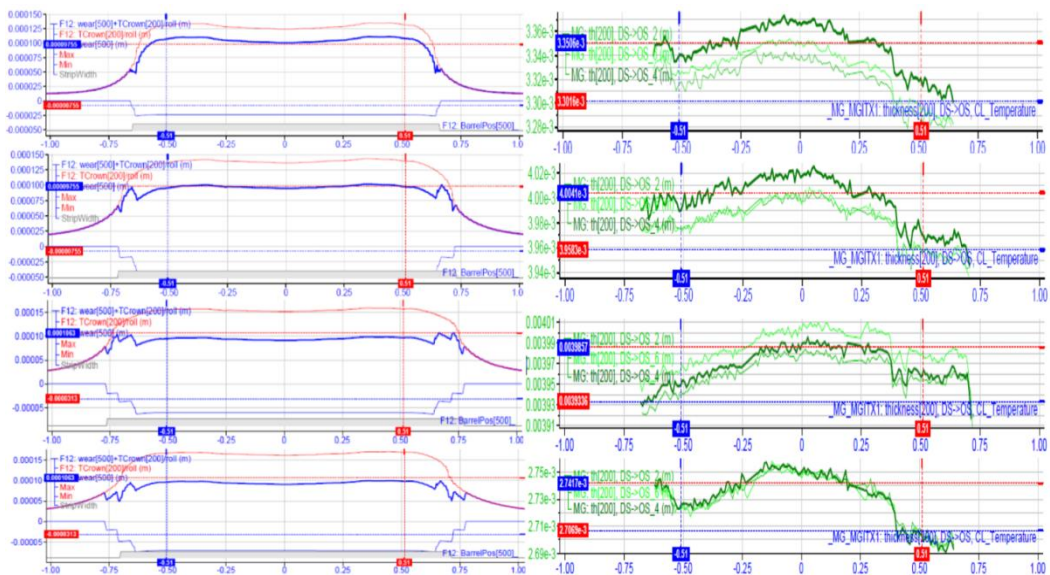


Figure 6: A Campaign that Reaches its Maximum Width with 53 Coils Demonstrates a Uneven Transition in the Roll's Thermal Profile, as well as in the Strip Crown

4.2 Impact of Warmup Section Length on Thermal Profile of Work Roll

During hot rolling, heat is transferred into the work roll primarily through conduction, with the outermost layer of the roll being heated by conduction and radiation from the hot strip, as well as by convection from air and water. The surface temperature of the work roll fluctuates rapidly due to its alternating contact with the hot strip and the cooling water during each rotation. Understanding

the thermal expansion of the work roll is crucial for controlling the profile and flatness of the hot-rolled strip.

When the campaign reaches its widest portion with 53 coils (figure 6), it is observed that the thermal profile of the work roll becomes more uneven compared to a campaign that reaches the widest section with only 34 coils (figure 7). This suggests that a shorter warm-up phase in the campaign, characterized by a quicker transition to wider strips, leads to greater irregularities in the thermal profile of the work roll.

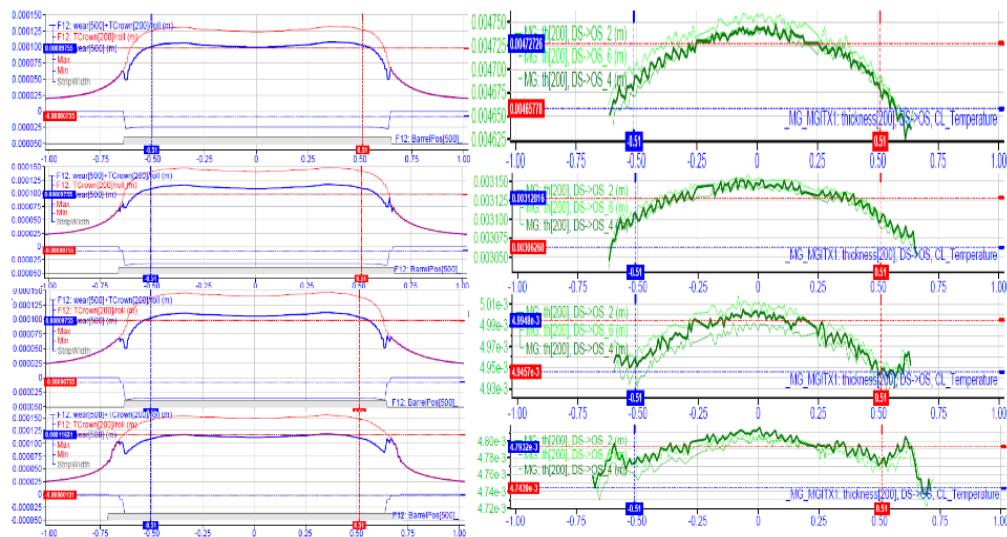


Figure 7: A Campaign that Reaches its Maximum Width with 34 Coils Demonstrates a Smooth Transition in the Roll's Thermal Profile, as well as in the Strip Crown

The thermal expansion, or crown, of the work roll plays a crucial role in controlling both the strip profile and the flatness of the strips. As the work roll's thermal profile becomes more uneven, it can negatively impact these key quality attributes. A well-managed thermal expansion is essential to maintaining the desired strip profile and ensuring consistent flatness throughout the rolling process.[9]

This relationship between the number of coils in the warm-up phase and the work roll's thermal profile underscores the importance of carefully planning the campaign's progression to minimize adverse effects on strip quality. As highlighted by Abbaspour and Saboonchi (2008) in their study on work roll thermal expansion control in hot strip mills, managing the thermal expansion of the work rolls is vital for optimal strip profile and flatness control. [10]

2.3 Impact of Warmup Section Length on Profile and Flatness of the Strip

Upon conducting a detailed analysis of 24 distinct rolling campaigns, each characterized by varying warm-up section lengths, several

key insights were uncovered regarding the relationship between the warm-up length, coil profile quality, and flatness (figures 8, 9). The campaigns were grouped into three categories based on the number of coils required to reach the widest part of the strip: Category 1: In campaigns where less than 20 coils were needed to reach the widest part, the average percentage of coils with a good profile was 83.13%, and better flatness was achieved in 71.86% of the coils. Category 2: For campaigns requiring less than 30 coils to reach the widest part, profile control was maintained in 80.85% of the coils, and flatness was observed in 76.8% of the coils. Category 3: In campaigns where less than 40 coils were needed to reach the widest part, 64.46% of the coils had a good profile, while flatness was achieved in 77.30% of the coils (figure 10). From these findings, it is evident that the flatness of the strip is not significantly impacted by how quickly the rolling process transitions to the widest slab. However, the profile quality, which is critical for ensuring the dimensional accuracy of the final product, shows substantial improvement when the warm-up section is shorter, and the process progresses more rapidly to the widest part of

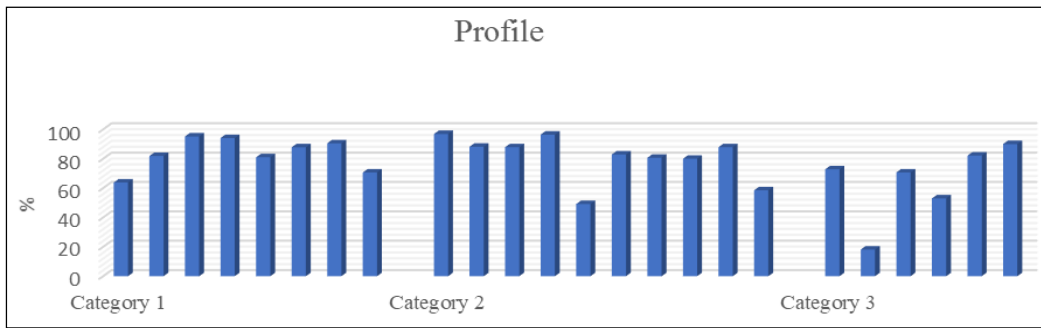


Figure 8: The Proportion of Coils that Managed to Achieve Satisfactory Profile Values (less than 50 μ) in Each Category is as Follows

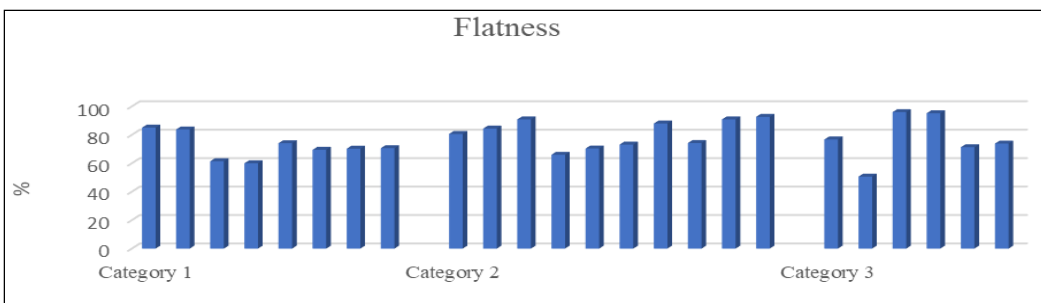
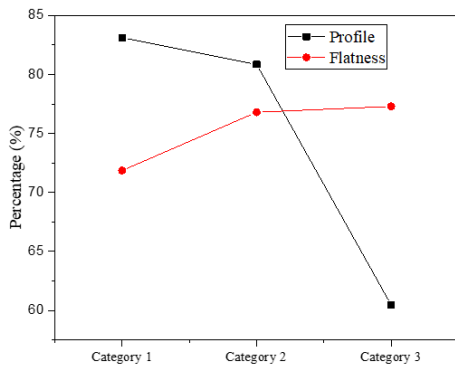


Figure 9: The Proportion of Coils that Managed to Achieve Satisfactory Flatness Values (less than 25 IU) in each category is as follows



	Profile (Ave) %	Flatness(Ave) %
Category 1	83.125	71.86
Category 2	80.85	76.8
Category 3	64.46	77.30

Figure 10: The Profile of the Strips is Influenced by the Design of the Rolling Campaign

the campaign. This suggests that optimizing the warm-up length is crucial for enhancing

profile accuracy, while flatness can be maintained across a broader range of warm-up lengths.

3. CONCLUSION

To assess the impact of reaching the maximum width within a rolling campaign on the profile and flatness of the strips, we carefully selected 24 distinct campaigns for in-depth analysis. These campaigns, characterized by their coffin-shaped profiles during the charging process, were subjected to a rigorous examination within the finishing mill. We categorized the campaigns into three distinct groups based on the number of coils required to achieve the wider segment of the charging profile: category 1: fewer than 20 coils category 2: fewer than 30 coils, category 3: fewer than 40 coils. Following an in-depth analysis, the study yields the following key conclusions:

1. **Flatness control:** The data shows that reaching the wider section with fewer than 20 coils does not yield substantial improvements in flatness. On the contrary, allowing the process to extend beyond 25 to 30 coils tends to produce better flatness results.
2. **Profile control:** In contrast, profile control benefits markedly from a quicker transition to the wider section. Campaigns that reach the wider portion within 20 coils demonstrate the best profile control, indicating that a more immediate adjustment to the wider section significantly enhances profile consistency.

ACKNOWLEDGEMENT

The authors wish to extend their sincere gratitude to SAIL - Bokaro Steel Plant (BSL). Special acknowledgments are due to the Hot Strip Mill (HSM) and RGBS teams for their invaluable contributions. Heartfelt thanks are also extended to all individuals who played a role, whether directly or indirectly, in the successful completion of this study.

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Establishing Microstructure for a Defence Order of Carbon Steel Flat at SAIL-VISL

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ABSTRACT: This paper attempts to establish the standard microstructure in a sample of plain carbon steel flat of 286 mm × 23 mm which fulfils the requirements of the defence order vis-à-vis required mechanical properties. Various samples drawn after heat treatment were compared against customer requirements of Microstructure, Macrostructure, US Test, Impact Test, Decarb, Inclusion Rate & Grain Structure. Microstructure of the samples which fulfil all requirements were examined and standardized microstructure was established so as to confirm the success of Hardening and Tempering process. Based on the sample results, modifications were done in the heat treatment process so as to achieve the correct microstructure of the sample. Modifications involved preparation of heat treatment beds, duration and temperature of hardening cycle, quenching media and quenching media temperature so as to control the rate of cooling during quenching. This becomes extremely important given the size of flats and its handling at above re-crystallization temperature. Several constraints were identified, such as maintaining material straightness during heating and efficiently handling materials during quenching. Innovative solutions, including the development of custom jigs and specialized handling methods, were implemented to address these challenges effectively. Aim of modification in heat treatment process was to expose each and every flat to same heating and quenching conditions so as to obtain uniform samples chosen from anywhere from the charge. Another aim was to avoid or to have minimum warping of the flats since any bends and twists introduced during heat treatment will be difficult to correct given the size of the flats.

Conclusion: Microstructure and its characterisation for a carbon steel flat of 286 × 23 mm for a defence order were established by modifying heat treatment cycles, quenching method and material handling procedures. This led to bagging of the order for which VISL is the sole supplier in India.

Keywords: Microstructure, Hardening, Quenching, Uniform samples, Quenching media, Jigs.

1. INTRODUCTION

Objective

The primary objective of this report is to offer a comprehensive analysis of the rolling mill and heat treatment operations involved in producing rolled steel flats for M/S. Yantra India Limited. This includes an

in-depth look at how the processes are executed, the quality control measures in place, and the methods used to address operational constraints. The goal is to ensure that the final product meets or exceeds customer expectations and adheres to industry standards.

Scope

- **Rolling Process:** Detailed examination of the process that transforms steel ingots into flat bars.
- **Heat Treatment Operations:** Insight into the controlled heating and cooling processes that enhance the material's properties.
- **Quality Control:** Strategies and techniques used to maintain high product quality.
- **Constraint Management:** Identification of challenges encountered during production and the solutions implemented to overcome them.

2. PRODUCT DETAILS

Customer

- M/S. Yantra India Limited, Nagpur.

Product Specifications

- **Type:** Rolled Flats.
- **Dimensions:** The final product dimensions are 23 mm thick (+2 mm tolerance) and 286 mm wide (+5 mm tolerance).
- **Supply Length:** Each rolled flat is cut to a length of 1430 mm.

These specifications are crucial as they define the precise requirements for the final product, ensuring that it fits the intended application and meets the quality expectations of M/S. Yantra India Limited.

3. ROLLING MILLS OPERATION

Process Overview: The rolling mill operation is a critical phase where steel ingots are mechanically deformed into flat bar dimensions. This process involves several key steps to achieve the final product specifications.

Steps Involved

1. Heating:

- **Temperature and Purpose:** Steel ingots are heated to approximately 1200°C to increase their malleability.
- **Method:** Uniform heating is achieved in a furnace.

2. Rolling:

- **Roughing Mills:** Reduces thickness and starts shaping into flat bars.
- **Finishing Mills:** Achieves final dimensions of 23 mm × 286 mm.
- **Control Measures:** Dimensional monitoring systems ensure consistency.

3. Quality Control:

- **Dimensional Monitoring:** Regular measurements to maintain specified tolerances.
- **Surface Inspection:** Detects surface defects.

4. Cutting and Bundling:

- **Cutting:** Flats are cut to 1430 mm length.
- **Bundling:** Flats are bundled for handling and transportation.

4. HEAT TREATMENT DEPARTMENT

4.1 Overview

Heat treatment refines mechanical properties of steel through controlled heating and cooling.

4.2 Process

1. Quenching:

- **Purpose:** Rapid cooling to harden and improve strength.
- **Method:** Steel is immersed in a quenching medium.

2. Tempering:

- **Purpose:** Reheating to reduce brittleness and enhance toughness.
- **Method:** Controlled heating and cooling.

4.3 Objectives

- **Hardness:** Ensures required hardness levels.
- **Toughness:** Enhances resilience to impacts.
- **Ductility:** Increases flexibility and resilience.

5. CONSTRAINTS AND SOLUTIONS

Constraint 1: Material Straightness

- **Issue:** Warping during heating led to deviations from desired dimensions.
- **Solution:** Introduced in-house jigs designed to securely hold the material during heating.
- **Impact of Jigs:** The introduction of jigs was pivotal in improving the straightness and consistency of the rolled flats. By ensuring uniform heating and preventing warping, jigs significantly enhanced both mechanical and metallurgical properties of the steel.
- **Outcome:** Enhanced straightness and reduced deviations.

Constraint 2: Quenching Process

- **Issue:** Efficient transfer during quenching while minimizing distortion.
- **Solution:** Utilized fork handling system.
- **Outcome:** Ensured minimal distortion and maintained steel quality.

Constraint 3: Straightening After Heat Treatment

- **Issue:** Warping post-heat treatment.
- **Solution:** Employed existing straightening machinery.
- **Outcome:** Effective removal of warping, leading to improved production efficiency and product quality.

6. QUALITY ASSURANCE AND TESTING

Chemical Composition

- **Standards:** Adherence to standards like TDC
- **Testing:** Regular chemical analysis.

Mechanical Properties

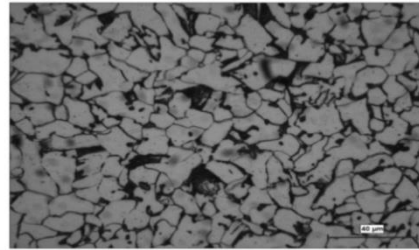
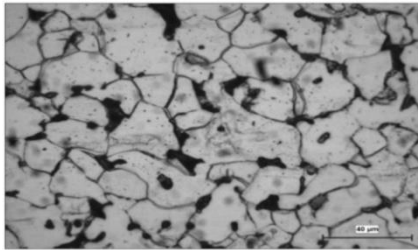
- **Ultimate Tensile Strength (UTS):** Measurement of maximum stress before breaking.
- **Ra (Surface Roughness):** Assessment of surface texture.
- **Impact Strength:** Evaluation of impact absorption.

Table 1

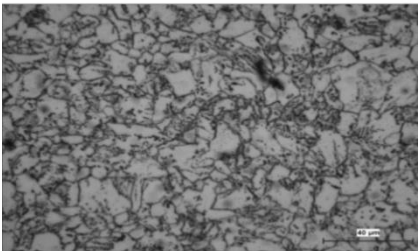
Property	Required	Obtained before Jigs	Obtained after Jigs
Ultimate Tensile Strength	34–41 kg/mm ²	37.85–40.17 kg/mm ²	37.85–40.17 kg/mm ²
Elongation	35 % Min.	33.08–34.0%	39.08–40.08%
Charpy Impact Strength (Transverse)	9 Min.	20.65–21.41 kg/m/cm ²	20.65–21.41 kg/m/cm ²
Charpy Impact Strength (Longitudinal)	15 Min.	32.38–33.91 kg/m/cm ²	32.38–33.91 kg/m/cm ²

<i>Property</i>	<i>Required</i>	<i>Obtained before Jigs</i>	<i>Obtained after Jigs</i>
Inclusion Rating (C)	3.0/0.0 Max.	1.0	1.0
Inclusion Rating (OC)	3.0/0.0 Max.	0.0–1.0	0.0–1.0
Inclusion Rating (OT)	3.0/0.0 Max.	1.0	1.0
Grain Size	–	6.5, 8.0	6.5, 8.0, 8.0, 9.0
Individual Grain Size	–	0.051 mm	0.051 mm
De-carburisation	–	<0.01 mm	<0.01 mm

Grade: Gr III-OA – Size: 23X286mm

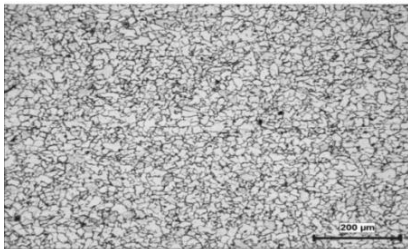


Mag: 500X, Microstructure found satisfactory

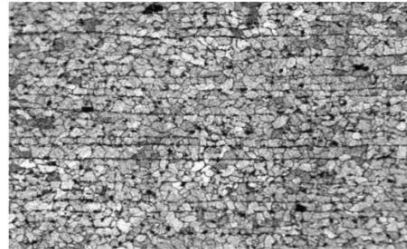


Mag: 500X, Microstructure not acceptable

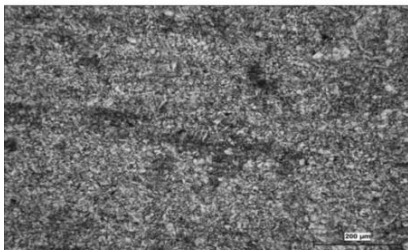
Grade: Gr III-OA – Size: 23X286mm



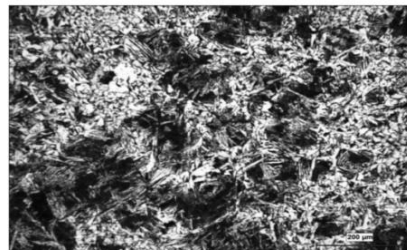
Mag: 100X, Microstructure found satisfactory



Mag: 100X, Microstructure not satisfactory due to banding



Mag: 100X, Microstructure not satisfactory due to Widmanstätten pattern



Mag: 100X, Microstructure not satisfactory due to Widmanstätten pattern

Impact of Jigs on Properties: The mechanical and metallurgical properties have shown significant improvement following the introduction of jigs. Data comparisons pre- and post-jigs implementation illustrate marked enhancements in impact strength, grain size, and overall quality.

- **Inclusion Rating:** Analysis of non-metallic inclusions.
- **Grain Size:** Measurement of average steel grain size.
- **Decarburization:** Evaluation of carbon loss.
- **Microstructure and Macrostructure:** Examination of steel's internal and external structures.

7. CONCLUSION

The introduction of jigs in the heat treatment department has been instrumental in addressing production constraints and significantly improving the mechanical and metallurgical properties of the rolled steel flats. By enhancing material straightness and consistency, jigs have contributed to higher product quality and efficiency.

Adherence to customer specifications and industry standards has been maintained throughout the production process, resulting in high-quality rolled steel flats that meet the requirements of M/S. Yantra India Limited. The improvements in process efficiency and product quality underscore our commitment to excellence in steel production.

Reduction in Pup Coil Generation at Hot Strip Mill

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ABSTRACT: *Pup coils were generated from hot rolled coil/strips at Hot Strip Mill, Tata Steel Limited due to defect in the mother coils which were not acceptable to customers for applications like, automotive body, tube making, galvanised products etc. Coils with non-conformity are sent to coil dividing line for rechecking and eliminating the defected area. If severity of defect is against the acceptance norms, it is discarded either as scrap (<5T) or parted coils (> 5T). The parted coils are generally low in coil weight (average weight of 8–9 MT) does not fit with min order weight of 14 T of the coil weight and hence consider as ETO (Extra to Order) and are not link to any order. Scrap (< 5T in weight) are either discarded in the form of end cuts, mid cuts, pup coils. These pup coils were the steel scrap generated which incurred loss to company in crores per annum and environment. Daily management manually was done at start of the study to monitor the pup coil generation with respect to defects and grades. After product wise analysis, it was found that cold rolling grades accounts for maximum pup generations due to critical acceptance norms. The top generated defects were identified to be slivers, scab, mill hanging, edge crack and edge damage. Detailed analysis for the generation of each defect and their root causes were identified. The manual monitoring of pup coil generation was converted to digital based monitoring. This study helped to reduce the defect generation which in turn reduced the generation of pup coils.*

Keywords: Pup Coil, Hot Rolled Coil/Strips, Sliver, Scab, Mill Hanging.

1. INTRODUCTION

1.1 Process flow of Hot Strip Mill, Tata Steel, Jamshedpur

Hot Strip Mill converts slabs supplied by HLD2 & Slab Caster (steel making unit) into Hot Rolled Coils with an aim to meet customer requirement, maximize the yield and minimize the conversion cost, in a safe manner. Here slabs of thickness 218 mm are converted into coils of thickness 1.6 to 14 mm, through various metallurgical processes starting with austenitization followed by recrystallization and phase transformation. The conforming coils are released to downstream or market and non-conforming coils are hold for further reprocessing or rework. Non-conforming coils are sent to

coil dividing line or gas cut for rework. Affected portions are discarded and the rest part of the coil is salvaged which are declared as prime. Non-conforming coil are regraded/ downgraded to alternative grades where it is fit for intended application. The process flow diagram for Hot Strip Mill is given below.

Coils from HSM are sent to our customers, both internal and external, for various applications like, automotive body, tube making, galvanised product etc. Coils with non-conformity are sent to coil dividing line for rechecking and eliminating the defected area. If severity of defect is against the acceptance norms, it is discarded either as scrap (<5T) or parted coils (> 5T). The parted coils are generally low in coil weight

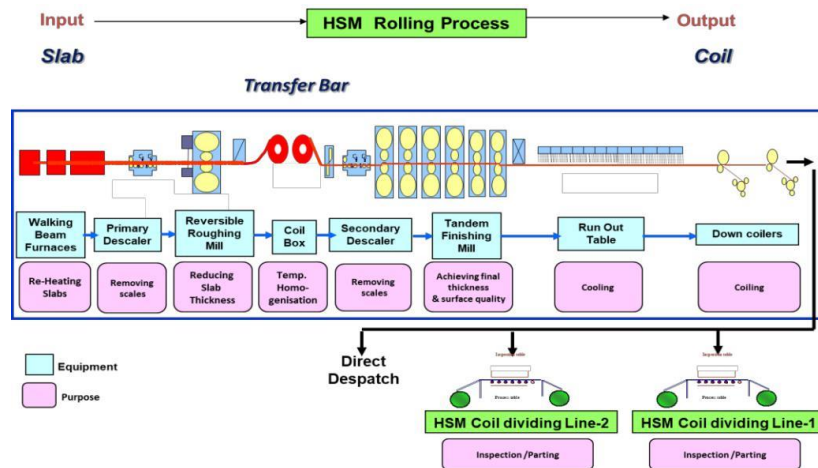


Figure 1: Process Flow Diagram for Hot Strip Mill, Tata Steel, Jamshedpur

(average weight of 8–9 MT) does not fit with min order weight of 14 T of the coil weight and hence consider as ETO (Extra to Order or Not link to any order). Scrap (<5T in weight) are either discarded in the form of end cuts, mid cuts, pup coils.

1.2 Pup Coils

According to Ministry of Steel, hot-rolled wide coil/strips are the flat rolled product in coils with a unit weight of less than 4 tons[1]. Scrap with weight <5T are known as pup coil

at HSM TSJ. These are either sold to market as scrap as “Saleable Scrap” or sent for re-charging in vessel “Remelting Scrap”. Pup coil losses constitute 80-90% of the entire rejections at CDL line.

2. DEFECTS FOR PUP COIL GENERATION

Daily basis tracking of pup weight and pup reasons was done for 3 continuous months to study various trends for defects of pup coil

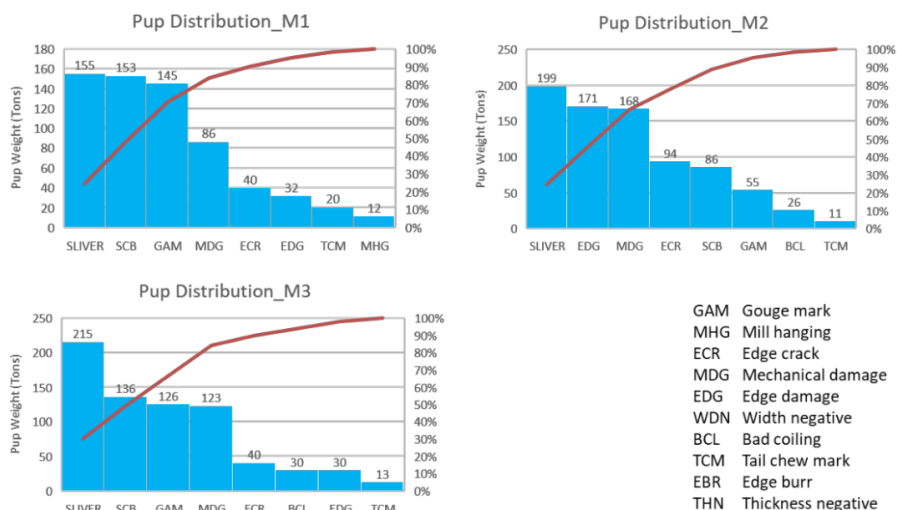


Figure 2: Defect Trends for Pup Coil Generation

generation. Pup coil generation defect reasons was digitalized in FPCIS (Flat Product Complex Information System), which helped in systematizing the pup coil generation detail and helped in analysis for defect genesis in hot strip mill or steel making shop.

Above data shows, mostly pup coils are generated on account of sliver, scabs and edge related damages.

3. DEFECTS FOR PUP COIL GENERATION

3.1 Sliver

Slivers are sub surface defects in slabs like non-metallic inclusions, mould powder entrapment, gaseous entrapment, etc which open up in subsequent hot/cold rolling. They can occur because of severe mould oscillation, mould level fluctuations, poor ductility, higher casting speed and so on. Unlike non-metallic inclusions (mostly Al_2O_3 based) which forms during steelmaking and surfaced during hot rolling; the origin point of FeO based sliver [2] is still not conclusive enough. Slivers which are generated during steel making can easily be identified by EDS as it shows peak for the entrapped elements like Ca, Si, Mg etc. The oxides of these elements get entrapped during steel making itself.

Slivers generated due to slab conditioning can also be identified. If slab contains defects surrounded by an oxide layer, then it can lead to FeO sliver after rolling. Slivers are broadly classified into three types based on appearance: Line sliver, edge sliver and chip out sliver.

3.2 Scab

Scab[3] are defects generated after the foreign material falling on strip surface and getting rolled. These defects generate from the fins/burr present in slab (mostly tail end or head end of the coil) or some extraneous material falling from mill during rolling.

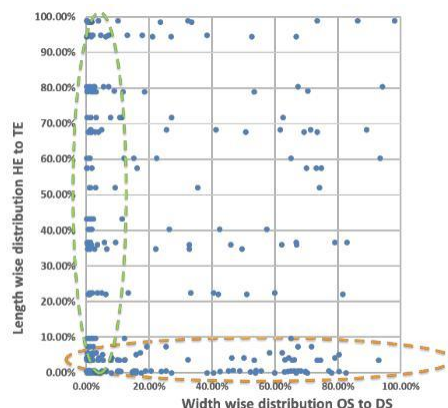


Figure 4: Occurrence of Scab wrt Side and End of Coil

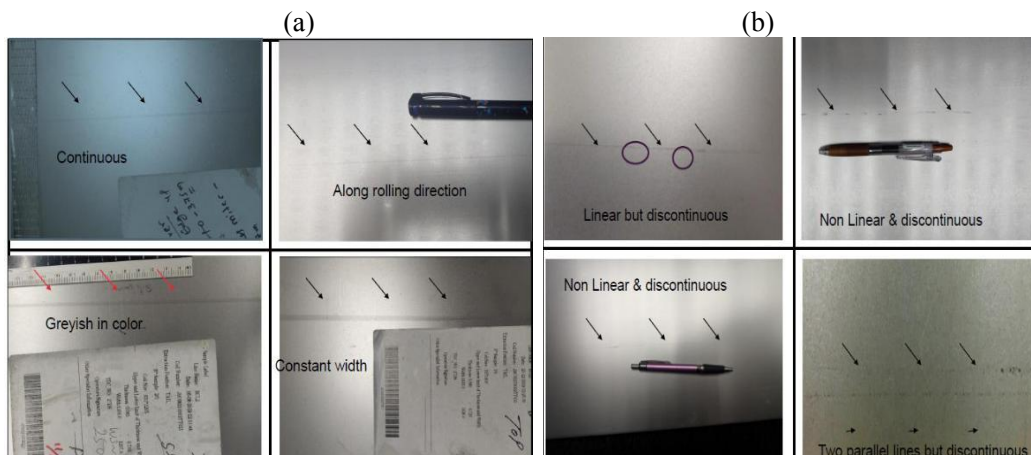


Figure 3: (a) Casting Sliver (b) FeO Sliver

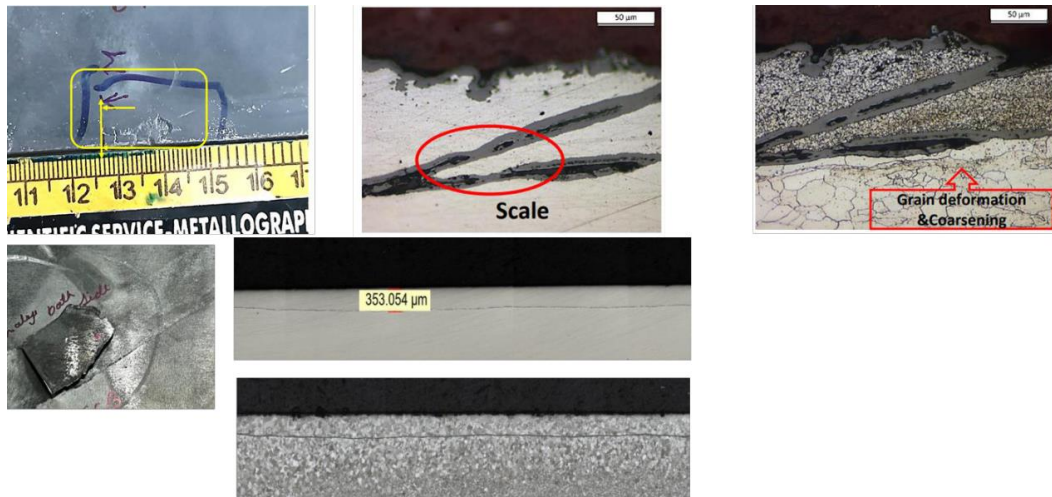


Figure 5: Metallography of Scab Defect

The metallographic analysis of scab sample states that the unetched micro revealed subsurface crack associated with scale at defect interface. The etched micro revealed defect microstructure was different from base metal. Scabs are open from both ends in a typical microstructure.

EDS spectrum revealed no prominent difference between defect and base metal. EDS spectrum revealed O, Ti, Al, Mn and

Fe. Voids and internal oxidation was observed inside the defect.

3.3 Edge Cracks (ECR)

Edge cracks [4] are cracks observed on the edges of hot rolled coils due to excess quenching effect. These occur because of excess water in ROT/FM/DC cooling the strip edges/body. Also because of un-flatness leading to water carryover.



Figure 6: Edge Crack Relation wrt Width, Thickness and Edging



Figure 7: Edge Crack Defect Metallography

It can be easily inferred from the graphs that coils of width 1100–1200 mm report maximum edge crack cases, an edging of 80–90 accounts for maximum edge crack cases and coils of thickness 3.5–4.0 mm are affected the most.

Visual observations revealed like edge damage and microstructure shows deformed and recrystallized grains suggesting generated at hot rolling stage in run out table in hot strip mill.

4. ACTIONS TO REDUCE DEFECTS

4.1 Sliver

The following measures taken for decreasing sliver defect such as regading ladle change over slabs in thicker grades to avoid sliver generation due to lesser reduction during hot rolling, audits and monitoring to reduce slab handling damages, controlled casting speed with proper secondary cooling rate.

4.2 Scab

To reduce scab defect following measures taken such Cross-functional audit at slab yard of HSM and LD2 for abnormality, slab audit on daily basis, roll flushing before rolling of critical grades affected with scab, daily management on guides and liners to reduce scabs on the edges, rope access cleaning to minimize loose hanging debris and using cross sprays to flush out the falling debris,

regular cleaning of scale accumulation along the table rolls.

4.3 Edge Cracks

To reduce edge crack defect following measures taken such as minimizing zero edging coils in roughing mill to impart edge deformation, control on Mn/S and Al*N ratio to reduce edge burst, controlled secondary cooling during casting of boron bearing grades, controlled guide pressure during entry and rolling of strips in finishing mill and downcoiler and maintaining interstand tension to minimize necking related phenomena.

5. CONCLUSION

It was concluded that pup coil is inevitable and cannot be reduced to zero, but with continuous daily management and tracking, it can surely be kept under control.

The genesis of various defects was studied with the root cause analysis and actions to reduce these defects.

The reduction in pup coil generation resulted in improve in yield.

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Defects in Steel Hot-Rolled Flat Products

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ABSTRACT: *Bhilai Steel Plant is an integrated Steel Plant of National repute and a flagship unit of Steel Authority of India Limited (SAIL). Plate Mill, BSP produces high quality hot-rolled steel Plates of varying Grades, complying to National & International Standards/Specifications. These special Plates are being supplied to various Industry Segments like Construction, Automotive, Energy, Pressure-vessel, Ship building etc. Plates rolled at BSP Plate Mill, have been supplied for various projects of National importance including the Gaganyaan/Chandrayaan Space programs, High-speed Rail Corridor & Naval ships for Surface/Under-water applications—thus making it conspicuous on “Land, Water & Space”.*

BSP Plate Mill, however, being an old mill commissioned in 1984, faces innumerable challenges to meet the current Customer & Market expectations w.r.t Production, Quality & timely Despatch—challenges due to technical limitations owing to poor Mill capabilities vis-à-vis the complex dynamics of Steel making, Casting and Plate rolling.

This technical paper focuses on major defects encountered during hot rolling of Special steels plates. The defects are broadly classified into two categories – i. Steel defects—those generated primarily during Steel making/Casting process & ii. Mill defects—those generated during Plate rolling. These defects adversely affect Productivity, Techno-economics, Quality and timely Plate Despatch to Customer. Timely despatch to Customer with adequate Quality meeting the Order requirements, is the key essence to survival, in today's dynamic Plate market scenario.

This technical paper provides statistical data and analysis of the major Plate defects, that can be attributed to the three M's - Man, Machine & Material, with an aim to derive the root cause. The only way to mitigate perennial defects is through Process Optimisation & strict control of Process parameters, in the entire process route of Steel making, Slab Casting & Plate Rolling.

Keywords: Hot Rolling, Steel & Mill Defects, Root Cause Analysis & Mitigation.

1. INTRODUCTION

Heat making, Slab casting and hot rolling are among the key processes, that form Cast-slabs and consequently finished plates. Since the rolling operation is often the last process step, the defects identified in the finished plates either due to the slabs or due to rolling process are very costly and hence

the quality control of the slab casting and rolling process is very important.

The defects generated in the finished plates can be broadly classified into two categories:

- Steel defects—those generated primarily during Steel making/Casting process.
- Mill defects—those generated during Plate rolling.

	Total-NCO	NCO-STEEL %							NCO-MILL %						
		STEEL	NMI	LC	SPC	NDT	EL	CA T-A	MIL L	LT+ OT+ ED	BEND	SH R	MDM	NTA	SL
TILL JULY -24	7.59	4.32	0.02	0.31	0.8	0.47	2.53	1.55	3.27	0.27	0.49	0.09	0.25	0.84	1.03

Figure 1: Statistics Data of Non-conformance of Plate (April to July'2024)

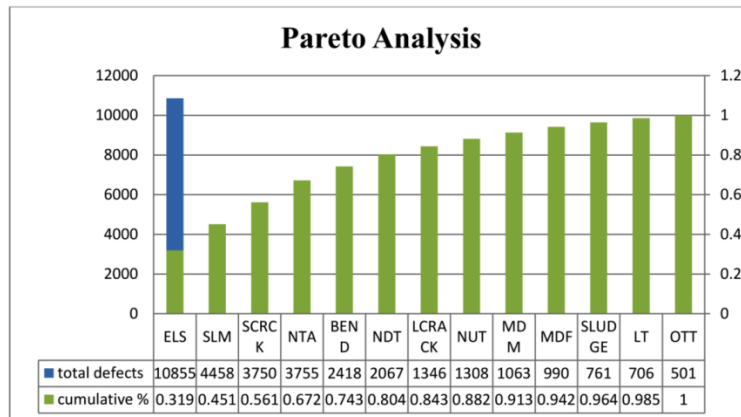


Figure 2: Pareto Analysis to Pinpoint the Primary Factors Causing Plate NCO

The Pareto Analysis reveals that length variations, spider cracks, bend issues and UT failures were the main contributors to Plate NCO. This paper will concentrate on NCO arising from length variations and spider cracks.

2. LITERATURE REVIEW ON STEEL DEFECTS

To produce a homogeneous slab, the sensitivity of the steel to defect formation has to be considered. It is necessary to have a detailed knowledge of the steel's properties over the whole temperature range and to take into account the machine design, the intended casting speed and the range of operating parameters available. The choice of casting conditions for high quality products depends on the impact of design features on product quality. Despite substantial advancements in manufacturing engineering and process optimization, surface defects in rolled steel products have not been eliminated. Consequently, steel manufacturers face the challenge of minimizing these undesirable

defects and keeping them within acceptable limits, to ensure that the product is suitable for its intended use.

Surface quality issues can arise from various sources, including unfavourable alloy chemistry, irregular casting practices and improper processing. These defects may develop during the initial steelmaking stages or later rolling operations.

Major Steel Defects

- Longitudinal cracks
- Transverse Spider crack
- Non Metallic Inclusion
- Ultrasonic testing failure
- Sludge

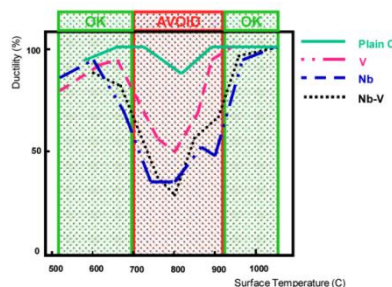
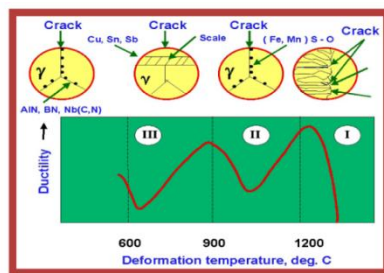
2.1 Reasons for Spider Crack Formation

Irregular cracks in the transverse direction of the rolling, appears in the form of an M or Z like path.

- Thermal and mechanical stresses acting in the surface area of slab shell when the

slab passes through the rollers of secondary cooling cause's gradual expansion of cracks along boundaries of grains contaminated by copper. The copper cooled mould walls may be the reason for diffusion of copper.

2. Stresses/strains are responsible for crack generation: High temp zone of low Ductility (>1340 deg.C): Liquid films of S&P in the inter-dendritic region Sensitive to all types of cracks
3. Intermediate zone of low ductility (800–1200°C): Sulphide precipitation along grain boundaries.
4. Low temp zone of low ductility (700–900°C): Precipitation of AlN & Nb-V (C, N) along grain boundaries & sensitive to Transverse Cracking.



5. Ferrite Potential is used to evaluate whether steel has inherent tendency to develop defects like cracks, surface depressions or uneven undulations. FP

falls within the range of 0.80 to 1.00 the steel then obeys peritectic mode of solidification and the chances of formation of cracks, depressions, uneven shell growth, entrapments, etc. become high.

3. METALLURGICAL INVESTIGATION

For the purpose of defect analysis, samples from 25 mm thick defective 2062 E350 BR grade steel plate was collected from Bhilai Steel Plant and sent to RDCIS. Chemical analysis, Metallographic analysis was done by RDCIS.

3.1 Results and Discussions:

Metallurgical Investigations Carried Out at RDCIS Chemical Analysis

1. Chemical composition of the IS 2062 350 BR steels satisfies the requirements of the relevant standards.
2. Nitrogen content of the steel was found below 60 ppm which suggests that the nitrogen content in the steel is controlled satisfactorily.

Microstructural Observations

1. The microstructure of the steel indicated that the matrix structure was ferrite-pearlitic as commonly observed in C-Mn steel plates.
2. No banding or any other microstructural abnormality in terms of unidirectional grain flow, grain coarsening or deformed grain structure could be observed in the steel.

Steel Grade	Element wt%							
	C	Si	S	P	Mn	Al	Nb	N2 ppm
IS 2062 E 350BR	0.16	0.27	0.021	0.03	1.39	0.013	0.0350	58

Figure 3: Chemical Composition of the IS 2062 350 BR Steels

3. The cracks were unbranched, unidirectional and heavily filled with grey coloured entrapments.
4. Presence of decarburized layer along or around the cracks. Decarburization must have occurred during reheating prior to rolling. These are usually casting defects which can be linked with the initial stages of solidification of steel slab. It is presumed that, during casting the solidifying shell experienced gross damage by action of pinch rolls of the slab caster, producing cracks. Subsequently during reheating of the slab before rolling, oxygen present in the reheating furnace must have ingressed through the crack opening and reacted with the carbon of the steel resulting in decarburization around the crack.

SEM and EDS

1. From SEM it was observed that all the crack crevices were heavily filled with grey-coloured entrapments and in many cases fragmentation of these entrapments occurred perhaps due to the deformation during rolling.
2. Incidence of numerous fine spherical particles uniformly dispersed in the steel matrix on either side of the cracks. EDS analyses confirmed these tiny globules to be of iron oxides containing high amount of Mn and Si resulting from internal oxidation. Manifestation of internal oxidation associated with the defects indicated that the cracks were pre-existing at the surface or subsurface locations in the cast product.
3. Fluorine (from the mould powder origin is found but Ca and Al was not found and hence the influence of mould powder is overlooked.
4. Presence of FeO–MnO–SiO₂ type oxides and FeO–MnO–Al₂O₃ type complex oxides. All the above oxide entrapments

are products of de-oxidation and therefore of exogenous origin.

5. FP of the investigated steel comes out to be 0.8055 which falls marginally within the peritectic solidification range as discussed earlier, thus becomes prone to development of metallurgical defects in the steel.

Routine data analysis from the shop was conducted during the occurrence of spider cracks.

3.2 Results and Discussions

Consolidated data collected after observing all heats failed in Spider cracks:

Heavy Water Leakages

1. Heavy water leakages found in segment 8 and 12; differential cooling might have led to spider cracks in high tensile heats.
2. Segment 8 and 12 changed, also cooling defects rectified.

Mould sticking tendency observed: Casting speed dropped to 0.3 mm/min, diffusion of copper and differential cooling might be the reason for generation of spider cracks.

SEN Changing

1. SEN changed at 19 mts during casting of heat, 19 mts of this slab might have undergone overcooling which might have led to the generation of thermal stresses leading to spider cracks.
2. The casting speed became 0 which means the nozzle was changed (either its life was over or there might be choking in SEN due to Alumina).

Influence of Straightening Temperatures:

The actual straightening temperature versus the target straightening temperature of the failed heats was observed. The target temperatures are much above the poor ductility range which is from 700–900°C whereas the actual temperatures were around 900°C.



Figure 4: Photograph of the as Received Steel Plate Sample of 25 mm Showing Defective Region



Figure 5: Optical micrographs of the steel plate in 2% nital etched condition showing decarburization along the upper half of the entire length of the transverse cracks and at the crack mouth; (a) 200X Mag.

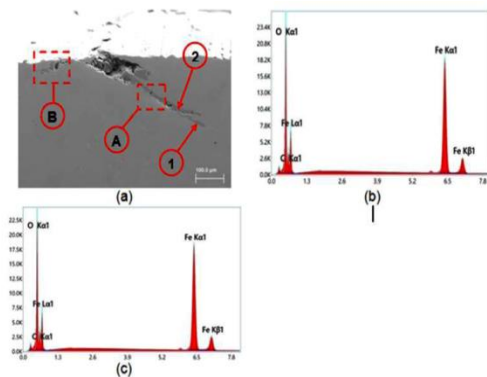


Figure 6: Scanning electron micrograph of the surface originated long and short transverse crack shown in Figure 5 (a) at 150 × Mag. and (b–c) corresponding EDS spectra obtained from the spots 1 and 2 on the entrancements in (a).

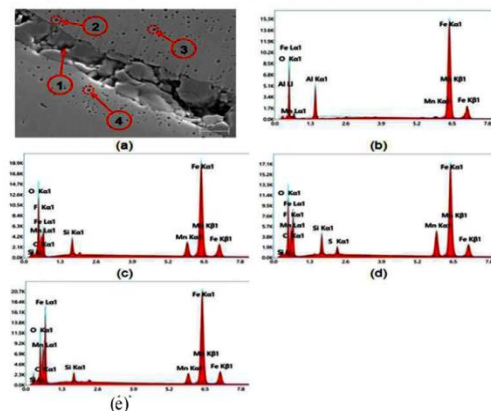


Figure 7: (a) Enlarged scanning electron micrograph of the location 'A' in Figure 6(a) at 1500 × Mag. and (b–e) corresponding EDS spectra obtained from the spots 1–4 in (a).

4. RECOMMENDATIONS

1. Low flow nozzles in bender, segment 1 and 2.
2. Regular secondary water nozzle cleaning.
3. Arresting off any leakage from rollers.
4. Maintaining temperature range above low ductility zone during unbending by tweaking water flow.
5. Using nickel coated mould to avoid erosion of copper.
6. Maintaining superheat at desired level so as to maintain desirable casting speed.

5. LITERATURE REVIEW ON MILL DEFECTS

BSP Plate Mill has been in operation for the past forty years of service and with the aging of equipment, Mill faces real challenges in maintaining consistence product quality, reducing defects and customer satisfaction. However, Plate Mill has made many improvements in the field of increasing productivity and improvement in quality. Also, it developed many new products as desired by the market from time to time and to meet customers' expectations. Despite old

mill, remarkable improvement has done through regular maintenance & repair, balance and alignment of Mill housing, replacement of old parts, skill enhancement and quality control checks.

Mill defects are those defects are those defects which are generated during rolling process. Defect generation can lead to reduce part quality, increase scrap rates and decrease productivity. These defects can be classified in two categories.

1. Geometrical Defects
2. Surface Defects

5.1 Geometrical Defects

Reducing the geometrical defects is a challenge that needs regular monitoring of many rolling parameters that are interlinked with each other.

Let us discuss the four major geometrical defects, their probable cause and the remedial actions to control the defects to a great extent.

Major Geometrical Defects

1. Short length of Plate (SLS& SLM)
2. Thickness deviation
3. Waviness
4. Sickleness

(a) Short Length of Plates (SLS/SLM)

This is one of the major deviations observed in plate rolling. The plates having length lesser than the ordered length are called **short length plates**.

Root cause of SL/EL Generation

SLS/EL-Slab is the input material for the plate. The Calculation of base length is based on the dimensional tolerances of the plates. Any dimensional deviation in the slab leads to differences in actual and theoretical weights, which directly affect the length of plate. Wrong and taper cutting of slabs by torch cutting machines of casters are also the probable reason for short length plate. In case, deviation in either width or thickness or both

exceeds the limit on the upper side, it will reduce the length of the plate considerably. Rolling above the specified upper tolerance in thickness/higher width will lead to short-length plates. It is often observed that on the narrow- width plates the edges of the plates will form a rounded shape due to more rolling at the center due to higher roll crown. This also leads to short-length plates. Extremely worn-out rolls also lead to short-length plates as the thickness at the center of plates rolled is more as compared to the edge thickness.

Sometimes the improper feeding of slabs at the roughing stand while forming widths also leads to tapered edges of the plates. After cropping the tapered edges the plates become shorter.

Initiative Taken by Plate Mill to Reduce the Length Deviation

Installation of Slab Weighing Machine during capital repair of Plate Mill:

A Slab weighing machine has been installed just before the charging point of slab on roll table at Mill area to find out whether the root cause of variation in length is due to Mill or steel. Also software screen has been developed in MES system which shows the differences between actual and theoretical weight. If the difference between both the weights is on higher side feedback is being given by quality department to the concerned department in order to take corrective action.



Figure 8: Slab Weighing Machine Installed at Plate Mill

After revisiting base length calculations, percentage of short length has been reduced

from 1.94% to 1.15% and directly enhancing the order fulfillment of customer by achieving ordered length. The length variation in Caster-1, has been reduced from 3.2% to 1.86% due to introduction of shrinkage allowance in base length calculation of slab.

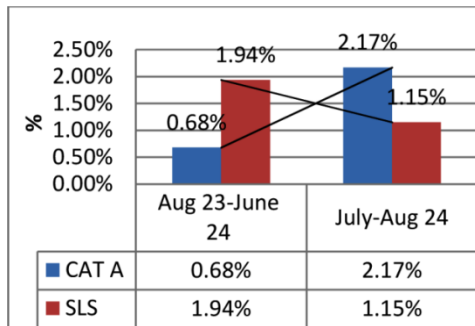


Figure 9: Comparison of Length Variation over a 2 years Period of 2 years - Machine 6

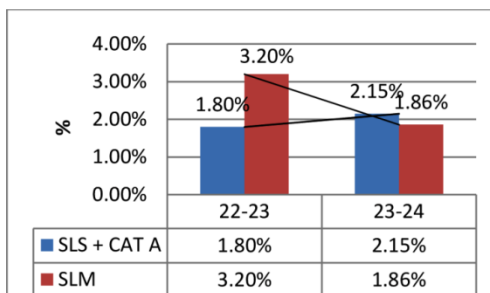


Figure 10: Comparison of Length Variation over a Period of Machine 1

Initiative taken by Steel Melting Shop-II to reduce the length deviation

Introduction of LASER sensor based Slab zero positioning system for TCM-2 of Slab caster-6 for reducing length variations due to slab.

In SMS-2 in TCM-2(Torch cutting machine of caster 6), a long slab is cut into three pieces by stopping one end of slab (towards Plate mill side) with the help of hydraulically operated stopper. The function of stopper is to stop the long slab at zero position & with respect to that PLC gives command to two carriages & torch mechanism for cutting of slab in three pieces. Any malfunction in

hydraulically operated slab stopper was resulting in wrong cutting of slabs and ultimately short length of plates.

To overcome this problem of stopper following actions were taken:

- A non-contact type system was introduced to position the slab at exact zero position and providing visual indication in TCM#2.
- A digital indicator was also introduced and programmed to provide slab position with respect to zero position.
- By introduction of this modification, the pulpit operator is able to position slab at exact zero position which further helps in proper cutting of slabs.

Intangible Benefits

- The complete design and modification job has been done with in-house resources.
- By introduction of this project, slab cutting accuracy has improved & due to this EL have minimized and instances of stopping of hot charging to plate mill due to failure of mechanical stopper have been reduced to zero.



Figure 11: LASER Sensor based Slab Zero Positioning System for TCM-2 of Slab Caster-6

(b) Thickness Deviation

Thickness deviation (Positive or negative) is common issue in hot rolled products, affecting their quality and performance. Thickness deviation is the result of rolling plates beyond the specified thickness

tolerances as per Product standard and sometimes the customer also specifies the tolerances according to their needs. Plates rolled above the positive tolerance will be classified as **over thickness** and the plates rolled below the negative tolerance will be clarified as **lower thickness**. Rolling of plates in twin stands is bit difficult comparing with the rolling of plate in single stand as far as profile is concerned. The draft schedule may vary depending on the metal received from the first stand as well as the mill spring of the finishing stand

(c) Waviness

Waviness in plates is a result of uneven elongation of the plates along the width of the plates. It happens mostly in thinner section plates. Waviness may be generated due to poor temperature of metal, improper crown of the roll, and the drafting schedule.

Waviness may be classified mainly into two major categories as edge waviness and center waviness. **Edge waviness** is produced by local increases in the strip elongation along the strip edges. **Centre waviness** is a result of local increases in the strip elongation along its center line.

Poor metal temperature needs higher than normal drafting schedule. It makes the rolls more bending which will create edge waviness. Insufficient crown of rolls causes edge waviness and excessive crown of rolls causes the center waviness.



Figure 12: Waviness in Plate

Changes in the thermal crown will also affect the flatness of plates. Higher draft schedule will cause edge waviness and lesser draft schedule will cause center waviness.



Figure 13: Sickles in Plates

(d) Sickleness

Sickle is also known as strip camber. It is the result of a gradual increase in the strip elongation across the entire width of the strip from one edge to the other. This defect will be more evident in case of thinner section rolling as small deviation between both edges will make a bigger strip camber.

Main causes for this defect is due to rolling of half cold slabs, wrong mill setting, and uneven wear out of rolls and poor rigidity of the stand.

Difference in the roll gap between the work rolls at the ends creates sickle plates. In case of twin stands the finishing stand mill setting also depends on input material coming from the roughing stand. Uneven worn out rolls also creates problem in setting the mill properly.

Rigidity of the stand gets disturbed in the course of time due to many reasons including worn out roll bearings and window liners.

5.2 Surface Defects

Among all the quality concerns, the surface integrity is an extremely important quality characteristic of rolled products. Surface defects remain as a weakness and could cause catastrophic failure when the rolled product is in use. Products with severe surface defects are to be scraped and salvaged.

Therefore, it is highly desired to detect, reduce and eventually eliminate the surface defects, if possible. Unfortunately the surface defects remain as the most troubling problems in the hot rolling process.

Major challenges in the surface quality control fall into the following two aspects.

1. Effective surface inspection of plates at beds.
2. The root causes of surface defects in hot rolling processes to be identified and eliminated.

Major Surface Defects

(a) Rolled in scale pits

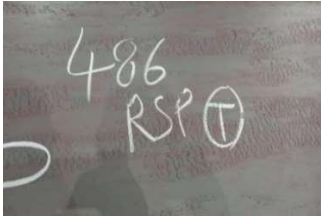
(b) Pit marks/scratches

(c) Mechanical damage due to mill

6. CONCLUSION

Geometric defects are generated in old mills mainly due to lack of Automation leading to variation in rolling practices. A minor effort in adopting the standard practices and increased awareness, will help in controlling these defects effectively, which is the need of the hour.

Facilities like better furnace controls, hydraulic automatic gauge control, and on line thickness gauge will also help in reducing these defects considerably.

A.	Rolled in scale Pits	Defect Description/Details and Possible Causes 	1. These appear as marks pitting on the rolled plate surface varying in shape, thickness and frequency. 2. Rolled in scale results from unsatisfactory removal of scale from the rolling stock before or rolling and processing. 3. There may be also local areas scale pressed into the surface of the stock during rolling.
B.	Mechanical Defect Due to Mill (MDM):	Defect Description/Details and Possible Causes 	1. This is a mechanical damage arising from furnace charging dry skids, furnace slots and slab extractors. This damage occurs only at the bottom of the slab. And damage appears at the bottom side of the plate. 3. Mechanical damage also happens at the top of the plate due to loose roughing and finishing stand balancing beam shoes or some time foreign particles fell down and rolled with plate surface.
C.	Scratches and Roll Pit Marks	Defect Description/Details and Possible Causes 	1. Scratch and pit marks are normally observed at the bottom of plate. These defects are introduced on the surface of the plate by roll table rolls. 2. A combination of the roll pressure and the defects in the rolls or contamination on the rolls determine the severity of roll scratch marks or pit marks. It is generally repetitive.

6.1 Monitoring of the following points is helpful to minimize the geometrical defects in plate rolling.

Recommendation to reduce the length variation of plates:

- The operators should be apprised of the specified tolerance and slab calculation on thickness of the plates.
- Ensure feeding of slabs correctly at Roughing stand such that the slab axis & the Mill axis are aligned.
- Proper mill scheduling based on the “Coffin model” to accommodate the crown requirement for rolling.
- Avoid extremely worn out rolls.
- Effective feedback to appraise the operator at each stage of measurement.
- Revisit the base length calculation formula of slabs, periodically.

Recommendation to achieve desired thickness of plates:

- Well soaked slabs.
- Entry temperature at finishing stand at a consistent level.
- Avoid frequent section changes.
- Educate the operators about tolerances and timely feed- back on mill conditions.

Recommendation to reduce the Sickleness of plates:

- Avoid rolling of half cold slabs.
- Proper mill setting before processing the thinner section plates.
- Maintaining the optimum roll campaign to preserve the roll profile.

- Maintain the rigidity of the stand.

Recommendation to reduce the Waviness of plates:

- Sufficient temperature of metal.
- Optimum mill scheduling.
- Proper draft schedule.
- Effective roll cooling.

6.2 Monitoring of the following points is helpful to minimize the Surface defects in plate rolling.

- ***Recommendation to reduce the MDM -*** This damage can be avoided by timely maintenance of equipment at furnace and mill area.
- ***Recommendation to reduce the Scratch and Pit Marks-*** Replacing damage rolls and grinding of scale deposits on rolls.
- ***Recommendation to reduce the surface defects caused by primary and secondary scale-*** Establishing furnace practices to produce a scale that tends to break up into sheets during descaling at main descaler. Establishing effective secondary descaling at roughing stand passes.

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Towards Zeroing Rejections in Flat Steel by Improving Mechanical Properties and Surface Quality

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ABSTRACT: *This abstract highlight two innovative studies aimed at significantly reducing rejections in flat steel production by addressing both mechanical property variations and surface quality issues.*

Study 1: Dynamic Processing for Controlled Mechanical Properties

This study tackles the issue of inconsistent mechanical properties in hot-rolled steel coils, a major contributor to rejections. A dynamic processing system is introduced, leveraging a multiple linear regression model to predict the mechanical properties of a steel heat based on its chemical composition and rolling parameters. This predictive model enables the optimization of downstream processing parameters to compensate for any variations in the upstream process. The dynamic system has been successfully implemented in a thin slab casting and hot rolling mill, resulting in a substantial reduction in both internal and external rejections. This system exemplifies Quality 4.0 principles, showcasing its adaptability and data-driven approach.

Study 2: Mitigating Coil Break Marks for Enhanced Surface Quality

This work focuses on mitigating coil break marks (CBMs), a prevalent surface defect that significantly impacts product rejections. A formable, low-carbon hot-rolled steel with improved surface appearance was developed through optimized hot rolling process parameters. The steel chemistry was modified by incorporating small amounts of titanium and boron, effectively reducing CBM severity without compromising the steel's mechanical properties. The optimized process results in a mixed-grain size of the ferrite phase, mitigating the yield point phenomenon and further contributing to improved surface quality. This study delves into the mechanisms behind CBM formation and presents a practical solution for its mitigation. The resulting high-quality, cost-effective low-carbon hot-rolled steel with enhanced surface appearance holds immense potential for the automotive industry, reducing the need for cold-rolled steel in light draw components and improving overall product quality. This innovative steel grade will eliminate the need for high-value cold-rolled steel, leading to significant cost savings for manufacturers.

These two studies demonstrate a comprehensive approach to addressing key challenges in flat steel production. By improving both mechanical properties and surface quality through innovative process modifications and dynamic control systems, a promising path towards zeroing rejections and enhancing overall product quality is achieved.

Keywords: Steel property variations, Dynamic rolling, Process Parameters Setting, Correction of steel properties, Chronic Steel Surface issues, Coil Break Marks, Process control for surface Quality, low carbon steel, hot rolling microstructure, yield point phenomenon, light draw applications.

1. INTRODUCTION

The pursuit of consistent quality in flat steel production faces a persistent challenge: inconsistencies in mechanical properties and the occurrence of surface defects, both leading to costly rejections. This paper addresses these crucial areas, proposing solutions through two distinct yet interconnected studies.

The first study tackles the issue of inconsistent mechanical properties, a major contributor to rejections, particularly in hot-rolled steel coils. Recognizing the impact of variations arising from upstream processes, this research introduces a dynamic processing system rooted in Quality 4.0 principles. This system employs a multiple linear regression model to predict the mechanical properties of a steel heat based on its chemical composition and rolling parameters. By anticipating potential inconsistencies, the system empowers real-time optimization of downstream processing parameters, effectively counterbalancing upstream variations. Implemented in a thin slab casting and hot rolling mill, the system demonstrates its efficacy through significant reductions in both internal and external rejections, marking a significant step towards a more precise and consistent final product.

The second study focuses on mitigating coil break marks (CBMs), a prevalent surface defect significantly impacting product acceptance. This research delves into the mechanisms behind CBM formation, ultimately developing a practical solution for its mitigation. By optimizing hot rolling process parameters and strategically modifying the steel chemistry with small amounts of titanium and boron, a formable, low-carbon hot-rolled steel with a superior surface finish is achieved. This modification

successfully reduces CBM severity without compromising the steel's mechanical properties. Notably, the optimized process cultivates a mixed-grain size within the ferrite phase, effectively mitigating the yield point phenomenon and further enhancing surface quality. The resulting high-quality, cost-effective low-carbon hot-rolled steel presents a compelling alternative to cold-rolled steel in light draw components, particularly within the automotive industry. This innovative steel grade promises to elevate overall product quality while simultaneously offering manufacturers substantial cost savings.

Together, these studies showcase a comprehensive approach to tackling key challenges in flat steel production. By enhancing both mechanical properties and surface quality through innovative process modifications and dynamic control systems, they pave a promising path toward eliminating rejections and maximizing product quality.

2. DYNAMIC PROCESSING FOR CONTROLLED MECHANICAL PROPERTIES

This paper presents a novel approach for minimizing variations in the mechanical properties of hot rolled (HR) coils by dynamically controlling process parameters based on real-time steel chemistry. Traditional hot rolling processes utilize fixed parameters for specific steel grades, often leading to inconsistencies in final product properties due to inherent upstream variations. This study implemented a dynamic control strategy at Tata Steel's Thin Slab Cast and Rolling (TSCR) plant, focusing on finish rolling temperature (FRT) and coiling temperature (CT) as key control parameters.

A statistical model was developed by correlating six months of process data, including steel chemistry, processing temperatures (finishing rolling temperature and coiling temperature), and tensile test results. This model was integrated into the Level-III automation system to calculate modified CTs for each heat based on its unique chemical composition, effectively compensating for upstream fluctuations.

Post-implementation results demonstrated a significant reduction in the variation of mechanical properties. Notably, the difference between the maximum and minimum yield strength (YS) values for a specific grade (Gr.-1) decreased by 48%, while the ultimate tensile strength (UTS) variation reduced by 55%. Additionally, an auxiliary system was developed to monitor real-time mechanical properties along the coil length, further validating the effectiveness of the dynamic CT control strategy.

This study highlights the potential for dynamic process parameter control in enhancing product consistency and reducing property variations in HR coils. Future work will focus on expanding this approach to other steel grades and optimizing additional process parameters for improved control and resource efficiency.

2.1 Correlating Process and Product

Tata Steel, a leading steel producer, continuously strives to deliver high-quality hot rolled coils with consistent properties. However, variations in upstream processes, particularly steel chemistry, can lead to inconsistencies in the final product. This paper presents a novel approach for minimizing these variations by dynamically controlling the coiling temperature (CT) during hot rolling based on real-time steel chemistry.

The new concept utilizing variable downstream process parameters (specifically within the Mill area, as shown in Figure 1) based on the heat's chemical composition has been applied to produce a standard grade of steel at our TSCR plant. This involved developing a model that correlates the chemical composition and hot rolling process parameters with the tested mechanical properties, utilizing process data from the previous six months. Necessary trials were conducted, and adaptive IT systems were developed to seamlessly integrate this concept without disrupting the normal production process at TSCR.

The mechanical properties of hot rolled coils are influenced by steel chemistry, micro-structure, and processing parameters. Focusing on a low carbon steel grade, a

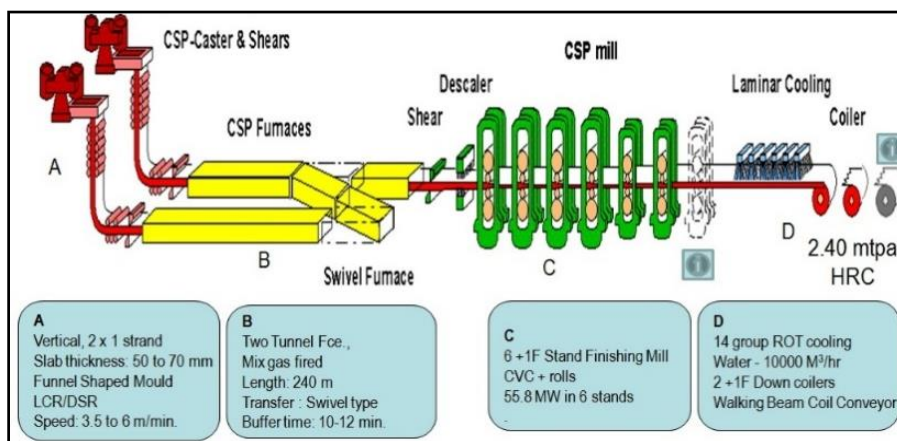


Figure 1: Route which Raw Materials Take to Emerge as Final Product
i.e. Hot Rolled Coils in TSCR

strong correlation was established between carbon equivalent (CE), finishing rolling temperature (FRT), coiling temperature (CT), and mechanical properties (YS and UTS) using historical process data.

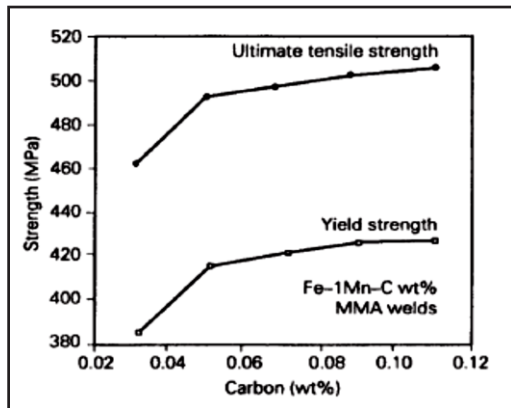


Figure 2: Variations in mechanical properties as a function of carbon concentration in Fe-1Mn-C wt% steel weld deposit using manual metal arc welding (1 kJ/mm). [1]

Literature well establishes that the effect of carbon is more pronounced (Figure 2) when its concentration changes within the range of 0.03 to 0.05 wt% [1,2]. In this case, the

cooling rate is significantly faster compared to the cooling at the run-out table (ROT) after rolling. This same behaviour is reflected in the changes in mechanical properties, as the strength of low-carbon steels is highly sensitive to carbon content.

2.2 Plant Trials and Validations

A series of trials were conducted (an example is posted in Figure 3) by rolling coils at different FRT and CT. Results confirmed the expected trends in mechanical properties based on the developed model, demonstrating the feasibility of dynamic process control.

2.3 Automating the New Dynamic Process

The model was integrated into the existing Level-III automation system at the TSCR plant. This integration enabled the system to automatically adjust the target FRT and CT for each coil based on its specific chemical composition and desired mechanical properties. This two-stage process is deployed within the production planning function:

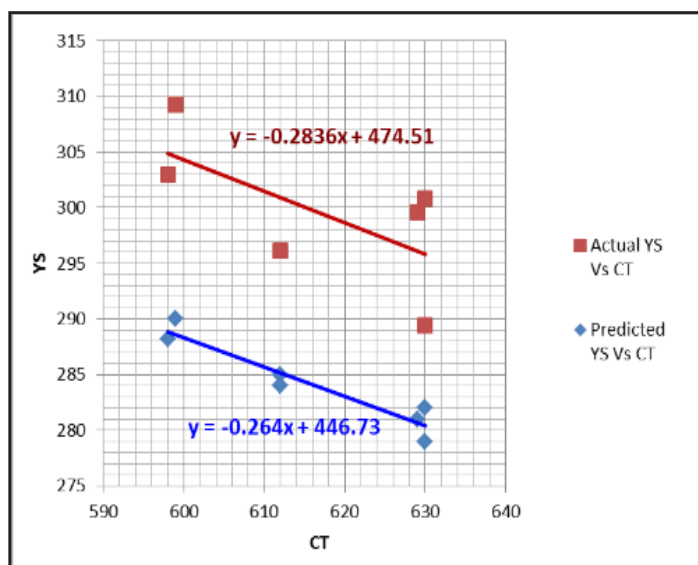


Figure 3: Trend of YS (test and prediction) w.r.t. Actual CT at Tail end Portion of the Coil

Stage 1: Quality Assurance in Order Management

The customer order process is designed to ensure the entire supply chain understands customer requirements. Each order is based on a Material number. This number maps to both the TDC (Technical Delivery Condition) and the GWT (Grade, Width, and Thickness) as shown in Figure 4.

Stage 2: Quality Assurance in Production Management

After an order is received through SAP (the L4 automation system), the production process is scheduled through the L3 system. The L3 system contains process charts with

fixed parameters based on the product grade and TDC. This project developed an L3 module to adjust these fixed parameters and accommodate variations in upstream processes, such as chemistry. By dynamically controlling rolling process parameters, like finish rolling temperature and coiling temperature, based on the chemistry of the steel, variations in the final product's mechanical properties are minimized. Figure 5 shows a typical variation in mechanical properties (YS and UTS in MPa along the length of a hot rolled coil under processing) with the process variation of FRT and CT is possible to monitor and make automatic corrections to achieve the targeted properties.

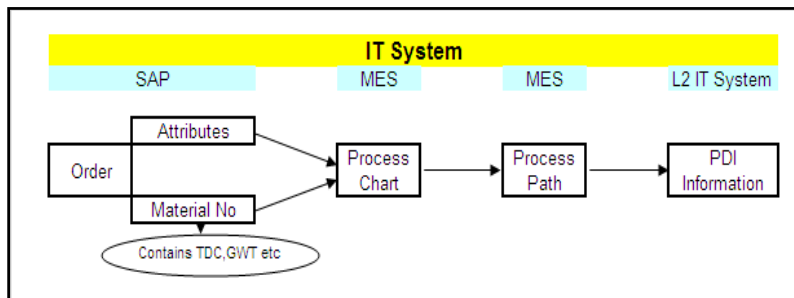


Figure 4: Order Flow in Flat Product Production Information System

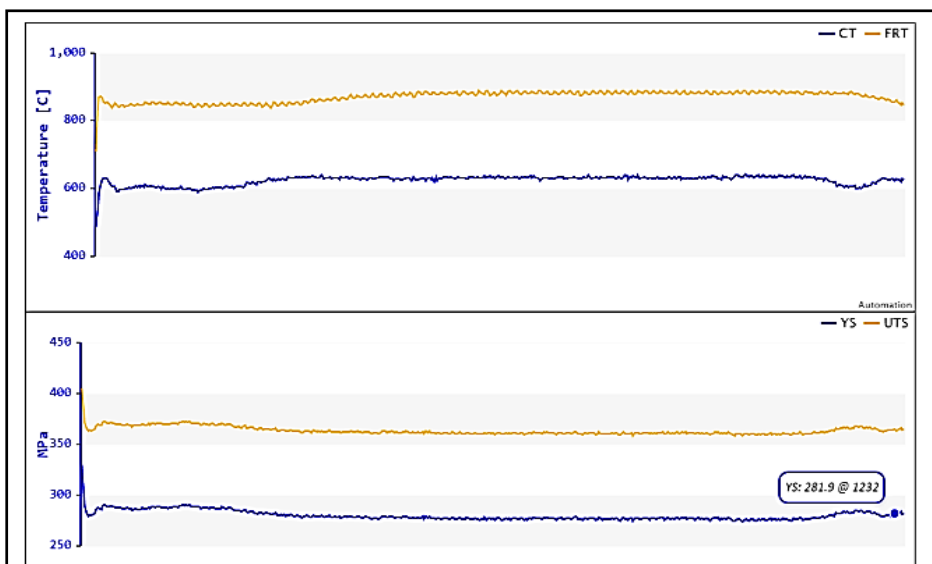


Figure 5: Online Dynamic Control of FRT and CT for Achieving Target Mechanical Properties

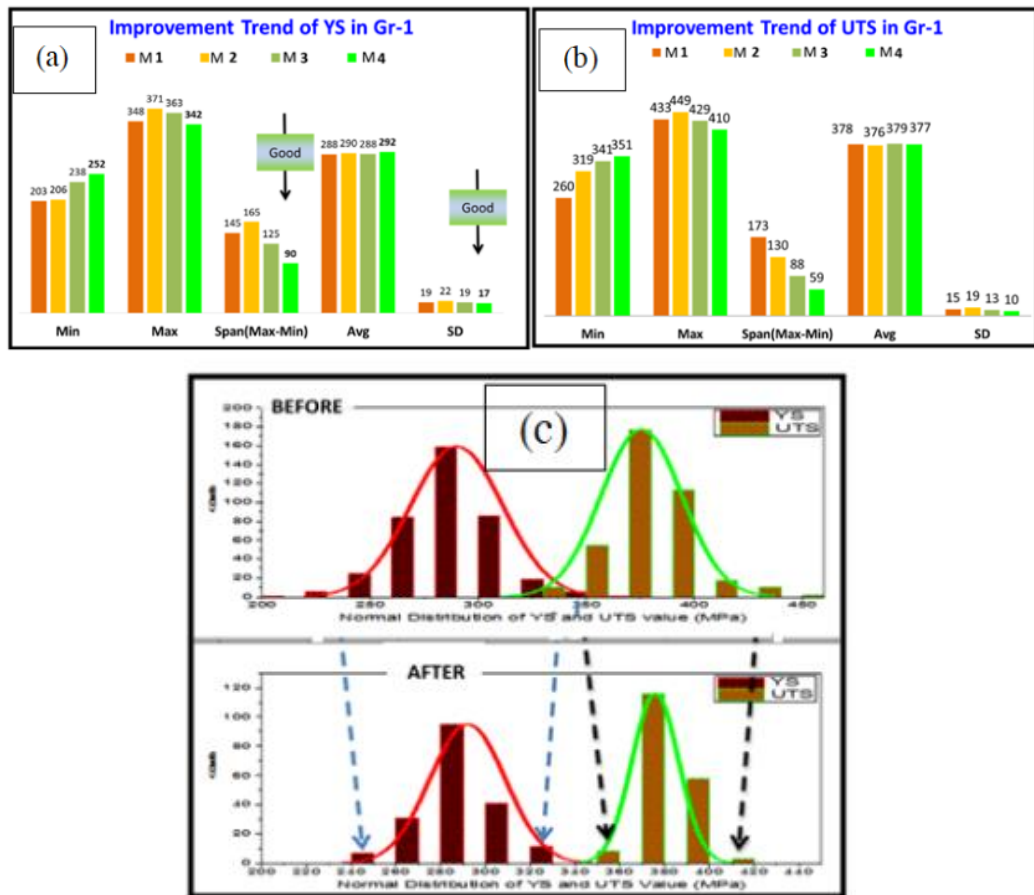


Figure 6: Month wise variation in mechanical properties before (M1, M2 & M3) and after (M4) implementation of the dynamic process control in a grade of low carbon steel shows the improvement in (a) YS, (b) UTS and (c) the histogram of the variations in YS and UTS.

2.4 Results after Implementation

The implementation of dynamic CT control led to a significant improvement in the consistency of mechanical properties. The span of YS and UTS values for Gr-1 decreased by 48% and 55%, respectively, compared to previous production. This improvement was further validated through run charts and histograms, showcasing the effectiveness of the dynamic control strategy in narrowing property variation and reducing abnormal fluctuations. Figure 6 illustrated the variation of YS and UTS before and after implementation of the dynamic processing at TSCR for a specific grade of steel.

2.5 Conclusion and Way Forward on Dynamic Process Control

This study successfully demonstrated the effectiveness of dynamically controlling coiling temperature based on real-time steel chemistry in minimizing variations and improving the consistency of mechanical properties in hot rolled coils. This novel approach offers significant potential for enhancing product quality, reducing rejections, and optimizing resource utilization within the steel industry.

The success of this work paves the way for wider implementation across various steel

grades and rolling mills. Further research will focus on:

- Extending dynamic process control to other steel grades produced at TSCR and different other Hot Strip Mills.
- Investigating the feasibility of utilizing dynamically adjusted downstream process parameters to process diverted slabs with minor chemical deviations within acceptable limits.
- Exploring the potential of dynamically controlling other critical process parameters like Furnace Heating Temperature and Time, Roughing mill entry and exit temperatures, Reduction in roughing mill and finishing mills, Runout table cooling strategy etc. in addition to FRT, CT for enhanced control and resource optimization.

3. MITIGATING COIL BREAK MARKS FOR ENHANCED SURFACE QUALITY

Coil break marks (CBMs), wrinkles or creases on hot rolled steel sheets, pose a persistent challenge in manufacturing, especially for light draw applications requiring high surface quality. This defect is particularly prevalent in low carbon steels due to the yield point phenomenon, where localized yielding and plastic deformation occur during coiling and uncoiling. CBMs are difficult to remove via

processing or painting, negatively impacting the final product's aesthetics and functionality. Figure 7 shows a typical picture of medium severity coil break marks on the hot rolled coil surface.

Traditionally, expensive cold-rolled steel has been used to circumvent CBM formation in light draw components. This study, however, presents a novel and cost-effective solution: a modified steel chemistry and optimized hot rolling process for low carbon hot strip steel production.

This study presents a novel and cost-effective solution to the persistent problem of coil break marks (CBMs) in low carbon hot strip steel production. Instead of relying on expensive cold-rolled steel to circumvent CBM formation in light draw components, this solution introduces a modified steel chemistry and optimized hot rolling process.

This study on the reduction of coil break mark in low carbon hot rolled steel sheet for light draw applications investigates the effectiveness of minimizing CBM occurrence in low carbon hot rolled steel sheets through two key approaches:

1. **Micro-alloying:** Introducing small amounts of titanium (Ti) and boron (B) into the steel composition.
2. **Process Optimization:** Refining the hot rolling process parameters to mitigate CBM formation.

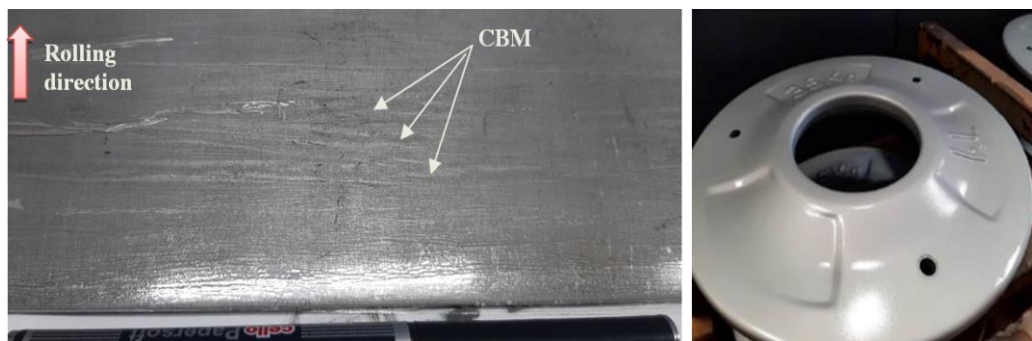


Figure 7: Picture exhibiting CBM perpendicular to the rolling direction (pen for size reference) and an application of these steel in an automotive light draw component

3.1 Methodology

The solution involves micro-alloying the steel with titanium and boron. This, combined with fine-tuned hot rolling parameters, yields CBM-free coils. This approach not only drastically reduces CBM severity but also guarantees the steel meets the IS1079 HR3 mechanical property standards. The effectiveness of this solution is evident in:

1. **Reduction of the tensile flow curve kink below 20 MPa:** This indicates a significant reduction in the yield point phenomenon, the root cause of CBMs.
2. **Formation of a mixed-grain ferrite microstructure:** This contributes to a uniform deformation behaviour, further mitigating CBM formation.

Guided trial production for automotive customers has validated the applicability of this new hot rolled steel grade for light draw applications. This novel steel is being introduced to the market, offering a CBM-free solution without compromising material yield or necessitating the use of costly alternatives like cold-rolled steel. This industrial solution signifies a substantial advancement in low carbon hot strip steel production for demanding automotive applications.

Trial heats were made with modified steel chemistry incorporating small additions of Ti (0.01–0.02 wt%) and B (20–30 ppm). The hot rolling parameters were optimized based on previous trials and theoretical calculations. CBM severity was visually assessed on the

produced coils, and tensile tests were performed to evaluate the mechanical properties and yield point behaviour. Micro-structural analysis was conducted to investigate the effect of the modifications on the ferrite grain size distribution.

3.2 Results and Discussion

CBM Severity: The modified steel composition and optimized hot rolling parameters resulted in a significant reduction of CBM. Visual inspection of the trial coils showed a surface free of visible CBM, as depicted in **Figure 8**.

Mechanical Properties: The added micro-alloying elements and adjusted rolling parameters did not negatively impact the mechanical properties. All measured values remained within the acceptable range specified by IS1079 HR3 for hot rolled steel sheets. And the difference between Upper YS (U_{YS}) and Lower YS (L_{YS}) is within 20 MPa. A typical tensile stress strain diagram from a CBM free coil is shown in **Figure 9**.

Yield Point Behavior: The characteristic kink in the tensile flow curve, representing the difference between the upper and lower yield strengths, was significantly reduced. **Figure 10** shows the tensile test samples without Luder's band marks. This reduction indicates a successful minimization of the yield point phenomenon, which is directly responsible for CBM formation.



Figure 8: Coil Surface Produced Free from CBM (not visible after manual close inspection)

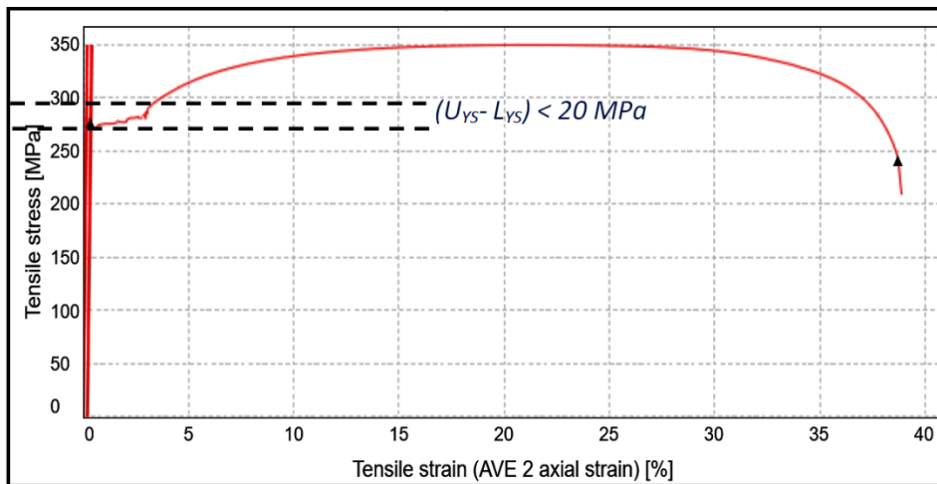


Figure 9: Engineering Stress Strain Diagram from the Tensile Sample of a CBM Free Coil



Figure 10: Pictures of post tensile test samples without Luder's band marks

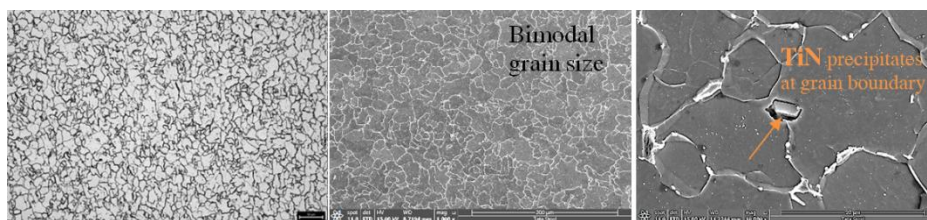


Figure 11: SEM Image of Microstructures of CBM Mark Free Coils at Different Magnifications

Microstructural Analysis: Heterogenous grain structure is obtained by small addition of Ti and B. A small precipitate of TiN formed during reheating restricts some recrystallised grains to grow and a small addition of B lowers the grain boundary energy to delay nucleation/ recrystallization of new grains. Typical microstructures obtained for the CBM mark free coils are shown in **Figure 11**.

3.3 Conclusion and Future Perspective from CBM Free Hot Rolled Coils

The implementation of micro-alloying with Ti and B, combined with the optimization of hot rolling parameters, successfully reduced CBM in low carbon hot rolled steel sheets. The resulting material exhibits:

- A visually CBM-free surface.

- Mechanical properties compliant with relevant standards.
- Reduced yield point elongation, minimizing the driving force for CBM formation.

This new steel, with a refined chemical composition and optimized hot rolling process, could potentially replace some expensive cold-rolled deep drawing steels. The refined process will undergo further evaluation based on valuable feedback from guided trials with automotive customers.

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Evolution of Thermomechanical Controlled Processing (TMCP) of Plates for Ever Growing Critical Applications

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ABSTRACT: Thermo-Mechanical controlled processing (TMCP) is a combination of controlled rolling and controlled cooling which is done to achieve high strength, high toughness and excellent weldability in plates. A general idea in earlier years was to use rolling only to achieve shape and dimensions and achieve metallurgical properties through offline heat treatment. But offline processing had its limitations both in quality and cost, which was the very need for an online process like TMCP. Addition of allowing elements to increase strength especially in High Tensile plates results in decrease in toughness and weldability. As steel plate has emerged as the prominent choice for more critical applications in oil and gas pipelines, offshore structures, high rise buildings, shipbuilding industry etc., it has been a challenge to increase strength without compromising toughness and weldability. This paper is a topical review about evolution of TMCP as the solution to address ever increasing metallurgical requirements in plates. This paper explains basic principles of TMCP through metallurgical concepts on how rolling is performed below T_{nr} temperatures and sometimes in inter-critical region of (Austenite/Ferrite), differences between conventional hot rolling process and TMCP, effect of microalloying elements on critical temperatures (T_{nr} , Ar_3 , Ar_1), solubility relation between C wt% and Microalloying elements wt % and how material property control technologies in plate production has evolved over the years. The paper will go through the basic configuration of Accelerated Cooling control system and chances of distortion in steel plates and its remedies upon treatment. The paper also highlights applications of TMCP steel in various industries such as shipbuilding, offshore structures, building construction, bridges, pipelines and unique property requirements in these areas.

Keywords: TMCP, NG-TMCP, ADCOS.

1. INTRODUCTION

The recent surge in steel demand for critical uses has promoted the requirement of ever evolving alloy design and a technological process aiding to micro-structural control. TMCP is one of such processes which help in achieving optimum properties for critical applications. Moreover, Microalloying elements with accelerated cooling systems manage conflicting requirements of Strength, Toughness and weldability through grain refinement. Higher weldability

is accomplished through lower carbon content or C_{eq} . This reduces the need for preheating before welding thus reducing fabrication costs. Welding is the main fabrication process for shipbuilding, offshore structures, pipelines and building construction.

1.1 History of Property Control in Plates

Strength and toughness in steel plates have traditionally been improved by adding alloys and by heat treatment. But by doing this,

manufacturing cost increases and weldability decreases. Any increases in carbon equivalent also increases the fabrication cost. The first water cooling was done in 1935 by quenching plates after reheating them to 900 deg Celsius which was called reheat quenching [2]. Plate quenching from elevated temperatures was followed by tempering at 600°C which resulted in high strength and tough plates. This method of heat treatment doesn't worry about cooling rate as undeformed austenite is directly quenched to form martensite. Later in 1956 an online process of quenching was commercially available which could easily produce plates of strength 600–800 Mpa [2]. TMCP is a modern-day process which optimizes meticulous addition of micro-alloying elements clubbed with water cooling to achieve properties which was not possible hitherto. Then from 1960s a plethora of research was carried out in determining optimum value of finish Rolling Temperature. Such research resulted in controlled rolling. Controlled rolling helped in reducing alloying elements and increasing weldability by controlling grain growth while rolling. Later from 1970s it was understood that addition of microalloying elements allows controlled rolling to be performed more smoothly and with better strength and toughness of plates.

1.2 Evolution of TMCP: Conventional Hot Rolling

Continuously cast steel was subjected to hot rolling starting at 1200–1300°C after reheating. The deformation by rolling leads to breaking down of original coarse microstructure of austenite by repeated recrystallization. Also, non-metallic inclusions are broken up, deformed and distributed throughout the plate during rolling. Conventional hot rolling, e.g., of pre-World War II C-Mn steels, made little attempt to control the rolling conditions and usually finished in the range 1050–900°C depending on product thickness. Then came concept of achieving

properties through modifications in R, F, T_{nr}, Ar₁ & Ar₃ (R-Roughing Passes, F-Finishing Passes, T_{nr}- is the temperature below which recrystallization doesn't occur., Ar₃ is the temperature during cooling at which austenite begins to transform to ferrite, Ar₁ is the temperature during cooling at which the transformation of austenite to ferrite is complete).

1.3 Evolution of TMCP: Controlled Rolling

Following unfortunate instances of brittle failure of hot rolled plates in ships hulls during the last world war, the 1950s witnessed many attempts to improve toughness, both by changes in steelmaking practices and, more interestingly, by the introduction of what we now call 'controlled rolling'. At that time, it was beginning to be appreciated that the ductile to brittle transition temperature of steel could be greatly improved by the refinement of ferrite (α) grain size. This could be achieved either by the normalizing of aluminium treated steels or by controlled, lower temperature, hot rolling to further refine the austenite at temperatures still above the Ar₃ but down to 800°C. This process plays with variables such as temperature, strain, number of rolling passes, finishing temperature etc. Before the second world war, strength was generated by adding carbon up to 0.4 wt% and Manganese 1.5 wt%. The microstructure was ferrite/pearlite and was lacking toughness properties. Toughness was measured by ductile to brittle transition and it was seen that toughness decreases with increase in carbon content (Also shown in Figure 1).

Finer size of ferrite grains was now the target to increase both strength and toughness. Whereas controlled rolling technology enhances toughness mainly by refinement of the ferrite microstructure, TMCP achieves high strength by utilizing the transformation to ferrite and bainite in addition to enhanced toughness.

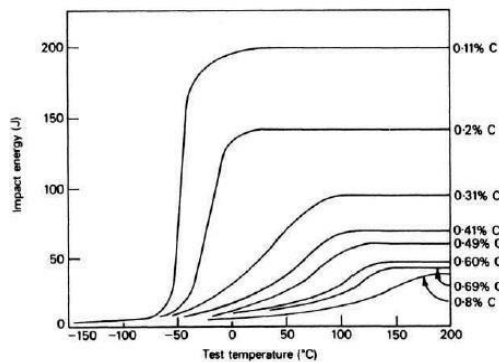


Figure 1: Effects of Carbon Content on Impact Properties [13]

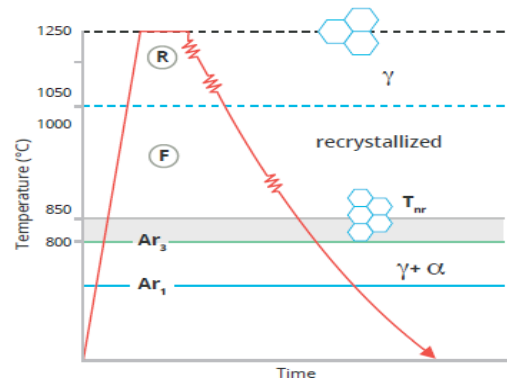


Figure 2: Controlled Rolling of C-Mn Steel [5]

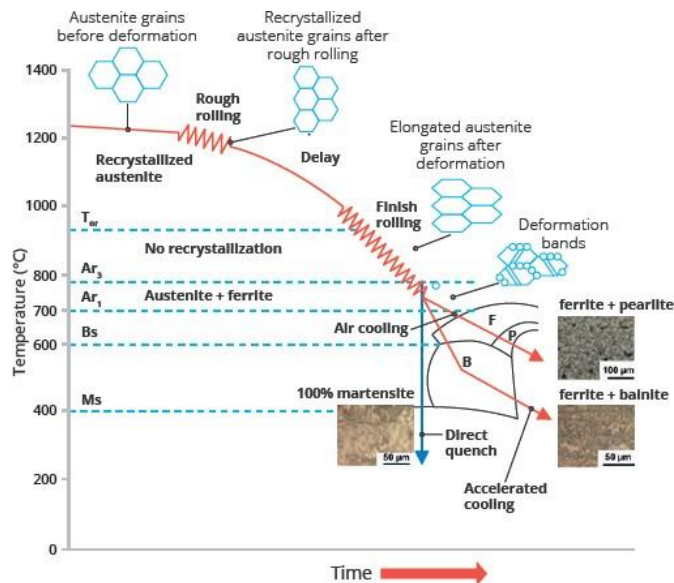


Figure 3: Features of TMCP [5]

1.4 Evolution of TMCP: Thermo-Mechanical Controlled Processing

TMCP has two stages in series which are controlled rolling and subsequent accelerated cooling. Controlled Rolling is done in two stages, first rolling is done in roughing Mill at high temperature and here due to recrystallization grains deform and break into new grains. After Roughing the plate is allowed to cool down at certain intermediate thickness which is around 2–3 times of target thickness also called waiting thickness. Once the plate temperature reaches below T_{nr} but

above Ar_3 the rolling is performed again in finishing Mill. Most of the finishing passes are carried out above Ar_3 but sometimes rolling is also done in the inter-critical region of austenite and ferrite. During Rolling below T_{nr} the austenite grains are elongated into a pancake shape which has ledges and deformation bands. These remain till accelerated cooling starts and the temperature is sufficiently low around 800°C . These bands and ledges are potential nucleating sites for austenite to ferrite transformation and thus aid in grain refinement. It is to be kept in mind that the austenite may

recrystallize several times during a controlled rolling schedule and by the time it reaches Ar_3 the grain has refined several times also. But as the steel reaches T_{nr} , recrystallization doesn't occur, and existing austenite grains only get deformed and elongated.

Once controlled rolling is complete and there are additional nucleating sites for transformation from austenite to ferrite the plate undergoes accelerated cooling. During accelerated cooling the grain growth is further suppressed by a higher cooling rate and grain refinement is achieved. This activity can be further controlled by addition of microalloying elements which form precipitates for grain pinning and controlling slab reheating temperatures to have finer austenite grains in the furnace. This results in good strength and toughness. After the controlled rolling austenite grain growth is further suppressed by rapid cooling from finish rolling temperature which allows Austenite to ferrite transformation to take place sub critically i.e., below Ar_1 . It's a normal practice to keep rolling into fully ferritic regions leading to even finer austenite grains, but this may cause higher load factors in rolling mills. Austenite is continuously recrystallized during

rolling as the temperature drops in roughing passes. The finishing passes are carried out below T_{nr} to avoid recrystallization till Ar_3 and sometimes between Ar_3 and Ar_1 . This results in the creation of additional nucleating sites for austenite to ferrite transformation.

2. EFFECT OF MICRO-ALLOYING ELEMENTS

Introduction of microalloying elements further increases the scope for TMCP. These elements (for example Nb) increase T_{nr} by 100°C [5] and decrease Ar_3 by similar amount approximately. This change impact temperature ranges where deformation and recrystallization can occur now in roughing (1000 – 950°C). Deformation below T_{nr} producing pancaking and more nucleating sites for ferrite. Below Ar_3 recrystallization cannot occur but austenite grains can be flattened and pancaked. The further possibility is to finish rolling in (Austenite Ferrite) region which increases strength and toughness both. Rolling between Ar_3 and Ar_1 is called rolling in intercritical region, and it leads various other issues which is why although rolling is done below T_{nr} but above Ar_3 .

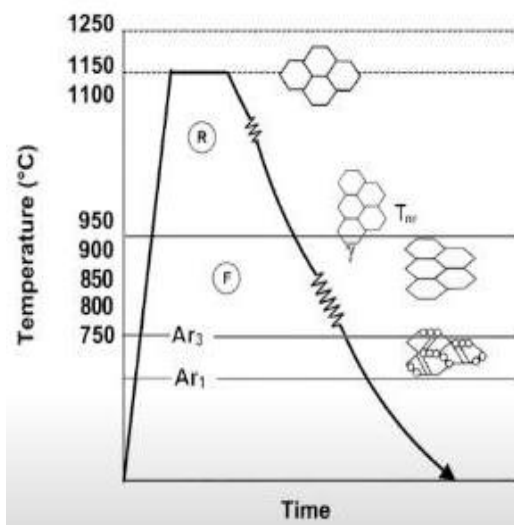


Figure 4: Thermo-mechanical Rolling Intercritical Region [5]

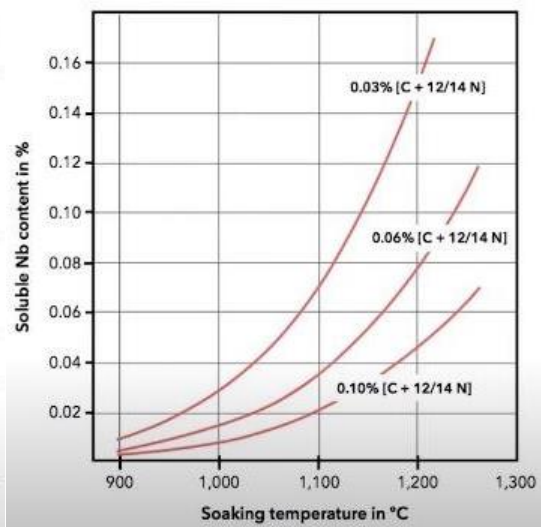


Figure 5: Solubility of Nb vs C wt% [13]

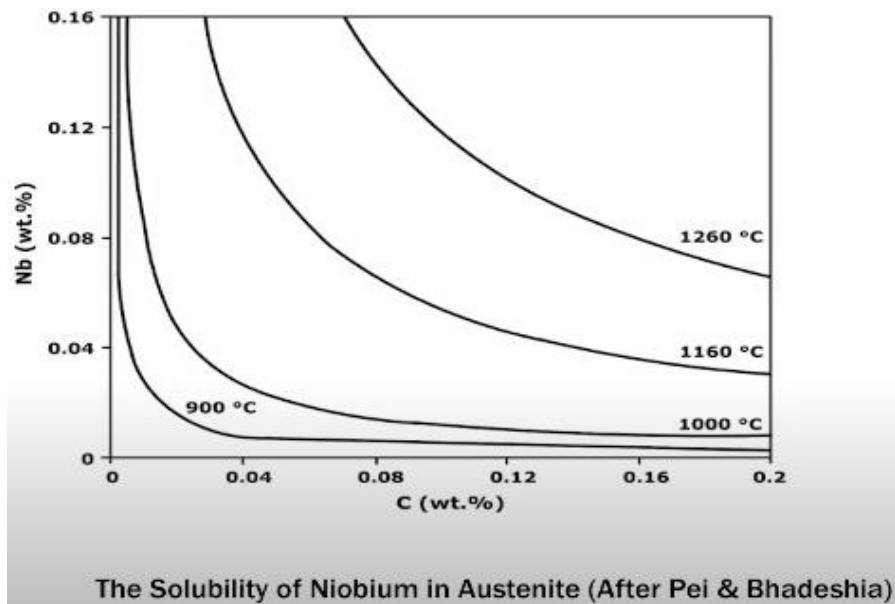


Figure 6: Solubility of Nb at Different Temperatures [13]

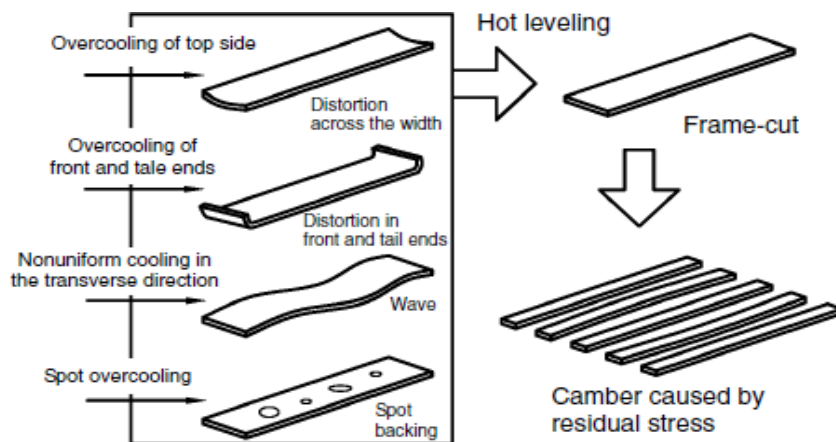


Figure 7: Shape Deformations during Treatment in Accelerated Cooling [1]

Niobium steels can contain maximum up to 0.06 wt% but as per the solubility curve at reheating temperature of around 1250°C for 0.1 wt% carbon steel [13]. But as slab reheating temperature decreases up to 1150°C the solubility decreases up to 0.03 wt%. This must be done through decreasing carbon even more. It is seen that with lower carbon percentages it is possible to add more soluble Nb in steel even up to 0.09 wt% at 1160°C for 0.04 wt % C steel [5]. As more microalloying

element is soluble in steel at reheating temperatures it will help in achieving properties. Combination of low carbon and high Nb allows high finish rolling temperatures with adequate properties for high strength pipeline steels one of the most critical applications. Higher temperature processing avoids need to roll into intercritical region at lower temperatures which results in excessive texturing not good for pipeline steel.

3. EQUIPMENT AND PRODUCTION TECHNOLOGIES FOR TMCP PLATES

There are basically three considerations when we plan for the equipment:

- Equipment should be able to cool the plate uniformly and the cooling arrangement should be controllable.
- Plate treated should be flat after cooling.
- Productivity of the ACC should be high enough to match the rolling rate of the mill.

Currently, accelerated cooling equipment is a continuous type where cooling zones are divided in the direction of plate movement. Here, top and bottom cooling is separately controlled. The focus has been to reach distortion free plates after treatment which basically require sharp control on cooling arrangement. This will result in uniform cooling of plates.

In the above figure some of the defects occurred in plates after cooling. These defects are mainly because of overcooling of both the longitudinal edges and, overcooling of top side, nonuniform cooling in the transverse direction and overcooling of head and tail ends. To control these defects certain features are employed in modern accelerated cooling systems like maintaining proper top and bottom water ratios, Edge masking to cover edges and prevent its overcooling and Head and tail masking to prevent overcooling of head and tail.

Heat transfer and boiling in the water cooling of steel plates are divided into nucleate and film boiling. Nucleate boiling occurs when the cooling water comes in direct contact with the plate surface and heat is transferred with the generation of steam bubbles. In film boiling, a film of steam is formed between the plate surface and the cooling water, and heat is transferred through the film. The cooling capacity in the case of nucleate boiling is known to be higher than that when a

film is formed. When the cooling process starts in the accelerated cooling of steel plates, the plate surface temperature is very high, and thus cooling proceeds under the film-boiling condition. As the surface cools, the steam film becomes unstable and local contact occurs between the cooling water and plate. The boiling mechanism then shifts gradually to the nucleate type, passing through a transition boiling type mechanism, where nucleate boiling and film boiling coexist. Water stagnant on the top surface of plates causes secondary cooling resulting in non-uniformity in properties and hence nowadays it's a trend to keep pre-leveller before accelerated cooling. The target in modern cooling arrangements is to start nucleate boiling as soon as possible to reach an even greater cooling rate and uniform cooling. [2]

Cooling arrangement in TMCP has evolved immensely and is moving towards achieving superior properties and saving energy and resources. The cooling demand has increased to achieve even finer microstructures like bainite which demand very high cooling rates. This has led to series of new development in this area which has been termed as NG-TMCP which also include Ultra-fast cooling and Inter-Pass cooling.

In 1978, JFE was the first company to begin online accelerated cooling at a plate mill. Super-OLAC was developed in 2001. Recent equipment like Super-OLAC developed by JFE steel corporation consist of several headers with closely arranged nozzles to power cool the plate with the aim to start nucleate boiling as soon as possible. The cooling capacity of Super-OLAC was two times more than the conventional cooling from 600°C to 1000°C with uniform cooling throughout the plate. With this equipment JFE was able develop steel for high rise building, pipeline, shipping industry, shipping containers etc. [9] [2] Nippon Steel and Sumitomo Metal also developed a new cooling device called CLC- μ in 2005 with ultra cooling function. Mulpic was

developed by Voestalpine VAI and CRM group for fast cooling of plates [11] [2]. The cooling range was large and adjustable leading to processing of wide variety of thickness and widths of plates. Some of the uniform cooling device parameters like water crown, edge, head and tail masking, and water ratio adjustment were introduced in this system. Also in China, Bao-steel enhanced laminar cooling device by increasing number of nozzles on the upper part, resulting in double water flow on the upper part as compared to ordinary laminar cooling device. It is indicated that such device can reach cooling rate up to 200°C on a 3mm thick strip in hot strip mill. POSCO in South Korea also developed their own ultra-fast cooling device HDC (High density cooling) [2].

3.1 Advanced Cooling Systems (ADCOS)

Uniformity of cooling has been the bottleneck for development of further grades through TMCP. The inclined jet cooling technology was adopted in ADCOS system for hot strips and plates instead of conventional laminar cooling.

In this ultra-fast cooling systems, slit nozzles and high-density nozzle arrangement has the jet pattern which can break through the vapor film initially formed to the hot steel surface under a certain pressure and turn heat transfer into effective nucleate boiling and forced convection, accordingly, leading to achieve the goal of faster effective heat transfer.



Figure 8: Inclined Jet Pattern in ADCOS [1]

The cooling capacity of ADCOS system is more than 2 times of conventional laminar cooling and cooling through a large temperature range can be easily controlled. Maximum cooling rates for steel plates of thickness 10 mm and 50 mm can be as high as 120°C and 10°C respectively [1].

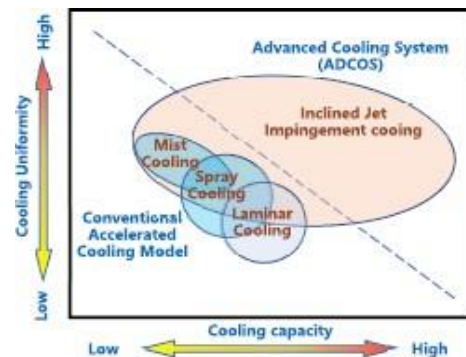


Figure 9: Efficiency of ADCOS over Other Cooling Systems [1]

The cooling capacity reflects the intensity or power of the cooling, including important parameters such as water pressure and flow density, and the most important performance of cooling capacity is the water-cooling rate. Currently, inclined jet and laminar cooling are the most widely used cooling methods in industrial applications. Due to technical indicators of industrial production, the maximum water pressure of the inclined jet cooling is up to 0.5 MPa, while the laminar cooling is ≤ 0.2 MPa. The flow density range of inclined jet and laminar cooling is 0–1 666 L/ (min·m²) and 0– 952 L/(min·m²), respectively. The cooling rate depends on factors such as plate thickness and water temperature, and the range of inclined jet and laminar cooling is 0–120°C/s and 0–60°C/s, respectively. Inclined jet cooling is more uniform which results in good flatness in steel plate. [1].

3.2 NG-TMCP (New Generation)

It is being developed with the core technology of Ultra-fast cooling. NG-TMCP can be

combined with high deformation and strain accumulation in continuous rolling without the requirement for high reduction in the lower finish rolling temperature. This allows high strength in steels without addition of alloys also termed nowadays as green strengthening. NG-TMCP is a breakthrough technology basically based on grain size control, precipitation control and phase transformation control.

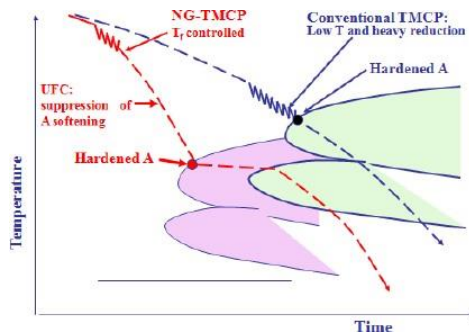


Figure 10: Faster Cooling Rates in NG-TMCP [1]

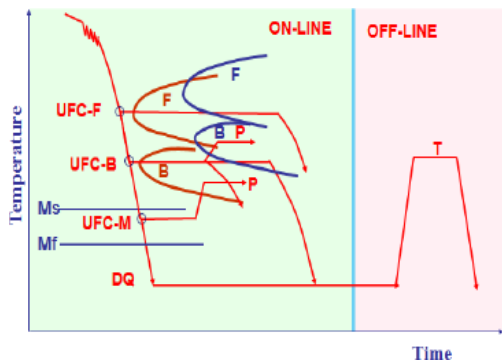


Figure 11: Ultra- Fast Cooling Technology [1]

For C-Mn steels with low alloy, stable fine grains can be obtained by directly reaching higher cooling rates with the help of advanced cooling systems as shown in the figure below. NG-TMCP with ultra-fast cooling technology can properly increase FRT and cooling rate after rolling which inhibit strain induced precipitation during hot rolling and keep more micro alloys into ferrite or bainite transformation region. This is done to optimise carbide precipitation process window.

In phase transformational control, ultra-fast cooling rate can inhibit austenite transformation at higher temperatures.

At-present Ultra-fast cooled Ferrite, Bainite and Martensite has been developed through precise control. These processes have been applied to production of low-cost alloy steel, high grade pipeline steel, engineering machinery steel, abrasion resistant steel and high-quality Quench & Partitioning (Q&P) steel. [1]

3.3 Rolling and Inter-Pass Cooling Technology

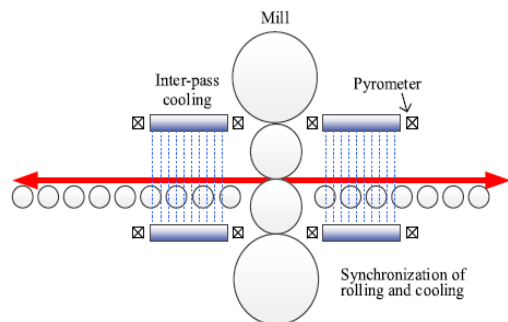


Figure 12: Inter-pass Cooling Technology [1]

Coordination and control of reduction and temperature is the core-technology for hot rolling process. Inter pass cooling of slab allows cooling of slabs between passes to control temperature of the slab. The rolling-cooling synchronous technology has obvious advantages for increasing deformation penetration and development of fine grain structure on the surface of steel plates. Water cooling amid rolling creates temperature gradient through the slab thickness. Slab surface is cooler, and deformation of surface is harder. Nowadays, rolling with inter-pass cooling technology has been applied to Nanjing Steel 5 000 mm, Tangshan Steel 3 500 mm and Shagang Group 3500 mm, and the internal deformation of heavy plate can be enhanced for improving quality [1].

Inter pass cooling technology is characterized by the accelerated cooling during rolling

followed by controlled rolling which is a reheating process. Ferrite grains are refined by their recovering and recrystallizing due to highly accumulated dislocations through hot deformation and increased ferrite nucleation by reheating supercooled austenite owing to the sufficient driving force for austenite to ferrite transformation.

4. TMCP PLATES FOR CRITICAL APPLICATIONS

There are many applications which require high strength plates but with lower carbon content which improves weldability and optimize the fabrication cost. They are listed below:

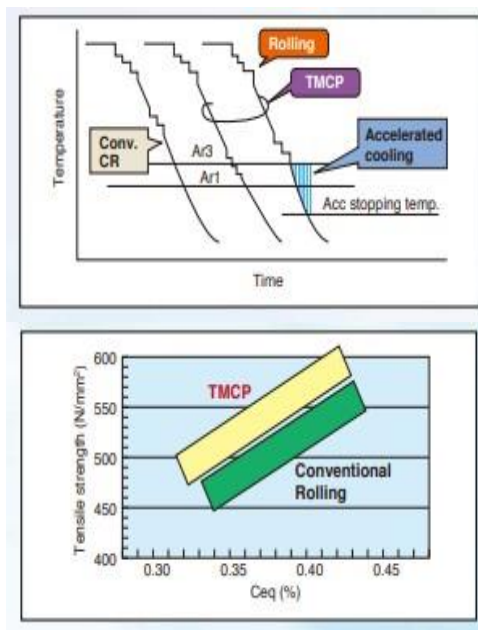


Figure 13: Superior Properties with Lower Ceq of TMCP Plates [7]

4.1 TMCP Steel Plates for Oil and Gas Pipelines

One of the most extensive applications of TMCP is in conveyance of natural gas and oil where lower C content is a great advantage. As the need of larger diameter pipes has grown, steels of higher yield stress

must be used to avoid excessive wall thicknesses.

Specific properties for carrying oil and gas pipelines are:

- High Strength with good weldability- Fine Bainitic structure is achieved which increases the strength and since Ceq is very low weldability is very good.
- Homogeneity in properties due to uniform laminar cooling in accelerated cooling system. Grades- X70, X80 etc.

4.2 TMCP Steel Plates for Shipbuilding



Increasing life of aging ships which face corrosion and fatigue and decreasing their life cycle cost has been the major focus of this shipbuilding industry. In the initial stages of TMCP development shipbuilding grades of YS390 Mpa were developed during 1980s to decrease the weight of manufactured ships. This was done together with lower Carbon equivalent which reduced welding costs as large heat input for welding decreased. Recently conditions for marine transportation have become harsher with the requirement for reduction of fuel consumption. As the upscaling of container ships tends to encourage the use of thicker steel materials, this required development of even higher strength steel plates around YS460 Mpa. [8]

From safety point of view against brittle failure of steel plates and welded structures, brittle crack arrest toughness is also demanded in the strength decks of large-scale container ships using heavy steel plates of thickness 50 mm–60 mm which must be produced through TMCP. [8]

4.3 TMCP Steel Plates for High Rise Buildings

Modern high-rise buildings are longer spanned and have more complex structures. High strength heavy steel plates are required for these applications. As far as earthquake resistance is considered a material which has low yield ratio (Yield strength/Tensile Strength), high toughness and good weldability is preferred.

Higher strength steel plates for building structures and frequently used in box section columns, and high efficiency submerged arc welding or electro-slag welding is applied in these assemblies. Since these welding methods are large heat input welding processes superior weldability properties are always desired.

Table 1: Grades for High Rise Building Developed by JFE [12]

Grade	Thickness (mm)	YS (MPa)	TS (MPa)	YR (%)	vE ₀ (J)
HBL™ 325	40 ≤ t ≤ 100	325–445	490–610	≤ 80	≥ 27
HBL™ 355	40 ≤ t ≤ 100	355–475	520–640	≤ 80	≥ 27
HBL™ 385L HBL™ 385	12 ≤ t ≤ 19 19 ≤ t ≤ 100	385–505	550–670	≤ 80	≥ 70
HBL™ 440	19 ≤ t ≤ 100	440–540	590–740	≤ 80	≥ 70
HBL™ 630L	12 ≤ t ≤ 40	630–750	780–930	≤ 85	≥ 70

YS: Yield strength TS: Tensile strength
YR: Yield ratio vE: Absorbed energy

TMCP steel plates of grade HBL 630 L developed by JFE were recently used in columns of Shinjuku Toho building [12].

Given below are high rise building grades developed by JFE:

5. CONCLUSION

This paper has reviewed how our evolving needs have shaped demand for futuristic steels. TMCP has evolved as a potent answer to our growing needs. We investigated the evolution of TMCP mainly after world war-II. We also touched on how online cooling

arrangement together with microalloying additions is modifying the microstructure in steel plates.

This paper has reviewed equipment used for online accelerated cooling and the changes it had in past years to address uniform cooling, fast cooling issues and shape problems. There have been advances in the field of Advance cooling systems and Inter-pass cooling to even expand the working area of TMCP nowadays known as NG-TMCP. (New Generation).

It is evident from the review that all our growing need is basically focused upon weight reduction, Life cycle cost reduction and fabrication time and energy reduction which all can be addressed through TMCP.

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SECTION-III

Cold Rolling and Coating Technology

Microstructure and Texture Evaluation of Nb-microalloyed Cold Rolled and Annealed Steel

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ABSTRACT: *HSLA steels increase strength primarily by micro-alloying elements contributing to fine carbide precipitation and grain-size refinement. These steels are used in body-in-white and increased in service load application components.*

The present paper described the development of low carbon batch annealed HSLA steel sheet having excellent formability with minimum anisotropy ratio of 1.2, tensile strength more than 440 MPa. The critical consideration during processing of this steel grade includes the hot coiling temperature, cold rolling reduction, and optimizing the hot & cold spot temperature in batch annealing furnace in 100% hydrogen atmosphere. Texture evaluation has been carried out at different stages of processing of steel and γ -Fibre, which is responsible for formability characteristics of cold rolled sheets, have been prominently observed in all the annealing condition. Inverse pole figure shows {101} planes are predominant in hot rolled samples and {111} planes are predominant in cold rolled, annealed condition. This steel grade has been successfully developed at Bokaro Steel Plant and under supply to various auto makers.

Keywords: Cold Rolled Annealed Steel, HSLA Steel, γ -Fibre, Texture.

1. INTRODUCTION

India has emerged as an Auto hub for the world with all the major international auto giants setting up their auto manufacturing facilities in India, targeting not only the Indian but also the Global market. Indian steel producers have come up with advanced steel making and processing facilities to meet the stringent requirement of cold rolled steel.

High strength steels increase strength primarily by micro-alloying elements contributing to fine carbide precipitation, substitutional and interstitial strengthening, and grain-size refinement. These steels are used in body-in-white and increased in service load application components.

In the quest for fuel economy, automobile manufacturers needed to reduce weight and

this translated to reduced thickness of steel sheets. This led to the explosive growth in the use of higher and higher strength steels for the manufacture of automobiles. Their applications can be broadly classified into: outer body panels and body-in-white parts. In the case of outer body panels, the major driver is weight reduction. This translates to more formable steels for manufacture of complex- design parts as well as part consolidation. In addition, reduction of gauge for weight savings has led to the use of high strength steels.

Recent high requirement for vehicle lightening in the automobile sector requirement flat carbon steel manufacturers to develop advanced newer grades of materials which are capable of fulfilling the gradually more stringent technical demand of

market (Figure 1). For this, the steel industries /automobile industries are regularly trying to produce newer kinds of steels with superior properties (Figure 2). HSLA steel is one of such kind which is having high strength, high elongation, high hardness and toughness. Low Carbon steel can be produced at a minimum cost by applying with carbon and manganese with add it in to micro-alloying elements like Nb, Ti & V. Separately from the positive economic impact, the superior mechanical properties were obtained by applying these two elements^[1]. Application

and merit/demerit of HSLA cold rolled steel are given in Table 1.

HSLA steels increase strength primarily by micro-alloying elements contributing to fine carbide precipitation, substitutional and interstitial strengthening, and grain-size refinement. These steels are used in body-in-white and increased in service load application components (Figure 2). A small amount i.e. 0.01% of titanium, vanadium, and niobium added for alloy formation resulting in increase of the yield point to 240–370 MPa and the tensile strength to 350–490MPa^[2].

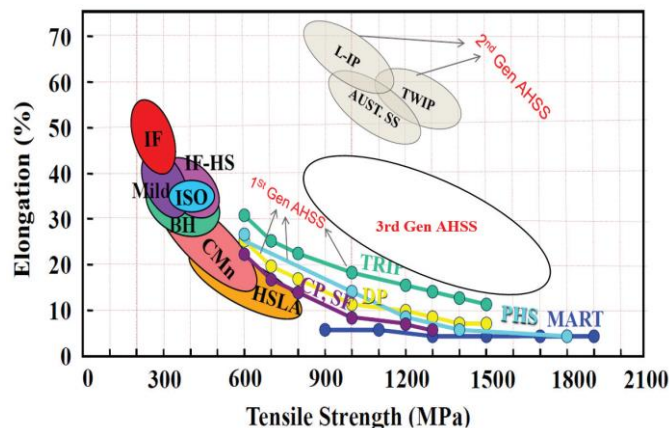


Figure 1: Ductility – Strength Relationship of Auto Grade Steels

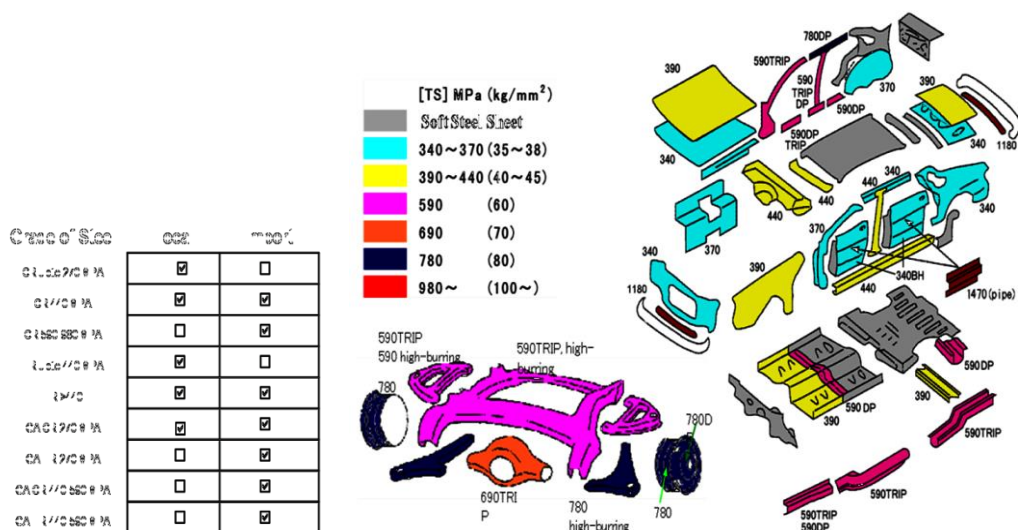


Figure 2: Typical Sourcing Pattern of Maruti Suzuki India Limited^[3]

Table 1: HSLA Cold Rolled Steel Application

<i>Product</i>	<i>Advantages</i>	<i>Dis-advantages</i>	<i>Best Applications</i>
High Strength C-Mn & HSLA Grade	• More uniform, less spring-back • Good Fatigue • Good weldability	Low formability	CAR/ Commercial vehicle: Front & Rear Rails, Pillars Multi Joining Members, Frame part
			Two wheeler & Three wheeler: frame part, handle rod & chasis parts

Table 2: IS 513:2016 (Part-2) HSLA Quality Grade Steel

<i>Grade</i>	<i>C</i>	<i>Mn</i>	<i>P</i>	<i>S</i>	<i>YS, MPa</i>	<i>UTS, MPa</i>	<i>% El min</i>
ISC410LA	0.12	1.50	0.030	0.025	340–420	410 min	21%

1.1 Indian Standards for High Strength Cold Rolled Grade

The Indian Standard IS 513: 2016 (Part-2) covers the requirements of cold reduced carbon steel sheets and strips for cold forming and drawing purpose and where the surface is of prime importance (Table 2). It covers sheets and strips up to 4.0 mm thick both in coil form and cut lengths.

The steel can be made with micro alloying elements like Chromium, Nickel, Niobium, Vanadium, Titanium, Molybdenum, Boron, Calcium and others, either added individually or in combination.

Microalloying additions to C-Mn steels for the automotive industry are mainly Ti and Nb (V is used mostly for non automotive applications)^[4]. The role of microalloying elements in cold rolled sheet is similar to that in hot strip material, i.e., providing grain refinement and precipitation hardening. However, owing to the recrystallization annealing process following the cold rolling operation, the absolute strength level is remarkably lower than in thermo-mechanically processed hot strip steel of the same chemical composition^[5]. As in typical hot strip alloy design, HSLA sheets preferably apply the microalloying element niobium acting mainly via grain refinement^[6]. For higher strength sheet the combination of

niobium plus titanium is often applied together with higher additions of solid solution hardening elements since the strength increasing effect of niobium alone is not sufficient to guarantee a higher yield strength than 350 MPa economically.

1.2 Hydrogen batch Annealing

Cold rolled steels are usually annealed to relieve internal stresses, soften the steel, develop new texture and improve mechanical properties such as formability, drawability and ductility. Two different principal annealing processes are normally employed, batch (or box) annealing and continuous annealing. Despite the advantages of continuous annealing, batch annealing is still widely used in industry.

Compared to conventional HNX batch annealing, greater heating and cooling rates are achieved with hydrogen batch annealing, coincident with a more uniform temperature distribution throughout the coils being annealed. Hydrogen gas has a thermal conductivity approximately seven times that of conventional nitrogen based annealing atmospheres. Pure hydrogen gas also has a greater reducing potential than conventional nitrogen based annealing atmosphere. Product quality benefits arrived at through the use of hydrogen batch annealing relative

to conventional batch annealing include improved uniformity of mechanical properties, improved surface cleanliness and the elimination of nitriding during batch annealing^[7].

On annealing, the excess dislocations arrange into lower energy configurations in the form of regular arrays or low angle grain boundaries (LAGBs). According to the Read-Shockley equation^[8], the energy of a tilt boundary increases with increasing mis-orientation and the energy per dislocation decreases with increasing mis-orientation. Therefore, there is a driving force to form fewer, more highly mis-oriented boundaries as recovery proceeds.

In recrystallization, a set of new grains formed. New crystals appear at points of high lattice strain energy such as slip-line intersections, deformation twin intersections, and in areas close to grain boundaries. The microstructure at any time is divided into recrystallized or non-recrystallized regions, and the fraction recrystallized increases from 0 to 1 as the transformation proceeds. To study the progress of recrystallization, many methods to quantify recrystallization fraction have been used. Some traditional methods are such as optical microscopy (OM), scanning electron microscopy (SEM).

Grain growth is the process involving the migration of grain boundaries when the driving force for migration is solely the reduction of the total grain boundary energy. Coarsening can take place by either 'normal' grain growth, whose main mechanism is the disappearance of the smallest grains in the distribution, or 'abnormal' grain growth.

1.3 The Effects of Different Alloy Additions on the Annealing Behavior

The chemical elements niobium, titanium and vanadium are very effective as microalloying additions in steel, influencing

the microstructure by both a solute drag effect and the formation of nitrides and carbides precipitates. Precipitation could be formed during cooling or formed during or after rolling between about 1000°C and 900°C that correspond to a commonly used temperature range for the completion of the hot rolling process. Precipitation during cooling is not likely to be significant, since precipitation in recrystallized austenite is normally very sluggish. Precipitation during or after rolling is the strain induced precipitation which could produce marked retardation of recrystallization. The precipitation of Nb-carbonitrides in ferrite is widely used in steels, especially for two main applications: for low solute contents (IF steels), the precipitation of NbC improves the drawability by removing C and N atoms out of solid solution^[9]; for higher solute contents (HSLA grades), the precipitation of Nb-carbonitrides provides important precipitation hardening^[10]. Dissolved niobium produces the largest effect on retarding recrystallization in comparison with any other microalloying elements. Solubility of carbonitrides at low temperatures in the austenitic range is very limited, practically precluding precipitation strengthening.

The effects of titanium on microstructure are strongly dependent on the amount of titanium added. Addition of a small amount of titanium produces titanium nitrides, TiN, having extremely limited solubility. The extremely stable titanium nitride practically does not dissolve at the soaking temperature, thus precluding any solid solution effect of titanium on recrystallization. The stability of the titanium nitride also precludes any noticeable strain inducement. The recrystallization kinetics of steels with additions of up to 0.04 wt% titanium is similar to those of plain carbon steel.

2. MATERIAL AND EXPERIMENT

Heat for experimental grade was made in 300 t converter (No-2, SMS-2) at BSL with following Chemistry (Table 3).

Table 3: Heat Chemistry of Experimental Steel (wt%)

<i>C</i>	<i>Mn</i>	<i>P</i>	<i>S</i>	<i>Si</i>	<i>Al</i>	<i>Nb</i>	<i>Ti</i>	<i>N</i>
0.087	1.02	0.015	0.005	0.227	0.039	0.022	Nil	45

Table 4: PLTCM Process Parameter during Cold Rolling of Experimental Steel

	<i>S1</i>	<i>S2</i>	<i>S3</i>	<i>S4</i>	<i>S5</i>
Entry: 3.78 mm	2.847 mm	2.069 mm	2.069 mm	1.730 mm	1.50 mm
Reduction %	24.3%	27.3%	0%	16.4%	13.3%
Max Load (MN)	13.39	14.89	By pass	13.98	6.53

Table 5: Annealing Cycle of CR Coils

<i>SI</i>	<i>CRM Coil ID</i>	<i>Hot Spot</i> (°C)	<i>Cold Spot</i> (°C)
1.	FD0189BPAO	690	640
2.	FD0196BPAO	680	630
3.	FD0190BPAO	650	630
4.	FD0191BPAO	640	620
5.	FD0192BPAO	640	620
6.	FD0194BPAO	640	620
7.	FD0194BPXO	640	620
8.	FD0195BPAO	640	620

After annealing, 1-2% reduction has been given at skin pass mill, CRM-3, BSL.

The heat was casted in caster-1 with casting speed 1.1 mtr/min. The slab size was 220 × 1320 mm. As carbon in the heat was above 0.08%, so, medium carbon grade casting powder was utilized with medium level-II cooling pattern.

All 8 slabs were hot rolled in 3.8 mm thickness with 1280 mm width. The finishing temperature was kept around 880 ± 15°C and coiling temperature was 630±18°C. All 8 coils were transferred to CRM-3, BSL for cold rolling and annealing. All HR Coils are cold rolled into 1.5 mm × 1252 mm size. The % reduction and load during cold rolling at PLTCM is given in Table 4.

As this high strength grade steel was first time processed at CRM-3, BSL, first coil was batch Annealed with temperature as per CR-2 Cycle i.e. Hot spot 690°C & cold spot 640°C.

After mechanical property evaluation, annealing cycle was modified and the annealing cycle given to coils are shown in Table 5.

3. RESULTS AND DISCUSSION

3.1 Mechanical Properties

Total 8 coils are cold rolled and annealed in 4 different annealing cycles. Cold rolled and batch annealed coils were characterized in terms of yield, ultimate tensile, percentage elongation and hardness values. One coil was annealed with keeping hot spot temperature at 690°C & cold spot temperature at 640°C. To evaluate the difference in mechanical properties between hot rolled and cold rolled & batch annealed condition, tensile tests & other mechanical characterization were conducted and the results are shown in Tables 6–8.

Table 6: Hot Band Strength of Experimental Heat

<i>HR Coil No</i>	<i>YS, MPa</i>	<i>UTS, MPa</i>	<i>% El</i>	<i>Hardness</i>
N483479	440	540	34 %	85 (HRB)

Table 7: Cold Rolled Un-annealed Strength of Experimental Heat

<i>CR Coil No</i>	<i>YS, MPa</i>	<i>UTS, MPa</i>	<i>% El</i>	<i>Hardness</i>
FD0189BPAO	Not detected	931	4 %	99 (HRB)

Table 8: Final Achieved Mechanical Properties of Experimental Heat

<i>SN</i>	<i>SPM Coil ID</i>	<i>YS, MPa</i>	<i>UTS, MPa</i>	<i>Cupping</i>	<i>r-bar</i>	<i>Hardness</i>	<i>% El</i>
1.	A56232	315	401	12.7	1.206	66	35
2.	A56868	323	407	12.8	1.268	64	33
3.	A57342	268	427	13.4	1.45	65	35
4.	A59694	266	446	—	—	69	32
5.	A59693	265	447	—	—	67	32
6.	A59695	268	456	12.5	1.260	66	32
7.	A59692	265	453	—	—	66	30
8.	A59691	270	443	—	—	67	30

3.2 Microstructure Analysis

Microstructure evaluation have been carried out for hot rolled, cold rolled- un annealed

coil and cold rolled-annealed coils. The microstructures are given in below (Figure 3).

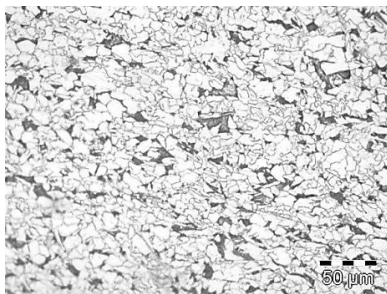


Fig. 3(a)

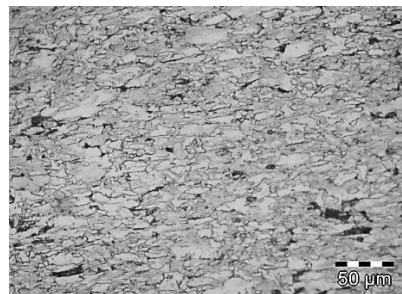


Fig. 3(b)



Fig. 3(c)



Fig. 3(d)

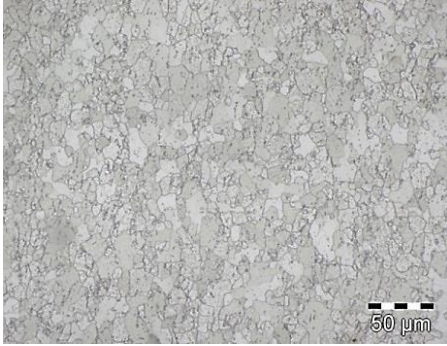


Fig. 3(e)

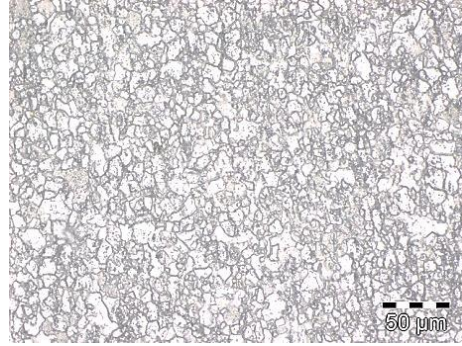


Fig. 3(f)

Figure 3: Optical Microstructure of (a) Hot Rolled (b) Coil Rolled-without annealing (c) Cold rolled and Annealed (HS 690°C & CS 640°C) (d) Cold rolled and Annealed (HS 680°C & CS 630°C) (e) Cold rolled and Annealed (HS 650°C & CS 630°C) (f) Cold rolled and Annealed (HS 640°C & CS 620°C) (all are in x500 magnification)

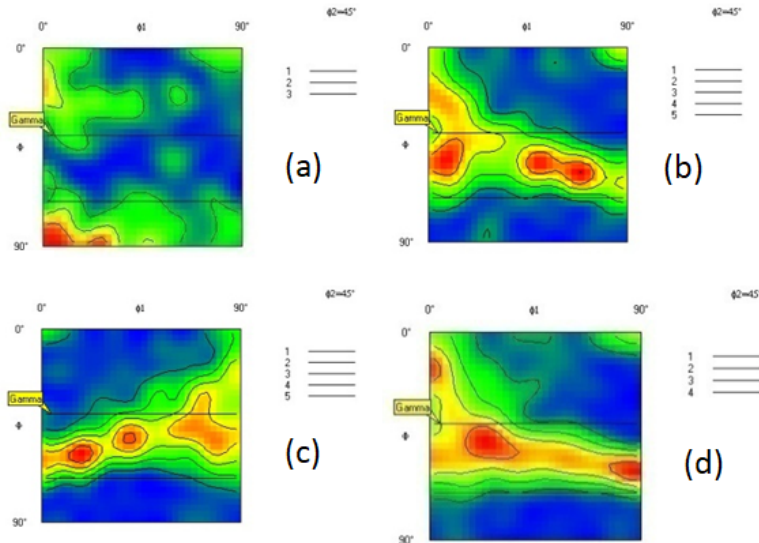


Figure 4: Mapping of γ -Fibre in (a) HR Coil (b) CR Coil-un-annealed (c) CR-Annealed (HS:690°C–CS:640°C) & (d) CR-Annealed (HS:640°C–CS:620°C)

3.3 Texture Analysis

Formability is important property of ISC390W/ISC440W grade steel which is attributed to the texture development during thermo-mechanical processing particularly during hot rolling and cold rolling. The texture of hot rolled, cold rolled and cold rolled annealed coils samples were analyzed using Zeiss EVO MA 10 model scanning electron microscope. A rectangular grid is

used and the step size (pixel spacing) is 4 μ m. The microscope is operated at 20KeV. The most important fibre in the texture of steel is the γ - fibre since it directly gives an idea about the formability of steels. Development of recrystallization texture in this high strength cold-rolled Nb-bearing steel was investigated and analyzed using the channel V data collection analysis software. The γ -fibre mapping is shown in Figure 4.

Grain size distribution in the matrix is mapped and shown in Figure 5 as distribution function (area fraction ($f_y(x)$) Vs grain diameter (μm).

Textures are represented on an inverse pole figure (Figure 6) which shows the distribution of crystallographic directions parallel to certain directions.

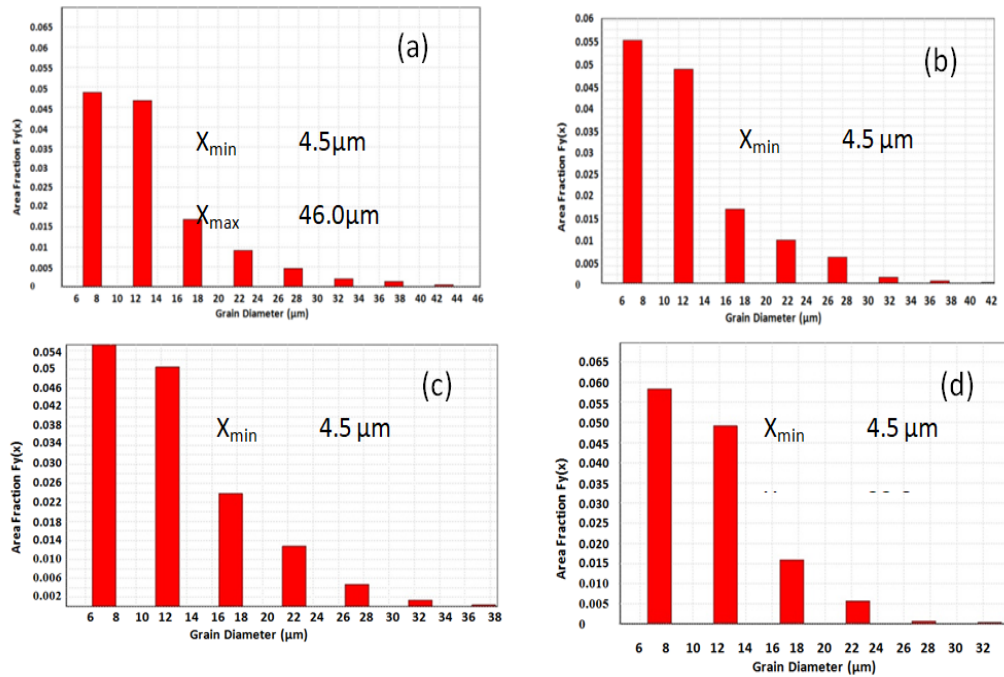


Figure 5: Grain Size Distribution (a) HR Coil (b) CR Coil-un-annealed (c) CR-Annealed (HS:690°C–CS:640°C) & (d) CR-Annealed (HS:640°C–CS:620°C)

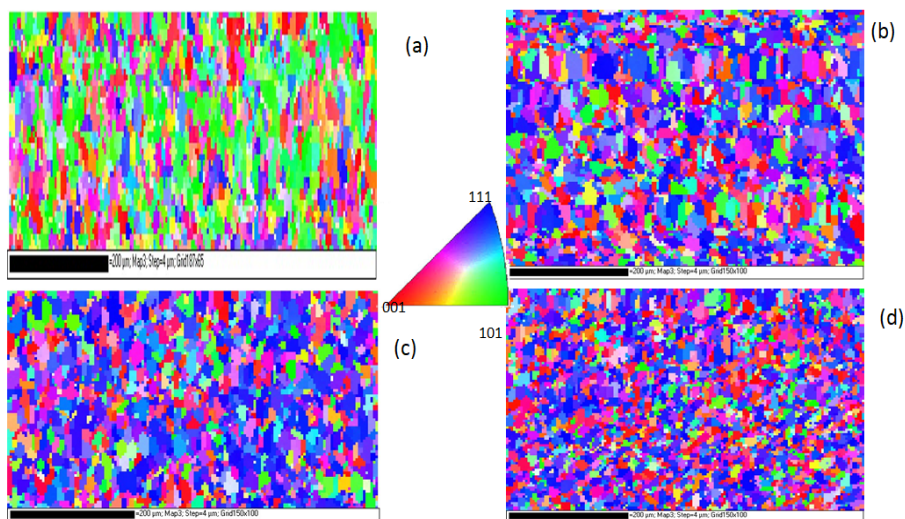


Figure 6: IPF Mapping (a) HR Coil (b) CR Coil-un-annealed (c) CR-Annealed (HS:690°C–CS:640°C) & (d) CR-Annealed (HS:640°C–CS:620°C)

The extent of recrystallization in deformed and annealed samples is determined by recrystallization fraction mapping (Figure 7).

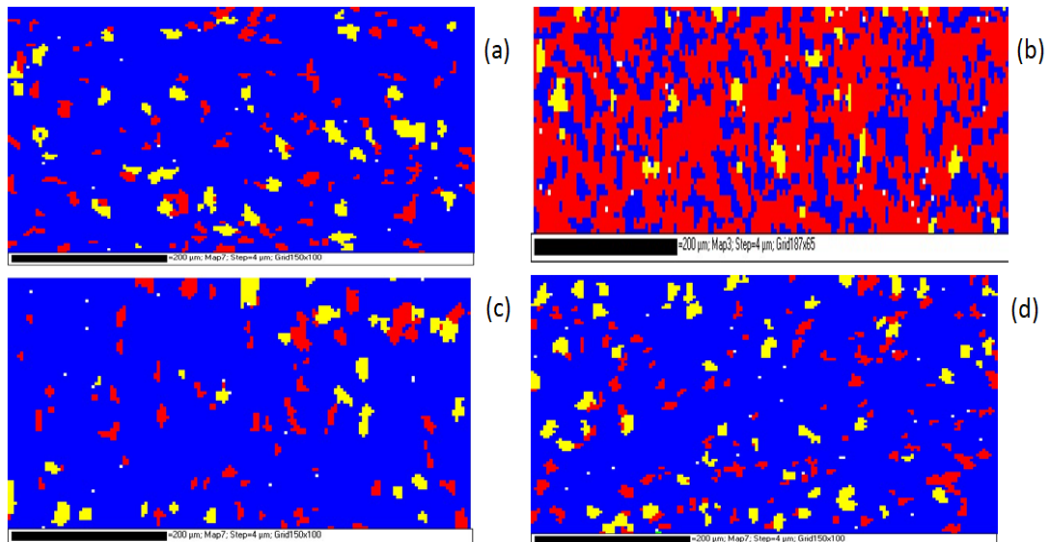


Figure 7: Recrystallization fraction (a) HR Coil (b) CR Coil-un-annealed (c) CR-Annealed (HS:690°C–CS:640°C) & (d) CR-Annealed (HS:640°C–CS:620°C)

Table 9: Recrystallization Grains, Deformed Grains and Sub-structured Grain Data

<i>Sample Condition</i>	<i>Recrystallized Grains</i>	<i>Deformed Grains</i>	<i>Sub-structured</i>
Hot Rolled	88.3%	6.3%	5.4%
Cold Rolled-Unannealed	34.5%	61.5%	4.0%
Cold Rolled & Annealed (HS:690°C–CS:640°C)	90.8%	5.2%	4.0%
Cold Rolled & Annealed (HS:640°C–CS:620°C)	81.3%	12.7%	6.0%

4. DISCUSSION

The extent of recrystallization in hot rolled, cold rolled and cold rolled-annealed samples have been determined by various methods such as optical metallography, and by using EBSD.

The hot band structure shows a very fine grain size having ASTM no around 10.5 with very well developed equiaxed Ferrite grain with little pearlitic structure in optical microscope. In un-annealed cold rolled sample shows a elongated grains. Grains coarsening occurred in cold rolled-annealed at higher temperature. In the annealing

temperature 690–640°C the grain size is bigger than the coil have annealed at 680–630°C, or 650–630°C temperature. In the annealing temperature 640–620°C, the microstructure shows an more equiaxed in nature, compared to other annealed samples. EBSD data analysis also confirmed the grain size distribution. The minimum grain size in all the cases are 4.5 μm. The largest grain was observed in hot rolled sample (46 μm). Largest grains in coil annealed at HS 640°C–CS 620°C is 33.8 μm. Grains coarsening during annealing at HS 690°C–CS 640°C has been observed and grain size fraction in between 16–18 μm is more compared to other

cycle. Also more than 80% recrystallization has been achieved in all the annealing condition and tabulated Table 9.

γ -Fibre, which is responsible for formability characteristics of cold rolled sheets, have been prominently observed in all the annealing condition. Inverse pole figure shows {101} planes are predominant in hot rolled samples and {111} planes are predominant in cold rolled, annealed samples.

Table 10: Crystallographic System Fraction

	(332)<113>	(112)<110>
Hot rolled	4.44%	9.16%
Cold rolled	22.4%	26.8%
Annealed (690–640°C)	21.9%	4.19%
Annealed (640–620°C)	22.4%	22.4%

These two components are responsible for development good tensile and yield strengths. Considering the drop of 70–80 MPa strength in cold rolled annealed coil, the alloy was designed to get hot band strength more than 520 MPa. Hot band strength of the material was achieved 540 MPa. During annealing at higher temperature i.e. HS: 690°C & CS: 640°C, the drop of UTS was more than 130 MPa. Also the hardness was dropped to 66 HRB. To get a mechanical property confirming to ISC440 W, the annealing cycle modified for next coils. The first 3 coils confirmed to the grade ISC390 W. However, the properties required for IS specification of grade ISC440 W, was achieved in 5 coils which have been annealed at HS: 640°C–CS: 620°C.

5. CONCLUSION

- Alloy designed for the grades ISC410LA utilizing principle of solid solution strengthening with fine ferrite grain and precipitate hardening.

- Nb-added high strength cold rolled steel is suitable to annealed in temperature having hot spot 640°C & cold spot 620°C. In this temperature range more than 80% grain recrystallized during batch annealing
- Structure property correlation established in high strength low carbon microalloyed steel with different annealing cycle with respect to microstructure evolution and mechanical properties.

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Advancements in Coated Steel Technologies: A Chronological Review

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ABSTRACT: Coated steel technologies have undergone remarkable evolution since the 19th century, with significant advancements in corrosion resistance, mechanical performance, and environmental sustainability. This paper provides a comprehensive chronological review of these advancements, tracing the history from early galvanizing processes to modern, high-performance coatings such as Zn-Al-Mg (ZAM) alloys and organic systems like pre-painted galvanized iron (PPGI) and pre-painted galvalume (PPGL). This paper provides a chronological review of advancements in coated steel technologies, tracing their evolution from the 19th-century invention of galvanizing to modern innovations such as Zn-Al-Mg (ZAM) alloys and organic coatings like PPGI and PPGL. Starting with the development of zinc-based coatings for corrosion protection, the review highlights key milestones, including the introduction of galvanized and galvalume coatings, which improved corrosion resistance, adhesion, and durability. Over time, innovations such as ZAM coatings have further enhanced performance, particularly in harsh environments like marine and industrial settings. Additionally, the paper explores the growing significance of organic coatings, which offer aesthetic and functional benefits, particularly in construction and architecture. Recent advances in eco-friendly coatings, such as low-VOC and bio-based systems, respond to increasing environmental regulations, while emerging trends in smart coatings, such as self-healing and nano-enhanced systems, promise to extend the lifespan of coated steel. By synthesizing insights from over 150 recent studies, this review presents a comprehensive look at the technological progress in coated steel and offers insights into future directions for smart, sustainable, and high-performance coatings. The chronological approach provides a clear understanding of how historical developments have shaped the future of steel protection.

Keywords: Coated Steel Technologies, Galvanizing, Galvalume, Zinc-Aluminum-Magnesium (ZAM) Alloys, Advanced Corrosion Resistance.

1. INTRODUCTION

Steel, one of the most versatile and essential materials in modern industry, owes much of its widespread adoption to its ability to resist corrosion when properly coated. From the mid-19th century when French engineer Stanislas Sorel first introduced galvanizing by dipping steel in molten zinc, to today's highly advanced, multi-layered, and alloyed coatings, the evolution of coated steel technologies has

been driven by the need for both durability and adaptability across a range of harsh environments [1].

Initially, steel faced rapid degradation in outdoor or marine environments due to the corrosive effects of water and air. However, the discovery that zinc could act as a sacrificial layer, protecting the underlying steel from rust, revolutionized the longevity of steel products. Over the years, the industry has built upon this principle, advancing

through alloy compositions and sophisticated application techniques to ensure better performance in more aggressive conditions [2].

This paper explores the chronological development of these technologies, focusing on major milestones such as the advent of galvanizing, the innovations that led to the development of galvanized and galvalume coatings, and more recent breakthroughs such as Zn-Al-Mg (ZAM) coatings. Each of these advancements not only extended the service life of steel but also enhanced its mechanical properties, leading to greater efficiency in automotive, construction, and marine applications [3,4].

As global industries become more reliant on high-performance materials, the demand for smart and eco-friendly coatings continues to rise. Today's cutting-edge research into self-

healing and nano-enhanced coatings represents the future of steel protection, promising to not only extend the lifespan of steel products but also reduce the environmental impact of production and maintenance [5].

In this review, we will examine over 150 recent studies that have charted the course of these advancements. By adopting a chronological approach, we aim to show how these innovations have been shaped by technological breakthroughs and industry demands, and how future trends are set to further revolutionize the coated steel industry. Table-1 classifies the works read, reviewed and used in formulating this manuscript. Remaining part of the manuscript is organized as per the classification detailed in Table 1.

Table 1: Summary of Classifications of the Chronological Review

<i>Classification</i>	<i>Description</i>	<i>Key Features</i>	<i>Applications</i>
Galvanized Coatings	Zinc coating applied to steel for corrosion resistance.	Sacrificial protection, uniform coating, cost-effective.	Construction, automotive, general infrastructure
Galvalume Coatings	Zinc-aluminum alloy (55% aluminum) providing enhanced corrosion resistance.	Barrier protection (aluminum), sacrificial protection (zinc), long-lasting in humid/saltwater environments.	Roofing, cladding, marine environments
Galvanized Coatings	Heat-treated zinc-iron alloy coating, ideal for paint adhesion and welding.	Excellent weldability, high corrosion resistance, good surface for painting.	Automotive panels, appliance manufacturing
Organic Coatings (PPGI, PPGL)	Pre-painted galvanized or galvalume steel offering aesthetic and functional protection.	Aesthetic appeal, UV resistance, customizable colors and finishes, scratch resistance.	Architecture, roofing, exterior applications
Zn-Al-Mg (ZAM) Coatings	Advanced zinc-aluminum-magnesium alloy coatings with superior corrosion resistance.	Enhanced corrosion resistance, self-healing properties, long-term performance in aggressive environments.	Marine, automotive, industrial infrastructure
Emerging Technologies	Smart and eco-friendly coatings, including self-healing and low-VOC or bio-based systems.	Self-healing, nano-enhanced properties, eco-friendly formulations, low environmental impact.	Marine, aerospace, renewable energy, automotive

2. THE EVOLUTION OF GALVANIZED COATINGS

2.1 Early Developments: From Discovery to Industrialization

The earliest known use of zinc to protect steel dates back to the 1830s, when galvanizing was patented as a method to coat steel with a layer of zinc, primarily as a means to prevent rusting in hostile environments [17]. This method, though simple, provided a remarkable improvement in steel's resistance to corrosion, particularly in humid or coastal areas where untreated steel would degrade rapidly [18].

The science behind galvanizing rests on the electrochemical properties of zinc. Zinc acts as a sacrificial anode, corroding in preference to the steel beneath it. This process not only forms a protective barrier but also offers cathodic protection by preventing rust even if the surface coating is damaged. This discovery paved the way for the widespread industrial use of galvanized steel in construction and infrastructure during the late 19th and early 20th centuries [19, 20].

However, the basic hot-dip process, though revolutionary, was not without its limitations. Researchers quickly realized that improving the composition of the zinc bath, and controlling the thickness of the zinc layer, would be key to enhancing the longevity and performance of galvanized coatings. By the 1960s, the addition of elements like aluminum and magnesium had started to become commonplace, leading to better adhesion, increased corrosion resistance, and a more aesthetically pleasing finish [21, 22].

2.2 Continuous Galvanizing: Efficiency and Innovation

The rise of continuous galvanizing lines (CGL) during the mid-20th century marked a pivotal shift in steel production, enabling manufacturers to produce large volumes of

galvanized steel efficiently and consistently [23]. By running steel sheets through a molten zinc bath, followed by rapid cooling and controlled wiping of excess zinc, CGLs were able to produce galvanized coatings with uniform thickness and better surface properties [24, 25].

These advances were especially significant for the automotive industry, where consistency in coating thickness and surface quality are essential for performance and aesthetics. Researchers in this period focused heavily on refining the wiping technology—such as nitrogen wiping systems—to control zinc coating thickness down to precise micron levels [26, 27].

In recent decades, continuous galvanizing has evolved further. Innovations such as in-line annealing, zinc bath alloying (with aluminum and magnesium), and the introduction of advanced sensors to monitor and control bath composition and wiping speeds have transformed the industry. These technological improvements have reduced the variability of the coating process, increased production speed, and significantly enhanced the protective properties of galvanized steel [28].

3. GALVALUME AND GALVANNEALED COATINGS

3.1 Galvalume: A Game Changer for Harsh Environments

Introduced in the early 1970s, galvalume coatings were designed to provide superior protection in highly corrosive environments, particularly those involving high humidity and saltwater exposure [42]. The alloy composition of galvalume, typically a mixture of 55% aluminum, 43.4% zinc, and 1.6% silicon, provides a unique combination of barrier protection (through the aluminum) and sacrificial protection (through the zinc) [43].

Research has demonstrated that galvalume-coated steel can last up to three times longer than traditional galvanized steel in marine environments, making it ideal for roofing and cladding in coastal and industrial settings [44, 45]. Recent studies have focused on further refining the composition of galvalume coatings, with the aim of enhancing their performance in highly aggressive environments. For example, the incorporation of trace elements such as silicon has been shown to improve the adhesion of the coating and prevent delamination under thermal stress [46, 47].

3.2 Galvannealed Steel: Strength and Weldability

While galvalume was revolutionizing the roofing and construction industries, galvannealed steel was quickly becoming the material of choice in the automotive sector [53]. Developed in the 1930s, galvannealed coatings result from heating galvanized steel to induce a reaction between the zinc and the steel substrate, forming a zinc-iron alloy [54]. The resulting coating provides not only excellent corrosion protection but also superior adhesion for paint and other surface treatments.

Galvannealed steel offers a unique combination of strength, corrosion resistance, and weldability, making it ideal for use in automotive body panels and other applications requiring formability and surface treatment [55, 56]. Modern advancements in galvannealed coatings have focused on controlling the alloying process to produce coatings with consistent thickness, improved surface quality, and enhanced mechanical properties [57].

In addition, studies have demonstrated that controlling the furnace atmosphere and cooling rates during production can significantly improve the uniformity of the Fe-Zn alloy layer, resulting in coatings that are more durable and easier to work with in high-stress applications [58, 59].

4. ADVANCES IN ORGANIC COATINGS: PPGI AND PPGL

4.1 Aesthetic and Functional Breakthroughs

The development of organic coatings, particularly pre-painted galvanized iron (PPGI) and pre-painted galvalume (PPGL), has added a new dimension to coated steel technologies. These products combine the corrosion-resistant properties of galvanized or galvalume coatings with the aesthetic and functional benefits of organic paints, making them a popular choice in architectural applications [67, 68].

PPGI and PPGL are highly customizable, allowing for a wide range of colors and finishes. This has made them a go-to material for roofing, cladding, and other exterior applications, where both appearance and performance are critical [69]. However, these coatings offer more than just good looks—recent innovations have significantly improved their durability. New formulations of organic coatings have been designed to enhance scratch resistance, UV protection, and corrosion resistance, making them suitable for use in more aggressive environments [70, 71].

4.2 Sustainable Alternatives

In response to growing environmental concerns, the coatings industry has made significant strides in developing eco-friendly alternatives to traditional organic coatings. Recent studies have focused on reducing the volatile organic compound (VOC) content of PPGI and PPGL coatings through the use of low-VOC binders and resins [73, 74]. Researchers have also developed bio-based coatings, which offer the same level of performance as traditional coatings but with a reduced environmental impact [75, 76].

One of the most promising innovations in this field has been the incorporation of

nanoparticles into organic coatings. These nano-enhanced coatings not only offer better mechanical properties but also provide additional protection against UV radiation and corrosion, further extending the lifespan of coated steel products [77, 78].

5. ZN-AL-MG (ZAM) COATINGS: THE NEW FRONTIER

5.1 Performance Beyond Traditional Coatings

ZAM coatings represent one of the most significant advancements in steel protection technology in recent years. By combining zinc, aluminum, and magnesium, ZAM coatings provide a level of corrosion resistance that far surpasses traditional galvanized or galvalume coatings [86]. Studies have shown that ZAM coatings can offer up to 20 times the corrosion resistance of standard galvanized coatings in salt-spray tests, making them an ideal solution for marine and industrial applications [87-89].

The presence of magnesium in ZAM coatings plays a critical role in their superior performance. Magnesium helps to form a stable, dense oxide layer on the surface of the coating, which acts as a barrier to corrosion. This oxide layer also has self-healing properties, allowing the coating to repair itself when scratched or damaged, further extending its service life [90-92].

5.2 Real-World Applications

ZAM coatings have been rapidly adopted in a variety of industries, including automotive, construction, and marine engineering. Their ability to provide long-term protection in harsh environments makes them particularly valuable in applications where maintenance is difficult or costly [93, 94]. Recent studies have also explored the potential of ZAM coatings to improve the sustainability of steel

products by reducing the frequency of maintenance and extending the overall lifespan of coated materials [95, 96].

Researchers are now focusing on optimizing the production process for ZAM coatings, with the aim of reducing costs and further enhancing their performance in extreme environments [97]. As industries continue to demand higher-performing materials with lower environmental impacts, ZAM coatings are likely to become a mainstay in the coated steel market [98-100].

5.3 Emerging Research on Alloy Optimization

Recent studies have focused on optimizing the composition of ZAM coatings by adjusting the ratios of zinc, aluminum, and magnesium to enhance their performance further. Research has shown that higher magnesium content can improve the corrosion resistance in harsh marine environments, as well as enhance the self-healing properties of the oxide layer [126]. Studies on the micro-structural evolution of ZAM coatings during heat treatment have revealed that the addition of magnesium leads to a denser, more uniform oxide layer, significantly improving the material's longevity in aggressive environments [127].

Additionally, researchers have investigated the impact of varying aluminum content on the mechanical properties of ZAM coatings. It has been found that fine-tuning the aluminum concentration can improve both the coating's corrosion resistance and its resistance to deformation under mechanical stress, making it particularly suitable for automotive and industrial applications [128]. Advances in nanoparticle incorporation have further boosted ZAM's performance, as nanoparticles help create a more compact and robust protective layer that enhances resistance to environmental wear [129, 130].

6. EMERGING TRENDS: SMART AND ECO-FRIENDLY COATINGS

6.1 The Future of Self-Healing Coatings : Applications of Nano-Technology

In the race to extend the lifespan and reduce the maintenance of steel products, researchers have turned to smart coatings that can autonomously repair themselves when damaged. These self-healing coatings contain microcapsules filled with healing agents that are released when the coating is scratched or worn, effectively sealing the damaged area and preventing further corrosion [104-106].

Recent developments in self-healing technology have focused on improving the efficiency and durability of these coatings. Studies have shown that incorporating nanoparticles into self-healing coatings can enhance their mechanical strength and speed up the healing process [107-109]. While self-healing coatings are still in the early stages of commercial development, their potential to revolutionize steel protection is undeniable [110].

The potential of nanoparticle-enhanced coatings, particularly in ZAM and organic coatings, continues to show promise. Recent work has demonstrated that adding nano-structured materials into traditional coatings can result in increased scratch resistance and anti-corrosion properties, particularly for steel used in high-wear industrial environments [131]. Furthermore, the use of nanotechnology in coatings has opened up opportunities for developing multifunctional coatings that not only protect steel but also provide additional benefits, such as self-cleaning or antibacterial properties, which are essential for applications in sectors such as healthcare and food processing [132, 133].

Recent research has also shown that self-healing coatings, especially those integrated

with nano-capsules containing healing agents, are increasingly capable of extending the service life of coated steel in demanding environments. These coatings can autonomously repair minor damage, such as scratches or cracks, thereby restoring the protective layer without requiring external intervention [134]. This innovation, particularly when combined with advanced ZAM alloys, offers the potential for reducing long-term maintenance costs in industries such as marine, aerospace, and energy infrastructure [135].

6.2 Eco-Friendly Solutions for a Sustainable Future

As environmental regulations become more stringent, the need for eco-friendly coating solutions has never been greater. Researchers are exploring a range of new materials and processes designed to reduce the environmental impact of steel coatings, from low-VOC and bio-based coatings to coatings that minimize energy consumption during production [117-120].

In addition to reducing emissions, eco-friendly coatings offer the potential for greater sustainability through improved durability. By extending the lifespan of steel products, these coatings can reduce the overall consumption of raw materials and energy, helping industries achieve their sustainability goals [121-125]. Researchers are exploring bio-based resins and low-VOC formulations that still meet the high-performance requirements of industries relying on coated steel [136]. For instance, the development of low-VOC coatings for automotive and architectural applications has led to the adoption of more sustainable practices, without compromising on the longevity and durability of the coatings [137].

The future of eco-friendly coatings also lies in the integration of renewable materials, such as biopolymers, which are derived from

natural sources and offer lower environmental impact than traditional petrochemical-based coatings [138, 139]. These advances align with global efforts to reduce the carbon footprint of industrial activities, contributing to more sustainable manufacturing processes [140].

7. CONCLUSION

The journey of coated steel technologies, from the early days of basic zinc-dipped steel to today's advanced multi-layered and alloyed systems, reflects an ongoing story of innovation, driven by both necessity and ingenuity. What began as a rudimentary process to protect steel from rust has evolved into a highly sophisticated domain of material science, where the balance between corrosion resistance, mechanical strength, aesthetics, and environmental sustainability continues to redefine industry standards.

In the past, the introduction of galvanizing in the 19th century was nothing short of revolutionary. By leveraging the sacrificial properties of zinc, engineers could finally protect steel from the elements, drastically extending its useful life. This period laid the groundwork for the widespread industrial applications of galvanized steel in everything from infrastructure to automotive manufacturing. As industries grew, so too did the demands placed on steel, prompting researchers to look for ways to enhance the basic zinc coating with the addition of elements like aluminum and magnesium, leading to the development of technologies like galvalume and galvanealed steel. These advancements catered to emerging sectors that required steel capable of enduring harsher environments and more complex processing.

In the present, coated steel technologies have reached unprecedented levels of sophistication. Continuous galvanizing lines now produce millions of tons of steel annually with remarkable consistency and precision. Zinc-

aluminum-magnesium (ZAM) coatings have pushed the boundaries of corrosion resistance, offering self-healing properties that were once considered the stuff of science fiction. The rise of organic coatings, such as PPGI and PPGL, has allowed coated steel to transcend its traditional utilitarian roles, integrating aesthetics with functionality to meet the needs of modern architecture and design. Furthermore, the industry's response to environmental concerns has spurred the development of low-VOC and bio-based coatings, showcasing a commitment to sustainability without compromising performance.

Yet, the future holds even greater promise. The next frontier lies in smart coatings—systems capable of self-repairing, adjusting to environmental changes, and even interacting with their surroundings to provide real-time data on their condition. Nanotechnology, which is already enhancing the mechanical properties of today's coatings, will likely play a central role in creating these next-generation solutions. Researchers are also exploring eco-friendly materials that not only reduce the environmental footprint of steel production but actively contribute to a circular economy. The goal is no longer just to protect steel but to imbue it with new functionalities that can enhance its performance across a wider range of applications.

As industries worldwide face new challenges—from the need for sustainable materials to the demand for longer-lasting infrastructure—the role of coated steel will continue to expand. The innovations of the past have provided the foundation, and the advancements of today are setting the stage for a future where steel, enhanced by cutting-edge coating technologies, remains a material of choice in a changing world. The blend of durability, adaptability, and sustainability will be the hallmark of coated steel's next chapter, ensuring it remains at the forefront of global industry for generations to come.

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SECTION-IV
Energy and Environment
Control in Steel Plant

Enhancing RE Power Generation and Captive Utilization in SAIL Towards Greener Steel

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ABSTRACT: *The manufacturing of iron and steel, though imminent for the development and growth of the nation, is a highly polluting process. A number of mitigation efforts are being taken to reduce the impact of the manufacturing processes on the environment. As the industry requires bulk power, sourced from coal, there has been a perceptible shift towards renewable energy (RE) generation and utilization in the industry.*

Steel Authority of India Limited (SAIL) has identified its power requirements till 2029–30 on account of proposed expansion and modernization of plants at Bokaro, Burnpur and Durgapur. In line with the Ministry of Power trajectory for Renewable Purchase Obligation (RPO) for fossil-fuel based captive power generation by 2029–30, the roadmap for RPO compliance through RE power generation and utilization has been finalized.

SAIL, through an Integrated Plan of Action is enhancing its RE generation for captive utilization. From an installed capacity of 12.91 MWp as of August 2024, SAIL has begun expanding its RE power generation and utilization capacity by installing ground-mounted, floating and roof top solar units across its plants/units. Salem Steel Plant also procures 12 MW bagasse-based power during the sugarcane crushing season through power exchange. Broadly, projects up to 10 MW capacity are being installed across SAIL through own CAPEX. Projects above 10 MW capacity are being executed through JV company NTPC-SAIL Power Co. Ltd. Proposal for 100 MW Solar Power from Solar Engineering Corporation of India for Bokaro Steel Plant is being submitted for SAIL Board approval. Damodar Valley Corporation, the grid utility of SAIL plants at Durgapur and Burnpur has confirmed supply of 50% of the grid power requirement of the two plants as Green Power with effect from 1st of September 2024.

RE power is poised to contribute its bit towards decarbonization of the steel-making process in SAIL.

1. INTRODUCTION

When the founding fathers of newly independent India laid out the blueprint for its development, self-sufficiency in manufacturing of essential products and services like education, healthcare, power, engineering, metals, agriculture, irrigation, highways and ports, etc. was considered an important area for the public sector to venture into. Though private players had already ventured into some of these areas, India was

largely dependent on imports to cater to the requirements of an aspirational nation and its growing population. Centuries of colonial rule had crippled many sectors of the economy. This required government intervention in a big way. As part of this thrust, three integrated steel plants were set up with foreign collaboration at Bhilai, Durgapur, and Rourkela.

As the nation and its requirement grew, so did the demand for the products and services mentioned above. Steel being an important

component of the infrastructure and manufacturing sectors, too expanded with first the government and subsequently post-liberalization, the private sector jumped in the fray.

The manufacturing of iron and steel is a highly polluting process. With climate change caused by rapid industrialization, mitigation efforts have received attention as all the industries attempt decarbonization. Steel industry too has devised a blueprint for reducing carbon emissions inherent to the prevalent technology that is carbon-centric. A number of mitigation efforts are being taken to reduce the impact of the manufacturing processes on the environment. Leading manufacturers in the iron and steel sector are trying to shift to technologies like direct reduction which do not require the use of coal in the production process.

The production of iron and steel requires bulk as well as reliable power, given the hazardous nature of the manufacturing processes. Hence, in addition to the power from the grid, integrated steel plants also have their own captive power plants for catering to the most critical Category-I loads. The process gases released in the chain of production units may be hazardous on the one hand, but are also the source of energy which is utilized in reheating furnaces and

cogeneration of power for captive utilization. With operations at high temperatures all along the production chain and a network of process gases criss-crossing the plant premises, reliable power supply is a must.

2. SAIL POWER CONSUMPTION IN FY 23–24

The power consumption of Steel Authority of India Limited (SAIL) is approx. 1450 MW. This includes power sourced from the grid as well as captive power plants. Table 1 gives an overview of the power consumption in SAIL plants in FY 23–24 vis-à-vis the key production parameters.

Approx. 65% of the total power requirement of SAIL generated at its CPPs – operated by SAIL or its JV partners NTPC-SAIL Power Co. Ltd. (NSPCL) and Bokaro Power Supply Co. Ltd. (BPSCL – JV with Damodar Valley Corporation). Thus SAIL relies heavily on bulk power from conventional sources. This is largely due to the nature of loads in an integrated steel plant which require reliable bulk power. SAIL also procures conventional as well as renewable power through Open Access. 15 MW captive power from PP-3, Bhilai is also wheeled to SSP under the Open Access regime.

Table 1: SAIL Power Consumption – FY 23–24

Plant	FY 2023–24 Production (in MT)			FY 2023–24 Power Consumption (in MW)		
	HM	CS	SS	Captive Generation	Grid Drawl	Total
BSP	5.985	5.675	5.228	339.61	34.40	374.01
DSP	2.570	2.305	2.206	110.98	61.25	172.23
RSP	4.494	4.161	4.211	268.57	69.62*	338.19
BSL	4.726	4.309	3.991	145.88	164.44	310.32
ISP	2.721	2.529	2.410	49.09	101.79	150.88
5 ISPs	20.496	18.979	18.046	926.18	431.50	1,345.63
SAIL (TOTAL) – incl. Spl. Steel Plants **						1,421.86

* incl. 4.34 MW Conventional Exchange Power procured by RSP in FY 23–24;

** Spl. Steel Plants: 76.23 MW {SSP (29.34 MW), VISL (1.11 MW), CFP (45.78 MW)}

The CPPs are of two types – coal-based and cogeneration units (commissioned under the previous MODEX at BSP, RSP and ISP). However, none of the upcoming CPP units at SAIL ISPs are coal-based. All new CPPs under the upcoming expansion and modernization have process-gas based units. This includes Top Recovery Turbo-Generators with new Blast Furnaces, power/steam generation from Coke Dry Quenching units with the new coke ovens, and process gas based Steam Turbo-Generators at all Integrated Steel Plants (ISPs).

3.1 SAIL Power Consumption in FY 30–31

Post-modernization by 2030–31, as the crude steel production capacity increases from

18.979 MT PA in FY 23–24 to 32.10 MT PA in 2030–31, the power consumption of SAIL is estimated to increase to approx. 2350 MW {refer Table 2}. These figures have been arrived at after referring to the Detailed Project Reports of the proposed Expansion & Modernization of the plants. As no expansion is proposed at the Special Steel Plants, hence it is assumed that there power requirement shall be the same as in FY 23–24.

SAIL shall also be retiring older CPP units viz., Old Power Plant at DSP (average generation: 4–5 MW), and 3 x 12 MW units at Power & Blowing Station-1 of BSP. Simultaneously, in line with statutory environmental compliance norms, Dry Sorbent Injection (DSI)/Flue Gas Desulphurization (FGD) systems are being installed at our JV CPPs by NSPCL/BPSCL.

Table 2: SAIL Power Consumption – FY 30–31

<i>Plant</i>	<i>Production Plan by 2030–31 MT PA</i>	<i>Power Requirement by 2030–31MW</i>		
	<i>CS</i>	<i>Captive Generation. (incl. JV)</i>	<i>Grid Drawl</i>	<i>Total Power Reqd.</i>
BSP	6.80	277	203*	480
DSP	6.09	75	357	432
RSP	5.20	325	44	369
BSL	7.03	390	109	499
ISP	6.98	130	366	496
SAIL-ISPs	32.10	1197	1079	2276
SAIL Total (incl. Spl. Steel Plants (considering same production level))				2352

* Proposed 40 MW RE RTC Power from power exchange for Township included.

Table 3: Renewable Purchase Obligation up to FY 29–20

<i>Captive Units Commissioned in Year</i>	<i>WIND (%)</i>	<i>HPO (%)</i>	<i>Others* (%)</i>	<i>Total RPO (%)</i>
2023–24	1.60	0.66	24.81	27.08
2024–25	2.46	1.08	26.37	29.91
2025–26	3.36	1.48	28.17	33.01
2026–27	4.29	1.80	29.86	35.95
2027–28	5.23	2.15	31.43	38.81
2028–29	6.16	2.51	32.69	41.36
2029–30	6.94	2.82	33.57	43.33

* Others includes Solar.

4. RENEWABLE PURCHASE OBLIGATION TRAJECTORY UP TO 2029–30

The Ministry of Power, Government of India vide Gazette Notification dated 20th October 2023 has notified the Renewable Purchase Obligation (RPO) Trajectory up to FY 29–30 (Table 3). All obligated entities which includes SAIL have to fulfill the RPO targets as a percentage of their captive power generation/consumption for those units that are commissioned in the respective year.

Bureau of Energy Efficiency (BEE) has been entrusted by the Ministry of Power with devising methodology for monitoring & compliance. Widespread consultations are being held with stakeholders by a High-Powered Committee. The RPO targets are likely to be revised, and a notification to this effect is expected by 2024-end.

5. RE POWER REQUIRED BY 2030–31 BY SAIL ISPS FOR RPO FULFILLMENT

Table 4 gives detailed calculations of the RPO targets of SAIL ISPs based on their proposed captive generation in FY 29–30 following the

modernization and expansion of the plants.

The share of captive generation in total power requirement of the five ISP shall be around 1200 MW {refer Table 3}. As per Ministry of Power trajectory for Renewable Purchase Obligations (RPO) for captive power generation {refer Table 3}. SAIL is required to have renewable power generation capacity of 175.30 MW at its Integrated Steel Plants {refer Table 4} by FY 29–30.

SAIL has identified renewable power projects totaling 196.73 MW to be installed on ground, water bodies and roof-tops, out of which 173.90 MW capacity projects have been identified at the five Integrated Steel Plants. Potential renewable projects of capacity 295 MW can be installed at the five ISPs subject to their techno-commercial viability, which is under examination. The balance renewable power that SAIL will have to source is 78.44 MW at its five Integrated Steel Plants to fulfill its RPO compliance in 2030–31. Options of sourcing renewable power are being explored e.g., from the Distribution Companies (DISCOMs), and Renewable Round-the-Clock (RTC) power through Power Exchange/RE Power Developers.

Table 4: RE Power Required by 2030–31 by SAIL ISPs for RPO Fulfillment for Captive Power Generation (including JVs)

PLANT	RE Power Req'd, in 2030–31 to fulfill RPO (Avg.) for Captive Power Genrn. as per MoP Notfn. Oct'23	RE Capacity identified through JV/ CAPEX	RE Power genrn. plant-wise Solar CUF/ (Actual genrn. from SHEP*)	Identified RE Power potential subject to viability	RE Power genrn. from Identified RE Potential Projs.	Total RE Power genrn. from all Projs	Balance RE Power to be sourced for RPO fulfillment
	A	B	C	D	E	F=C+E	G=A – F
BSP	24.26	44.15	8.83	35.00	7.00	15.83	8.43
DSP	20.33	36.29	6.17	60.00	10.20	16.37	3.96
RSP	40.90	10.25	4.05*	100.00	20.00	24.05	16.85
BSL	42.63	50.00	10.00	100.00	25.00	35.00	7.63
ISP	47.22	33.20	5.64	–	–	5.64	41.58
SAIL 5 ISPs	175.30	173.90	30.64	295.00	62.20	96.89	78.44

Note: 1. Capacity Utilization Factor (CUF): 20% for BSP, BSL & RSP; 17% for DSP & ISP.

2. *Avg. Annual Power generation from Small Hydro-Electric Project (SHEP), RSP=4 MW.

3. CO₂ emission reduction per MW of Solar Power is 1081.86 T per annum.

The RPO compliance by obligated entities includes captive power generators/ consumers like SAIL as the captive power generation capacity of SAIL is fossil fuel-based. As per Ministry of Power Clarification on Orders related to Renewable Purchase Obligation 3, dated 1st February 2019, RPO of the CPP may be pegged at the RPO level applicable in the year in which the CPP was commissioned. As and when the fossil fuel-based CPP capacity is augmented, the RPO applicable in the year in which the CPP capacity has been enhanced shall be applicable for the augmented captive power generation in that financial year.

6. INTEGRATED PLAN OF ACTION FOR INSTALLATION OF RE PROJECTS IN SAIL

As decided by a Committee of Directors (C.O.D.) on 20.05.2023, an Inter-Plant Committee was formed to prepare *RE Master Plan for SAIL* by identifying land parcels/ water bodies not required for plants' expansion, for setting up solar power plants.

- All ground-mounted/floating solar projects above 10 MW capacity to be executed through Power JVs (NSPCL/ BPSCL)
 - Status of progress of Solar Projects assigned to NSPCL is at Table 5.

- RE Projects up to 10 MW capacity decided to be executed through Plants' CAPEX.
- 15 MW floating solar project at BSP through NSPCL put up for SAIL Board approval as per the above strategy.
 - Board approval received on 21.07.2023.
 - Work awarded on 17.05.2024; likely commissioning – June 2025.

The Inter-Plant Committee submitted report in September 2023.

The C.O.D. further recommended that:

- Corporate Power Group should explore sourcing of cost-effective bulk RE power from solar power developers (SPDs).
 - Proposal for 100 MW Solar Power from Solar Energy Corporation of India (SECI) for BSL being put up to SAIL Board for in-principle approval
- Corporate Power Group should explore procurement of RE power from DVC.
 - DSP & ISP have been sourcing 50% of their Grid Power from DVC as Green Power w.e. from 1st of September 2024.

Corporate Power Group and Solar Project Coordinators in Plants are monitoring the progress of and identifying more locations for RE Project installations, as well as evaluating other cost-effective RE proposals for all SAIL Plants / Units.

Table 5: Status of Progress of Solar Projects Assigned to NSPCL

S.N	Unit	Location	Type	Potential (MW)	Mode	Remarks
1	BSP	Maroda Dam 1	Floating	15	Captive	Approved by SAIL Board in July'23 Work awarded in May'24. Likely commissioning – June 2025
		Maroda Dam 2	Floating	20	Captive	Clearance given by BSP; FAR/DPR under preparation.
		Nandini Air Strip	Land	35	Captive	Clearance given by BSP; Feasibility under evaluation.

<i>S.N</i>	<i>Unit</i>	<i>Location</i>	<i>Type</i>	<i>Potential (MW)</i>	<i>Mode</i>	<i>Remarks</i>
2	BSL	Township	Land	20	Captive	DPR, FAR approved by NSPCL Board on 03.06.2024. Proposal being put up to PAG. Board Note shall then be initiated.
		Cooling Pond 1	Floating	30		
3	Kulti	Township	Land	25	Captive to ISP	For Power Evacuation from Kulti to ISP, Survey Package – work awarded on 22.07.2024; survey started.
4	DSP	Township	Land	20	Captive	DPR/FAR received from NSPCL on 05.07.2024. Clearance for land conversion from forest to non-forest pending with State Govt.
		Kamarpur/ Sovapur	Land	40–60	Not decided	Under preliminary discussion – both sites 15 kms away from plant; power evacuation thru’ DVC Parulia S/S proposed. 100 acres land parcel at Kamalpur under legal dispute.
		Waria Pond	Floating	15	Captive	Dredging, De-Silting in progress by DSP; likely completion by Sept. ’25
<i>NSPCL SOLAR POWER PROJECTS</i> <i>(subject to techno-commercial viability)</i>						
5	SSP	Township	Land	140	20 MW CPP; 120 MW IPP	PFR under preparation
6	RSP	Mandira Dam	Floating	100	CPP/IPP	PFR prepared by NVVN submitted by NSPCL
7	JSU	Plant	Land	80	IPP	PFR submitted by NSPCL; Land lease not with SAIL - matter sub-judice
8	VISL	Plant/ Township	Land/Pond	14 G + 2 F	CPP/IPP	Plant load is 0.4 – 4.0 MW; maxm. 4 MW feasible in CPP mode, balance in IPP

7. OTHER RENEWABLE PROJECTS/PROPOSALS IN SAIL

In line with the mandate given by the Committee of Directors, the Corporate Power

Group of SAIL at Supervisory Load Control Centre (SLCC), Kolkata is pursuing other renewable projects and proposals. Salem Steel Plant has been procuring 12 MW bagasse-based power during the sugarcane crushing season through power exchange from

Rajshree Sugars & Chemicals Ltd., Coimbatore since December 2021 during the sugarcane crushing season. As mentioned above, proposal for 100 MW Solar Power from SECI for BSL is being put up to SAIL Board for in-principle approval.

Damodar Valley Corporation (DVC), the DSICOM for both DSP & ISP has offered Green Power in multiples of 25% of the total grid drawal for a minimum period of six months at a Green Tariff which 50 paise over and above the retail tariff. When set off against the additional surcharge on fuel and power purchase which is 60–70 paise over and above the retail tariff, green power is not only economical but also comes with the benefit of CO₂ emission reduction in the steel-making process. Hence, both DSP and ISP have begun procuring 50% of their grid power as green power from DVC with effect from 1st of September 2024.

Chadrapur Ferro Alloy Plant (CFP) has engaged Power Trading Corporation (PTC) as a consultant for procurement of 50 MW RE-RTC power. PTC has submitted its report and recommended an investment of Rs. 200 cr in a JV with Re power developer to be identified through tendering. The proposal is being finalized and shall be put up for the approval of SAIL Board.

8. CONCLUSION

SAIL has charted its RE roadmap for the coming years on the basis of its power requirement by FY 29-30 following expansion and modernization. The enhancement in renewable power capacity through installation or procurement will help SAIL not only fulfill its RPO targets as directed by the Ministry of Power but also help decarbonize its steel-making process. SAIL's strategy is three pronged, viz., Installation of ground-mounted, floating, and rooftop installations

through its power JVs or own CAPEX; Procurement of Power through Open Access; and Procurement of Green Power directly from DISCOMs.

The successful integration of 100 MW Solar Power from SECI for BSL and 50 MW RE-RTC Power for CFP shall be important milestones in SAIL's journey for enhancement in its RE Power Portfolio, much like the commissioning of the first Floating Solar Power Project of 4 MW capacity at ISP through own CAPEX or the first Floating Solar Power Project of 15 MW capacity at BSP through Power JV NSPCL.

As can be seen from Table-IV, SAIL shall require an additional 78.44 MW RE-RTC power to fulfill its RPO targets. CO₂ emission reduction per MW of Solar Power is 1081.86 T per annum. Hence the journey of RE power enhancement is an ongoing one, with all possible avenues for installation having been identified. The RE quest shall continue as options like storage (battery and pumped) and Wind offer options for Hybrid RE Power in combination with Solar Energy.

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GHG Reduction in Iron & Steel through Technological Interventions

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ABSTRACT

Steel Scenario

India is the world's second largest steel producer, with overall Crude Steel production of 111.245 Million tonnes (MT). India's steel production is also expected to increase from 111.245 MT to 120 MT by 2022. India's per capita consumption of steel grew to 86.7 kgs, during 2022–23. National Steel Policy 2017 aims to increase the per capita steel consumption to 160 kgs by 2030–31. The National Steel Policy, 2017, has envisaged 300 million tonnes of production capacity by 2030–31. India is poised to play a pivotal role as growth engine of the world. But apart from quality production and contribution in the GDP Industrial fraternities of India have also a statutory and moral responsibility of proper disposal of by-products including solid wastes generated during the process. Although Indian steel Industry is facing numerous challenges including shortage of Quality Iron Ore Lump and increase in cost of Coking Coal however Indian steel sector is also having following competitive advantages & inherent disadvantages:

Advantage

1. Robust demand of Steel.
2. Increasing investment in Steel sector.
3. Policy support by the Government
4. Availability of Iron ore & Manpower.

Disadvantage

1. Poor logistic for supply of bulk materials.
2. Environmental issues & energy consumption.
3. Shortage of metallurgical coke.
4. Use of old/inefficient technology for steel production.
5. Poor waste management.

GHG reduction in Iron & Steel

The major lever for GHG reduction in Iron & Steel Industry include Raw Material Quality Improvement, Process Improvement, Technology addition and Deep Decarbonization using Carbon Capture and use of Hydrogen as a reducing agent in place of coke. Circular economy and resource efficiency will also play a crucial role in decarbonisation journey of steel industry in India. The principles of reduction, reuse and recycling (3 'R's) in many ways can improve the sustainability of the industry. Waste management consists of generation, prevention, characterization, monitoring, proper treatment, handling and proper reuse. It also helps to preserves natural resources by decreasing the demand for virgin materials. Various technological interventions and initiatives taken for resource efficiency have also been highlighted in the paper which can help Steel Industries to reduce its Carbon Footprint.

1. STEEL INDUSTRY IN INDIA

Perhaps as early as 300 BCE—although certainly by 200 CE—high-quality steel

was being produced in India. History of modern era of steelmaking in India is depicted below (Figure 1).

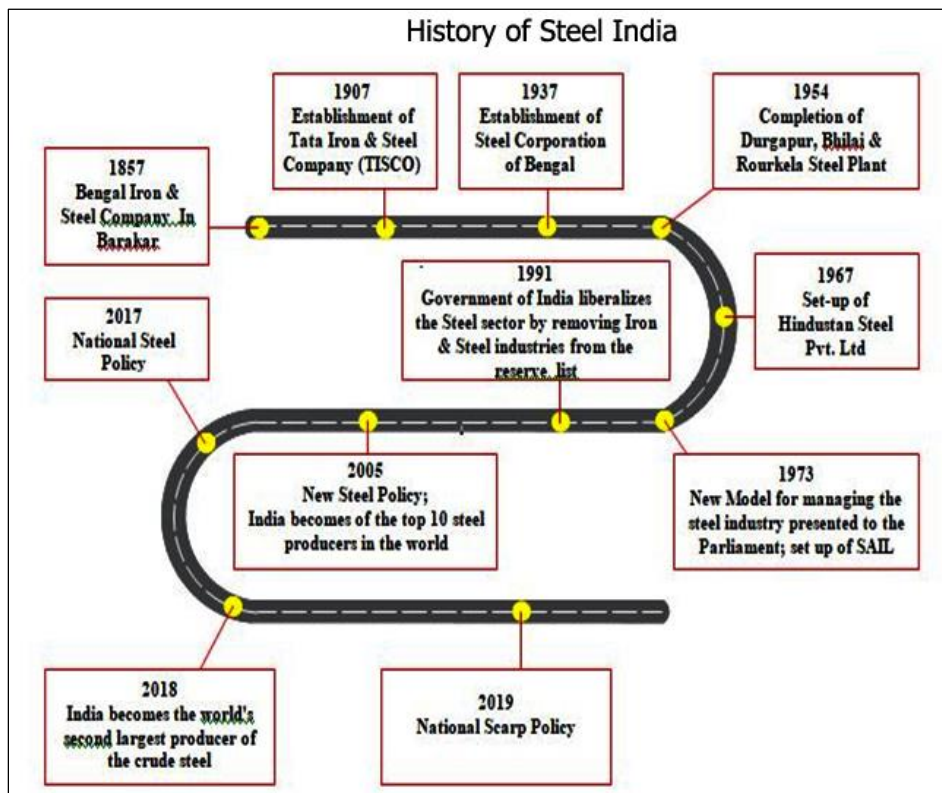


Figure 1: History of Steel Industry in India

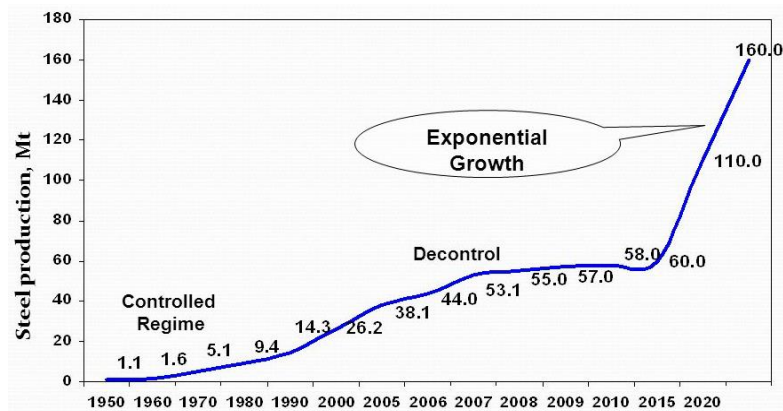


Figure 2: Growth of Steel Industry in India

2. INDIAN STEEL INDUSTRY

The structure of the Indian Steel Industry has witnessed a significant change since the start of economic liberalization in India. Figure 2 gives an idea of growth of Steel Industry in India.

Average world steel use per capita has steadily increased from 150 kgs in 2001 to around 230 kgs in 2020s. We in India have a per capita consumption of about 75 kg – **issue is low consumption in rural areas** which is 19 kgs. Government's plan of an investment

of Rs. 100 lakh crores for infrastructure development in the next five years (**Figure 3**) will boost the demand. The Government's

National Steel Policy 2017 aims to increase the per capita steel consumption to 160 kgs by 2030–31:

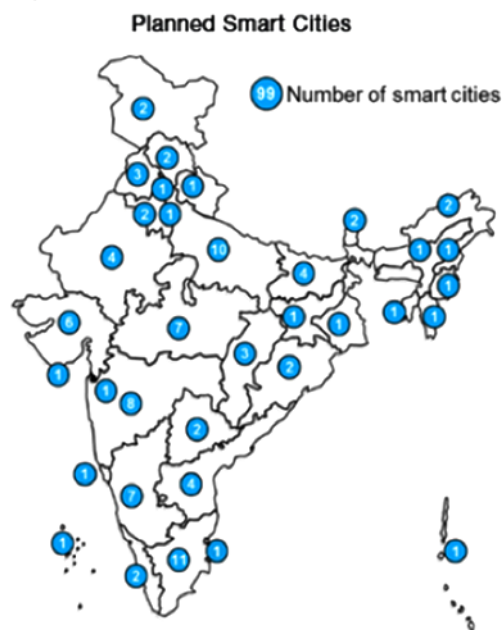
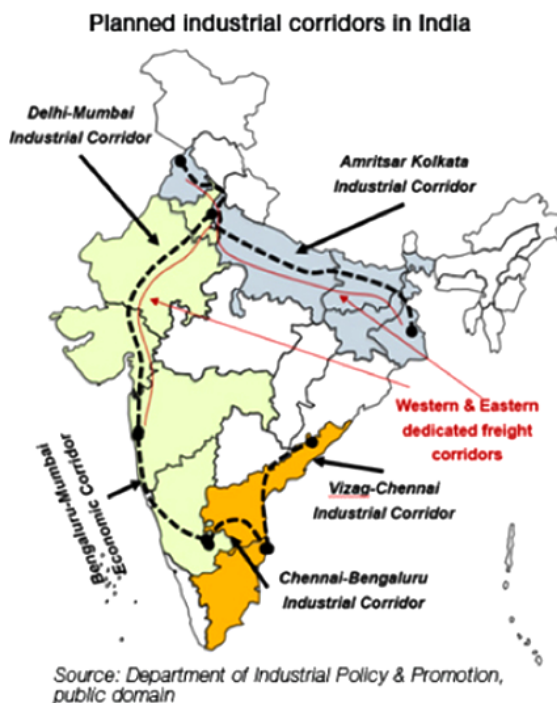


Figure 3: Proposed Infrastructure Development

India has increased installed capacity of production of steel by 50% to 155 million tons (Mt) in 2022 from around 100 million tons in 2014. As of April 2022, India was the world's second-largest producer of crude steel where in the production of crude steel and finished steel stood at 133.596 Mt and 120.01 Mt respectively. Government has taken various steps to boost the sector including the introduction of National Steel Policy 2017 and allowing 100% Foreign Direct Investment (FDI). The Policy has put a target of production at 300 Mt by 2030. As per Reports prepared by TERI the capacity of Steel production in 2050 would be around 500 Mt. It is anticipated that the capacity of Steel production would be around 600 – 700 Mt by 2070.

3. NET ZERO EMISSIONS – INDIA'S COMMITMENT

The United Nations Climate Change Conference, 2021 (COP26) held in Glasgow. India found itself in the eye of a storm with decarbonisation goals focused largely on the domestic steel industry.

The steel industry bears the brunt of climate activists from across the world as it generates about 7–8% of global CO₂ emissions. Amongst considerable advancements, captured CO₂ from steel plants is being harnessed and use of Green hydrogen, produced from renewable electricity such as biomass, is another notable progress.

India's aim to nearly triple its crude steel production clashes with Prime Minister's pledge at COP26 of aiming to reach net-zero emissions by 2070. The bold promises include installing non-fossil fuel electricity capacity of 500 GW by 2030; sourcing 50% of energy requirement from renewables by 2030; achieving carbon intensity reduction of 45% over 2005 levels by 2030 which also translates to around 1 billion tonnes of emissions reduction till 2030 and achieving net zero by 2070.

If steel were a nation, it would be the 5th largest producer of direct carbon emissions in the world. In 2019, Steel Sector emitted 3.6 Giga Ton (Gt) of CO₂. BF-BOF steel production emitted around 3.1 Gt CO₂ and EAF production emitted around 0.5 Gt CO₂. High CO₂ intensities of EAFs in China and India because of their use of large share coal-based direct reduced iron (DRI) as feedstock instead of steel scrap in EAFs causes an increase in global EAF's CO₂ emissions. Carbon dioxide emissions from the steel industry in India are projected to jump to 800 million tons by 2050 from 250 million tons now & may contribute more than 33% of nation's total fossil fuel combustion emissions from 12% currently if no concerted action to decarbonize it is taken. **SAIL/Bokaro has set target for reducing CO₂ emissions less than 2 T/TCS by 2030** from current level of 2.47 T/TCS. Ministry of Steel set target for reducing GHG emissions in Iron & Steel sector by 2030:

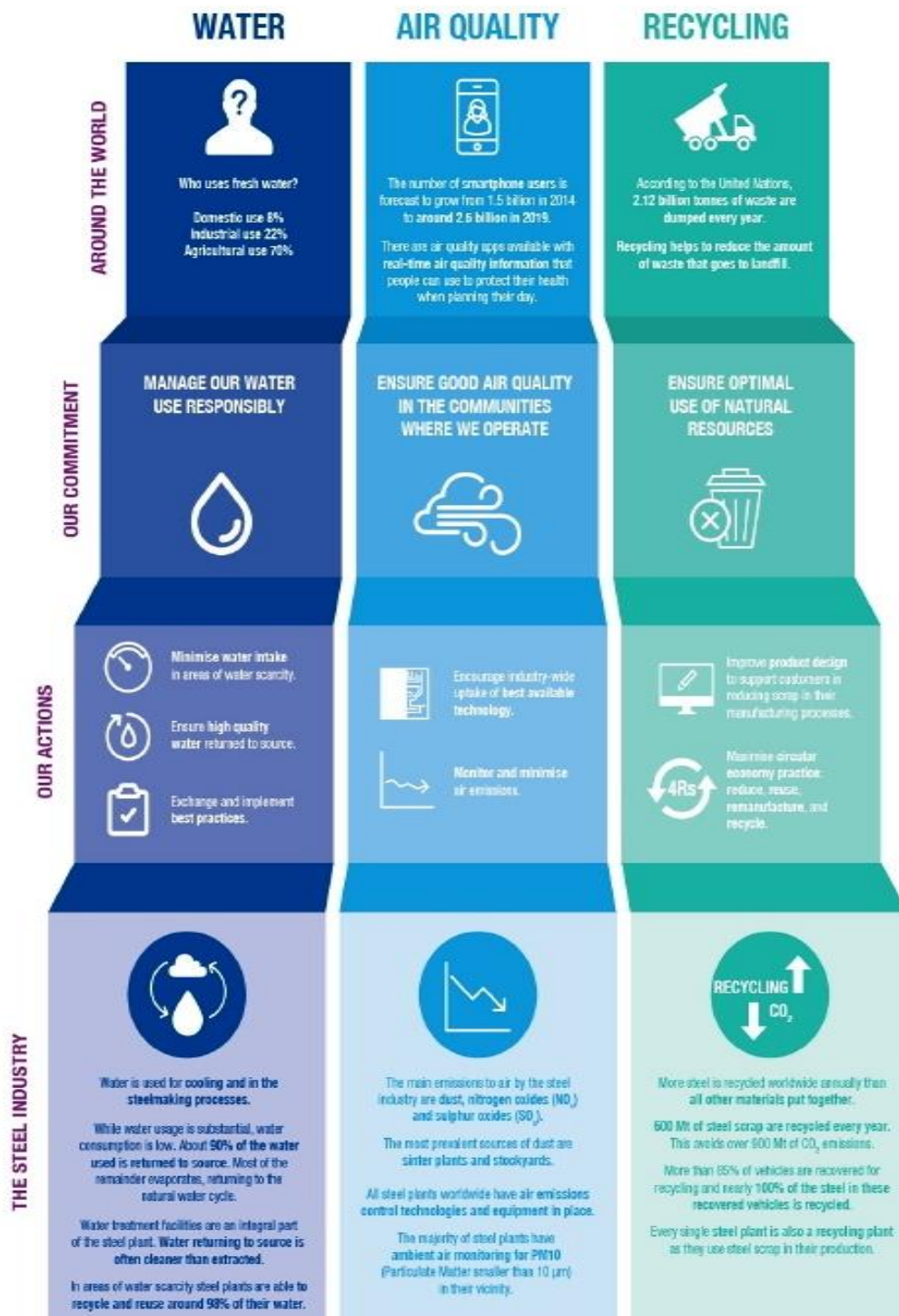
- (a) 2.2 -2.4 T/TCS in BF-BOF route
- (b) 2.6- 2.7 T/TCS in DRI- EAF route

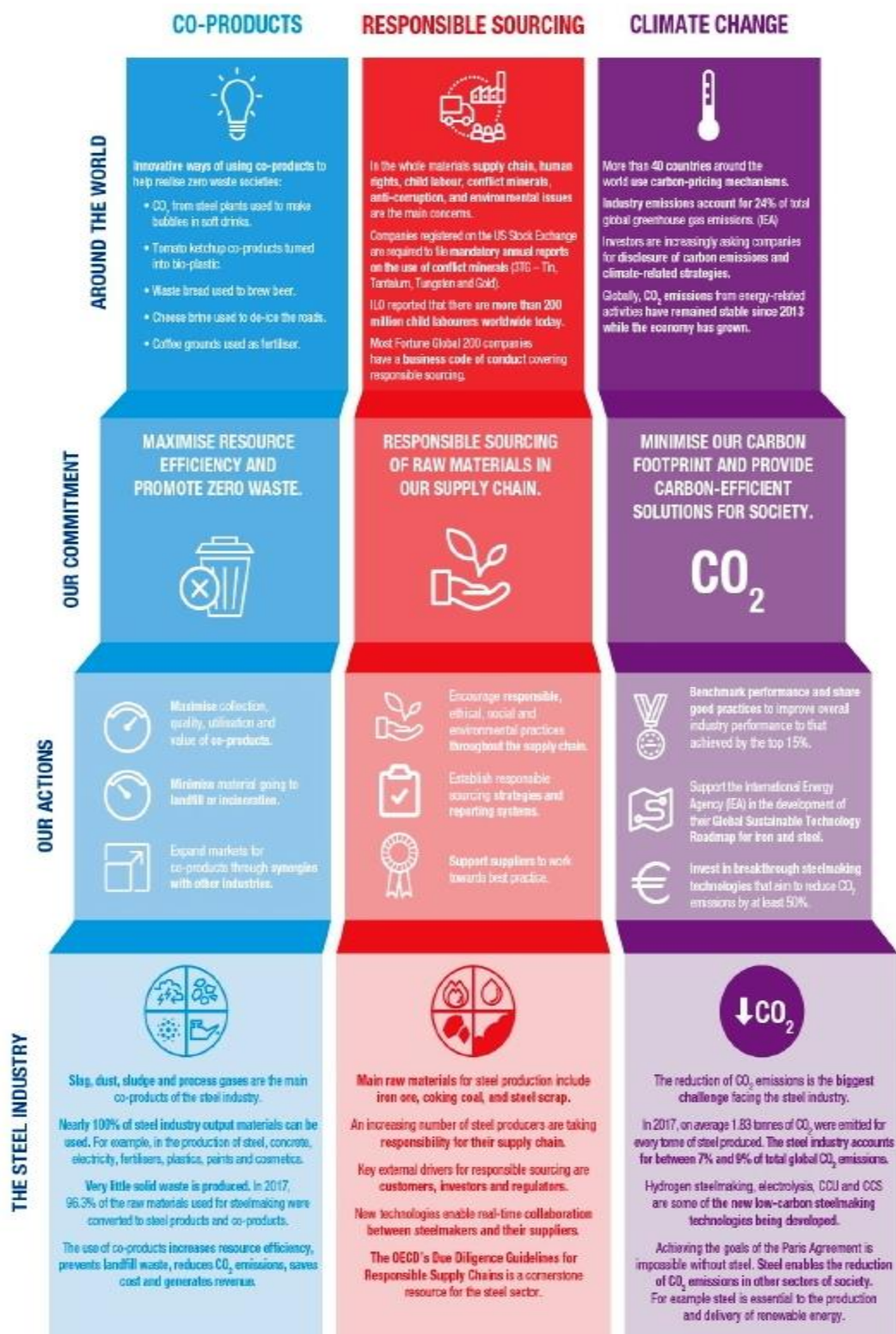
4. ROLE OF STEEL IN ACHIEVING NET-ZERO

Steel is vital to modern economies and so over the coming decades global demand for steel is expected to grow to meet rising social and economic welfare needs. The sector is currently responsible for about 8% of global final energy demand and 7% of energy sector CO₂ emissions (including process emissions). However, through innovation, low-carbon technology deployment and resource efficiency, iron and steel producers have a major opportunity to reduce energy consumption and greenhouse gas emissions, develop more sustainable products and enhance their competitiveness. Steel is going to play a big role in reduction of overall GHG emission as far as Energy, infrastructure & mobility industries are concerned. Rising demand for greener approaches creates an imperative for the Steel industry to seize the moment, adopt new mind-sets, and set standards for the transition to a greener future.

Figure 4 gives an idea of utilization of steel in various sectors of economy and its role in reduction of emissions (source World Steel

Association – Sustainable Steel Indicators and steel applications 2017, 2018 & 2020).





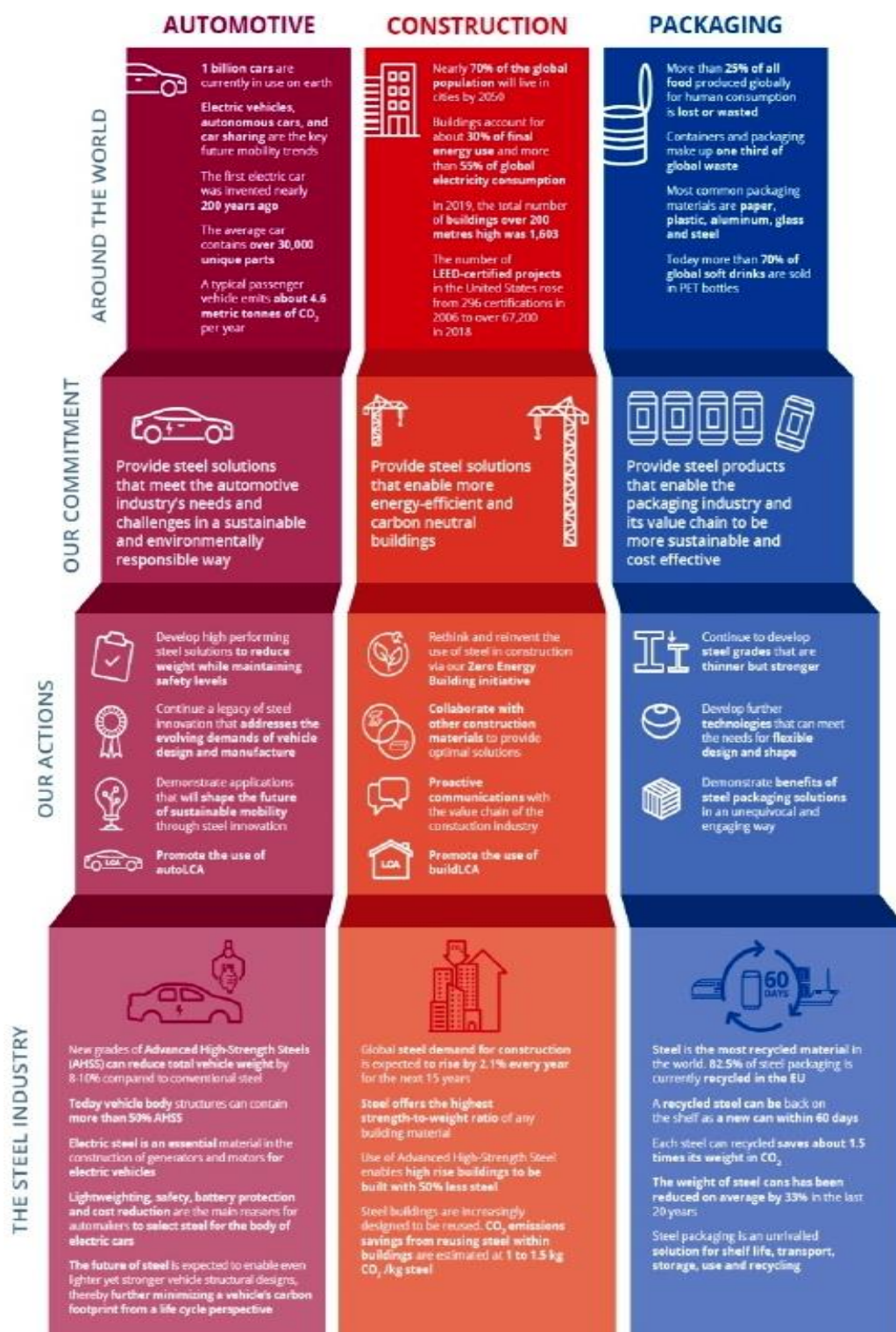


Figure 4: Utilization & role of Steel in GHG mitigation in other Sectors

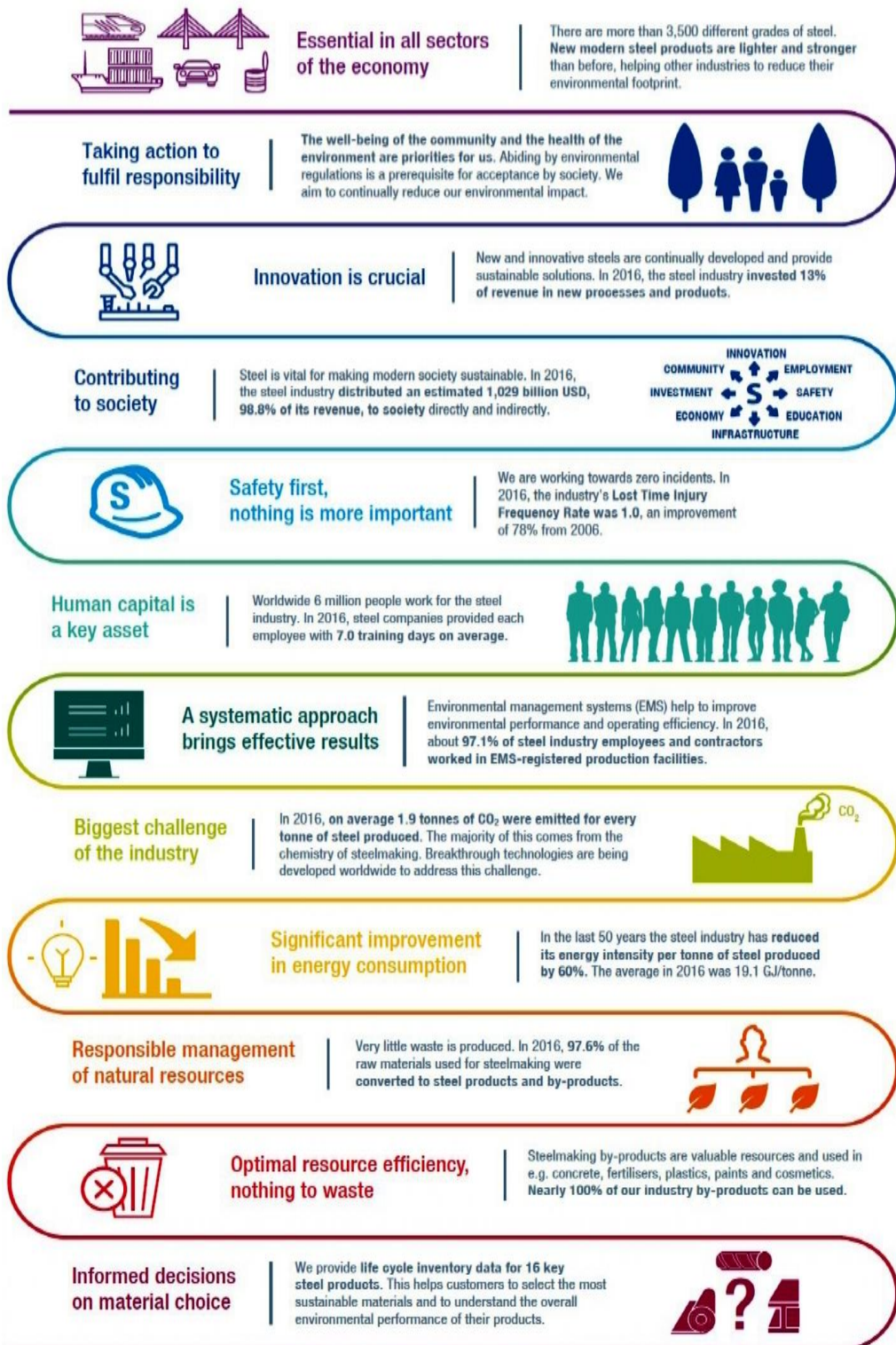


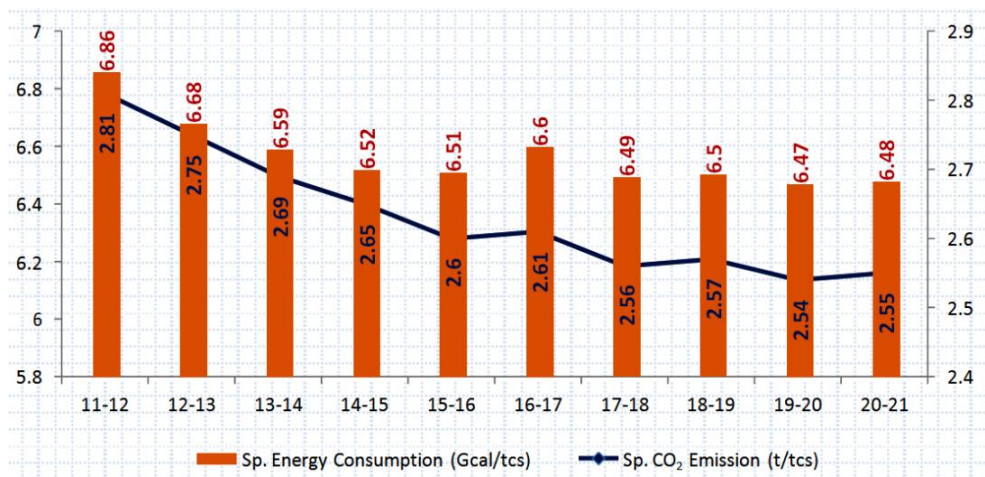
Figure 5: Importance and Development of Various Parameters of Steel

5. STEEL SECTOR AT THE CORE OF SUSTAINABLE WORLD

Hydrogen is going to play a big role as source of energy & achieving Net zero target & for that steel is going to play critical role for making large electrolyzers which can help in production of Green Hydrogen. Similarly infrastructure for Renewable Energy including Wind turbines & Solar Power generation facilities are not possible without better grade of steel. Similarly steel will play a critical role in Electric Vehicle segments by development of composite steel which will make Electric vehicle safer, lighter & affordable. Steel because of its inherent advantage of 100% recyclable can provide an option for replacement of Plastic & Aluminium cans. India's steel manufacturing industry relies heavily on coal for steel production. This sector accounts for approximately 13 % of the nation's overall CO₂ emissions making steel the highest emitting industrial sector. With the growing demand, CO₂ emissions are expected to increase 2.5-times over the next three decades (392 million tonnes in 2022 to 989 million tonnes in 2050). **Figure 5** gives an idea of importance and development of various parameters of steel (source World

Steel Association – Sustainable Steel Indicators and steel applications 2017).

Mitigating climate change is the need of the hour for the steel industry to move towards “Green Steel” or “Low Carbon Steel” manufacturing in India. It is possible for steel industry to support and meet the 1.5°C goal as set out in Paris in 2015. This will happen in three phases. Phase 1 will initially need to rely on improved efficiency in making and using steel. Phase two will allow for a larger portion of production to rely on recycled scrap and so reduce the average CO₂ intensity. In the third phase the focus will be on using hydrogen and new production methods to reduce the CO₂ intensity of industry further. Steel sector is a capital intensive Industry with average life of say a Blast-Furnace to be -20–25 Years. This means in case the steel makers make a decision to invest of energy-efficient & large Blast Furnace today in 2022 instead of DRI-EAF route. The Government is working on schemes like Coal Gasification, National Hydrogen Mission to reduce the dependence of steel industry on coal/coke. SAIL on its part making efforts consistently and its performance over last 10 years and impact of energy efficient technologies after Modernization & Expansion on GHG is given in graph below:



<i>Particular</i>	<i>Unit</i>	<i>2005–06</i>	<i>2020–21</i>	<i>% change</i>
Specific Energy Consumption	GCal/tcs	7.24	6.48	10.50% improvement
Specific CO ₂ Emissions	T/tcs	3.10	2.55	17.74% improvement

<i>GHG 2023–24</i>	<i>GHG 2030–31</i>	<i>Major Enablers</i>
2.67	2.10	RM Quality Improvement: Operationalization of new blocks at KIOM/MIOM; Expansion of GOM with Beneficiation facility & Pellet plant. Process improvement: TRT & WHR in BF #5; Enhancement in CDI; Gas based power plant; WHR in SPs; Modifications in RHF of HSM; phasing out of old COBs. Technology Addition: New stamp charge COBs & CDCP; New BF & new Mills. Deep decarbonisation: CCUS for value added products.

GHG mitigation at SAIL Bokaro by adopting Energy Efficient Technology.

6. DECARBONISATION IN STEEL SECTOR: GLOBAL SCENARIO

The steel industry bears the brunt of climate activists from across the world as it generates about 8% of global CO₂ emissions. Fortunately however, the global steel giants have already been taking significant strides in adopting various climate-friendly technologies. A number of efforts are aiming to lower emissions. Some examples are given below

CCUS

Shougang operate a large- scale facility to convert steel plant process gases to ethanol.

Arcelor Mittal are building a similar commercial facility in Belgium.

CCS

At Emirates Steel up to 800kt of CO₂ per year is captured from the CO₂-rich gas stream from the iron making plant and stored. Arcelor Mittal are part of the Norwegian “Northern Lights” CCS project.

Hydrogen

HBIS is building a 1.2Mt capacity hydrogen metallurgy DRI demonstration project. Voestalpine’s SuSteel project is looking to apply hydrogen plasma reduction to iron-making.

Biomass

Aço Verde doBrasil exclusively using sustainably grown biomass for their steel production.

Renewable energy

Evraz’s Rocky Mountain Steel in Colorado, USA, is transitioning from coal to solar.

Electricity

The Siderwin project (currently at TRL4), being led by ArcelorMittal, is looking at using low temperature electrolysis using a water- based electrolyte. **Figure 6** gives an idea of Cost of Production of Steel through various process routes and **Figure 7** highlights Global scenario for Low carbon path of Steel.

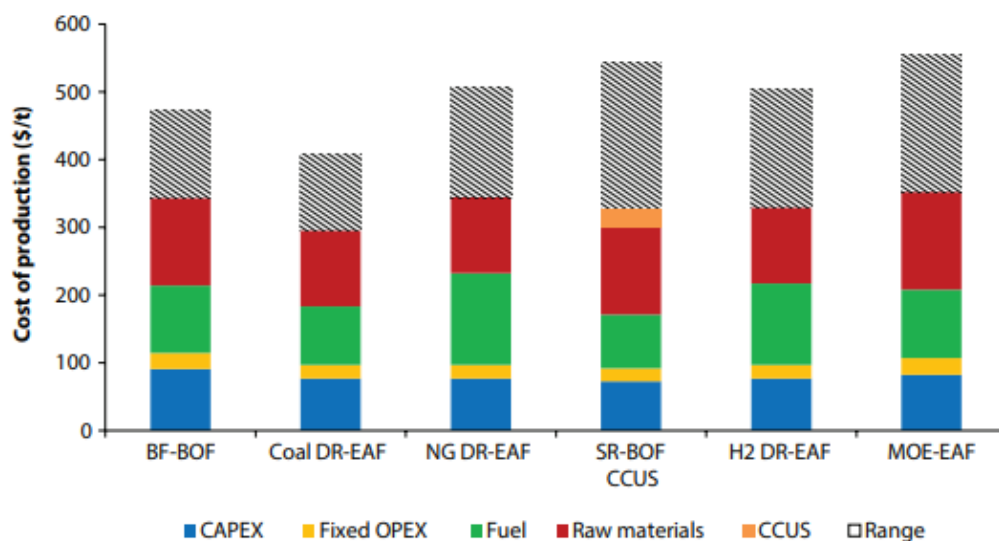


Figure 6: Cost of Production of Steel through Various Process Routes

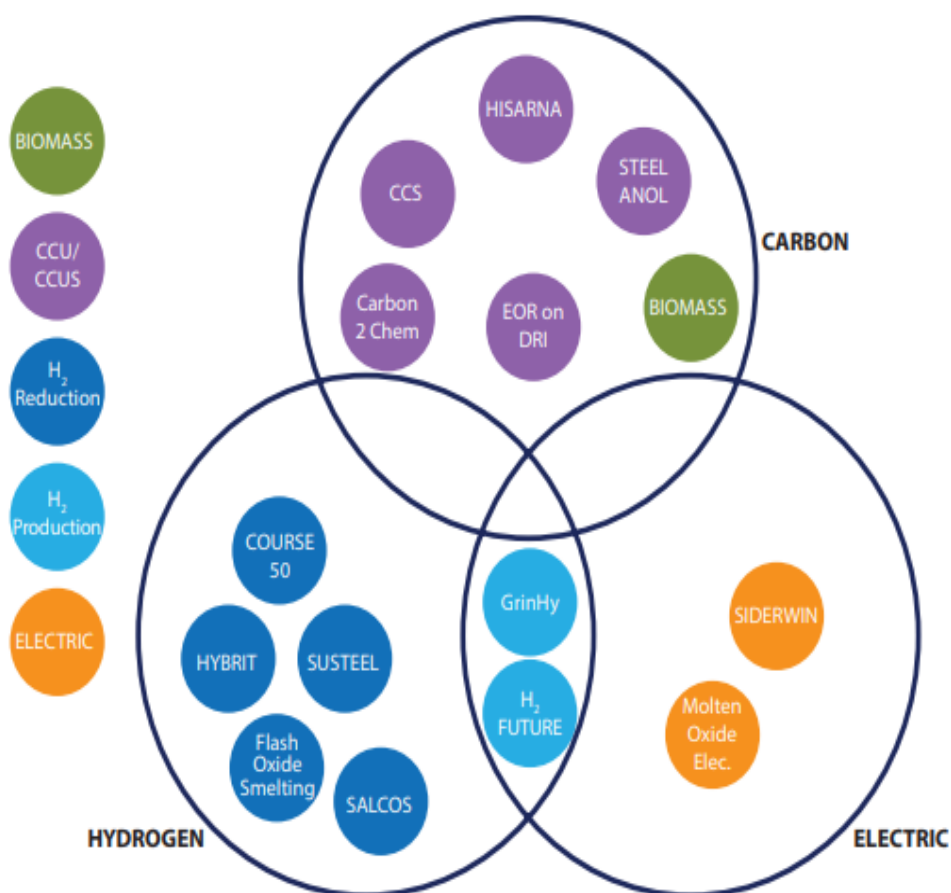


Figure 7: Global Scenarios for Low Carbon Path of Steel

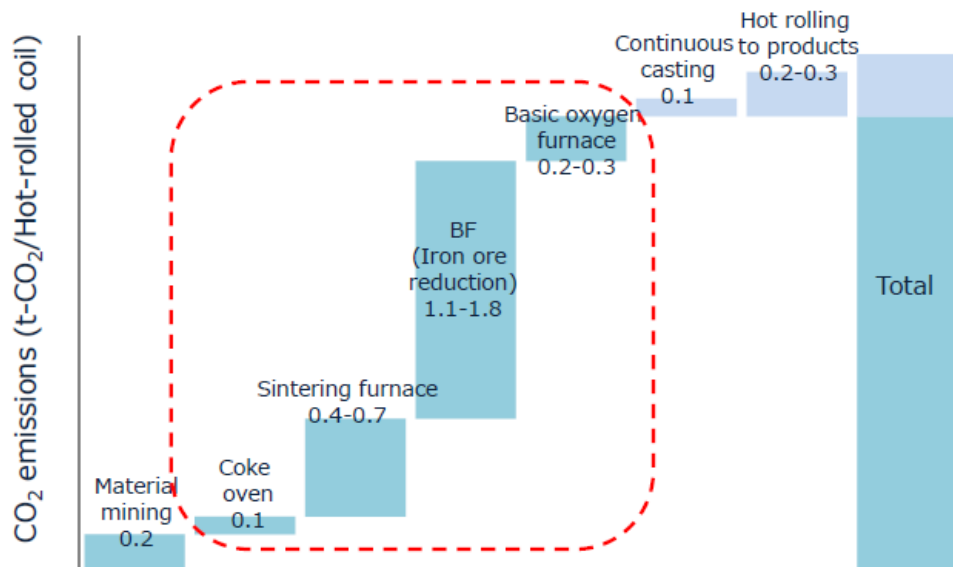


Figure 8: Break up Unit wise CO₂ Emissions (t-CO₂/Hot Rolled Coil)

6. INDIAN SCENARIO

India-based integrated steel manufacturers have not been far behind in the path to decarbonisation. JSW Steel has invested in a carbon capture plant in Maharashtra which aims to cut emissions to as low as 1.95 tonnes of CO₂ equivalent per tonne of steel produced by 2030. Tata Steel, at its Jamshedpur plant, has been successfully reducing emissions by recycling higher quantities of its scrap and have also put up a Carbon capture unit.

Use of pellets and reducing the usage of sinters is another step in this direction. Notably, the average pellet feed ratio by Indian steel plants has reached 40–45% as against the earlier 10–15%.

Steel scrap also helps reduce industry emissions and the consumption of resources. It allows manufacturers to produce new alloy steel products with fewer resources, which is cheaper and safer for the environment. Going forward, steel producers need to assess, evaluate, and decide on a technologically and economically viable way to decrease their carbon footprint. **Majority of CO₂ emissions**

is derived from the iron ore reduction process in the Blast Furnace. **Figure 8** gives break up unit wise CO₂ emissions (t-CO₂ / Hot Rolled Coil).

7. FUTURE DECARBONIZING - INDIA STEEL SECTOR

Steel can be produced via two main processes: using an integrated blast furnace (BF)/basic oxygen furnace (BOF) or an electric arc furnace (EAF). While integrated players produce steel from iron ore and need coal as a reductant, EAF producers use steel scrap or direct reduced iron (DRI) as their main raw material. Number of decarbonization strategies are being adopted. These include:

7.1 BF/BOF Efficiency Programs

Such programs improve efficiency and/or decrease production losses in different ways, for example: 1) optimizing the BF burden mix by maximizing the iron content in raw materials to decrease the usage of coal as a reductant, 2) increasing the use of fuel injection through, for example, pulverized

coal injection (PCI), natural gas, plastics, biomass, or hydrogen (as an additional reagent on top), or 3) using coke oven gas in the BF as an energy source, just to name some of the

options. Over the years, a number of innovative technological improvements have taken place. List of such technologies are given below.

Sl.	Title of Technology	Effect of Technologies	
		Fuel Savings (GJ/t of Product)	CO ₂ Reduction (Kg-CO ₂ /t of product)
1.	Sinter Plant Heat Recovery (Steam Recovery from Sinter Cooler Waste Heat)	0.251/ t-sinter	23.9/t-sinter
2.	Sinter Plant Heat Recovery (Power Generation from Sinter Cooler Waste Heat)	–	19.9/t-sinter
3.	High Efficient (COG) Burner in Ignition Furnace for Sinter Plant	0.011/t-sinter	0.50/t-sinter
4.	Coke Dry Quenching (CDQ)	1.9/t-coke	135/t-coke
5.	Coal Moisture Control (CMC)	0.3/t-coke	27.6/t-coke
6.	BF Top Pressure Recovery Turbine (TRT)	–	45.0/t-pig iron
7.	Pulverized Coal Injection (PCI) System	1.55/t-pig iron (at 125kg coal inj.)	147/t-pig iron
8.	BF Hot Stove Waste Heat Recovery	0.08/t-pig iron	7.8/t-pig iron
9.	BOF Converter Gas Recovery Device	0.84/t-steel	79.8/t-steel
10.	BOF Converter Gas Sensible Heat Recovery Device	0.126/t-steel	12.0/t-steel
11.	Ecological and Economical Arc Furnace	–	135 /t-steel
12.	Waste Heat Recovery from Electric Arc Furnace	–	78.9 /t-steel
13.	Regenerative Burner Total System for reheating furnace	0.17-0.21/t-billet	16.2-20.0/t-billet
14.	Energy Monitoring and Management System	0.12/t-steel	11.4/t-steel
15.	Cogeneration (include Gas Turbine Combined Cycle (GTCC))	–	56.1/t-steel

Enablers for GHG Mitigation

<i>SI</i>	<i>Enabler</i>	<i>Action Plan</i>
1.	Enhancement in Fe Content of Lump Ore	Sourcing of good quality iron ore
		Ensuring consistent homogeneity of high-quality lump ore for supply to BF with proper intermixing of available ore.
2.	Enhancement in Fe Content of Sinter	Sourcing of better-quality fines
		Installation of Slime Beneficiation Plant/Silica Reduction project
		Ensure blend with higher Fe % in sinter feed charge.
3.	Use of Pellets	Installation of Pellet Plant.
4.	Pulverized Coal Injection	To enhance PCI
5.	Increased BF Top Pressure	For Power generation
6.	Hot Blast Temperature	To reduce Coke consumption in BF
7.	Ensuring availability of high strength Coke for PCI enhancement.	New Stamp Charge Coke Oven Battery.
8.	Enhancing utilization of BOF slag	BOF slag utilization for soil conditioner in agriculture.
9.	Enhancement in BOF gas recovery	BOF gas for Power Generation (70–80% of the recovered gas)
10.	Top gas Pressure Recovery Turbine (TRT)	Installation of TRT
11.	Hot charging facility	Possibility of hot charging of slabs in mills to be explored along with development of adequate logistical support facilities.
11.	Energy efficient LED lighting system	Complete switchover to LED lighting.
14.	Energy efficient drives and motors.	Installation of VVVF Drives in motor & IE3 Motors.
15.	Use of Renewable Power (50% by 2030)	Installation of Floating Solar Power Plant on Cooling Ponds
		Sourcing of green energy from external agencies using bilateral/multi-lateral agreements and other instruments.

7.2 Biomass Reductants

This process uses biomass, such as heated and dried sugar, energy cane, or pyrolyzed eucalyptus, as an alternative reductant or fuel. As such it is regionally dependent and mainly important in areas where the biomass supply is guaranteed.

7.3 Carbon Capture and Usage

This uses emissions to create new products for the chemical industry, such as ammoniac or bioethanol. At present, carbon capture and usage remains technologically premature and yet to be proven economically.

7.4 Increase Share of Scrap-Based EAFs

This process maximizes secondary flows and recycling by melting more scrap in EAFs. EAF producers are more environmentally friendly. However, shifting to EAF-based steel production requires the future supply of renewable electricity and sufficient supply of high-quality steel scrap.

7.5 Optimize DRI and EAF

This requires boosting usage of DRI in combination with EAF. DRI-based reduction emits less carbon dioxide than the integrated method and enables the production of high-quality products in the EAF. DRI production requires cheap and readily available natural gas..

7.6 Hydrogen is the Key

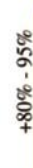
Although hydrogen is one of the most abundant elements on earth, in its pure form it is rare. Extracting hydrogen from its compounds requires a lot of energy. There are generally two ways to use hydrogen in steel production. **First, it can be used as an alternative injection material to PCI, to improve the performance of conventional blast furnaces.** However, while the injection

of (green) hydrogen into blast furnaces can reduce carbon emissions by up to 20 percent, this does not offer carbon-neutral steel production because regular coking coal is still a necessary reductant agent in the blast furnace.

Second, Hydrogen can be used as an alternative reductant to produce DRI that can be further processed into steel using an EAF. This DRI/EAF route is a proven production process that is currently applied using natural gas as a reductant. Based on the use of green hydrogen as well as renewable electricity from wind, solar, or water, a DRI/EAF setup enables nearly carbon-neutral steel production.

8. POSSIBLE SOLUTIONS

As **BF/BOF efficiency programs only result in a reduction in carbon dioxide emissions, without eliminating them entirely,** they cannot be a long-term solution. Biomass reductants and carbon capture and usage are still in the early stages of development. The share of EAFs producing high-quality steel will increase but requires the availability of scrap and DRI. Hence, adopting an approach combining scrap, DRI, and EAF using hydrogen is currently considered the most viable option and the long-term solution to achieving carbon-neutral steel production. Hydrogen, carbon capture, use and storage (CCUS), bio-energy and direct electrification all constitute avenues for achieving deep emission reductions in steelmaking, with multiple new process designs being explored today. Energy prices, technology costs, the availability of raw materials and the regional policy landscape are all factors that shape the technology portfolio in the Sustainable Development Scenario. Innovative smelting reduction, gas-based DRI and various innovative blast furnace concepts, all equipped with CCUS, prevail in areas where the local policy context is favourable and

A comparison of emerging and new technology production methods for greener steel						
Emerging technology	Commercial	Incremental prod. costs	Potential CO ₂ reduction	Commercial horizon	Benefits	Challenges
Scrap EAF		-		Commercial	High potential of CO ₂ reduction; technology readily available; useful in case of low supply of high-quality coal	High scrap required; energy needs of EAF can add to emissions
Smelting reduction		-		Commercial	Lower operation cost; possible elimination of sinter or pellet and coke plants	High calorific value export gas generated; lower economic scale of operations
BF/BOF with biofuel		-		Commercial	Easier to implement by altering the input mix in BF	High quality of biofuel required; increased storage and transportation cost; high moisture content of biofuels
BF/BOF with carbon capture		+30% - 50%		5-10 Years	Can easily to integrated of BF/BOF; advantage from R&D going on for a long time	Large infrastructure investment for storage and transport; difficult to capture all CO ₂ emissions
BF/BOF with hydrogen		-		-10 Years	Potential to reduce emissions both in coke plant (reduced amount of coal required) and BF	Difficult to replace reducing agent by hydrogen beyond a point to maintain operations.
Nature Gas DRI (NG-DRI and EAF)		-		Commercial	High energy and emissions saving	Adequate and affordable supply of natural gas critical to determine profitability
Blue hydrogen DRI (H2-DRI and EAF)		+35% - 55%		10-20 Years	Flexibility; scalability of producing blue hydrogen in some areas	Production cost of blue hydrogen; ~US\$2/Kg compared with black hydrogen; ~US\$1.7/kg ; dose not address emissions from pellets
Green hydrogen DRI (H2-DRI and EAF)		+60% - 90%		10-20 Years	Increased flexibility as hydrogen and HBI can be stored	High green hydrogen cost; ~ US\$5/kg compared with black hydrogen cost of ~ US\$1.7/kg
Iron electrolysis		Not determined		20-30 Years	Largest potential in CO ₂ reduction	Steel at an early stage of development, only been tried at a lab scale
Sources: BNP Paribas, BHP, IEA, Arcelor Mittal, EY analysis						
Note :- Potential CO2 reduction for scrap-based EAF; Smelting reduction process considered compared with BF. Estimates majority for transition to low-emissions steelmaking in Europe.						
Incremental production costs (opex and capex) compared with average annual net income of steel industry.						
Value compared for crude steel production.						

Comparison of Emerging and New Technology Production Methods

cheap fossil fuels are abundant. **Hydrogen and CCUS together account for around one-quarter of the cumulative emission reductions in the Sustainable Development Scenario.** A rapid roll-out of technologies that are currently at early stages of development will need to accompany this shift. The concurrent deployment of CCUS-equipped plants requires around 0.4 Gt CO₂ capture globally in 2050, equivalent to the deployment of a large CCUS installation (1 million tonnes CO₂ capture per year) every 2–3 weeks from 2030. **Table below gives a comparison of emerging and new technology production methods for greener steel:**

9. WAY FORWARD

A sustainable transition for the iron and steel sector will not come about on its own; governments will play a central role. Policy portfolios will be diverse, but the following recommendations serve as a starting point for those seeking to effect change and accelerate the transition:

1. Establish a long-term and increasing signal for CO₂ emission reductions.
2. Manage existing assets and near-term investment.
3. Maximize energy efficiency.
4. Increase scraps utilisation.
5. Introduce green product standards
6. Promote technical research & development and setup demonstration plants.
7. Domestic carbon trading market.
8. Support for commercial-scale plants.
9. Implement a carbon border tariff.
10. Retire older, polluting facilities.
11. Create a market for near-zero emissions steel.
12. Support the demonstration of near-zero emission steelmaking technologies.
13. Digitization of various processes to enhance Energy & resource efficiency

14. Accelerate material efficiency.
15. Increase international co-operation and ensure a level global playing field.
16. Develop supporting infrastructure for near-zero emission technologies.
17. Track progress and improve data collection.

For a net zero by 2070 scenario, it is assumed that largely gas based direct reduction plants are installed during the 2020s, primarily using natural gas. When low-cost hydrogen is available, these plants can switch over to hydrogen. The existing blast furnaces would need to be steadily decommissioned as they reach the end of their economic life. This might require consideration for some form of fiscal/ financial packages to facilitate this process. By 2070, a limited number of blast furnaces would remain, and those that do would be fitted with carbon capture technology. Coal-based direct reduction units have a shorter lifetime and higher emissions versus blast furnaces and so these units would need to be phased out before 2050, with natural gas and hydrogen based direct reduction units being deployed in their place. **Figure 9** gives Net Zero scenarios for Indian Steel Sector:

For achieving the roadmap of carbon neutrality by 2070, we need to adopt multi-track approach to develop super-innovative technologies, focusing on carbon recycling blast furnace + CCU and hydrogen ironmaking (direct reduction) and maximize utilization of industry-leading electric arc furnace technology. There is need to accelerate research and development for early establishment of new technologies. **TERI in a recent Report on Achieving Green Steel Roadmap to a Net Zero Steel Sector** in India has come out with a roadmap for achieving Net Zero. The same is reproduced as **Figure 10**.

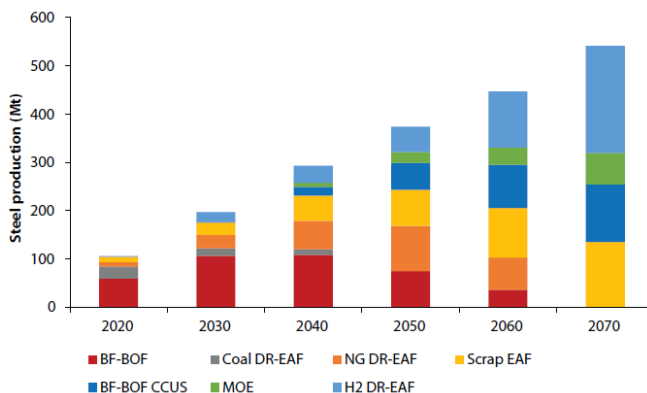


Figure 9: Net Zero Scenarios for Indian Steel Sector

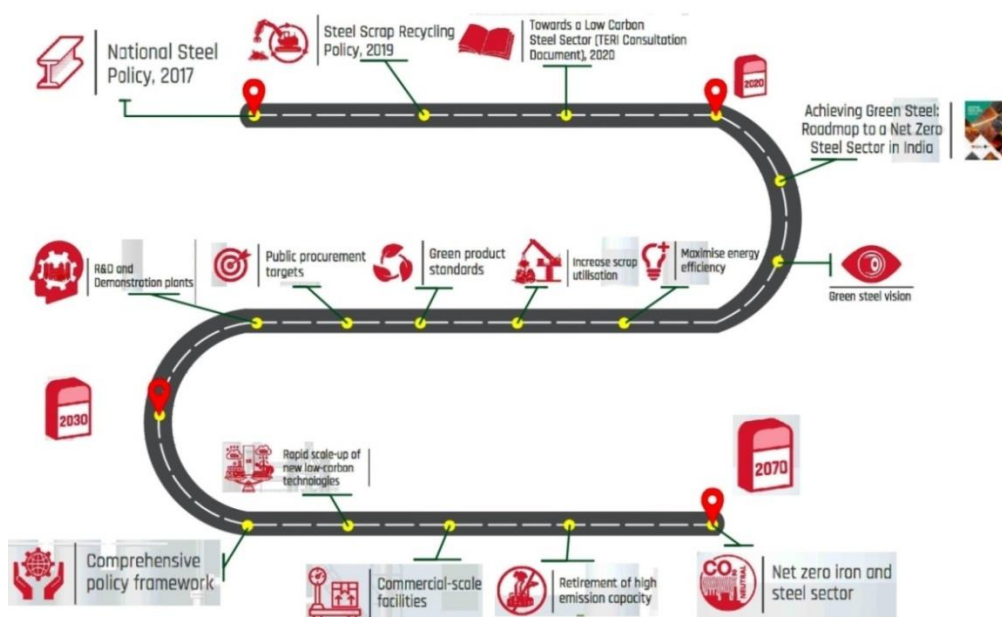


Figure 10: TERI's Roadmap for Achieving Net Zero

10. CONCLUSION

Steel is the solutions to infrastructure and construction needs around the world. It is the material to build climate resilient cities and coastal protection. Steel also enables major GHG mitigation in other Industries including Solar, Wind, Transport, Infrastructure, Energy, Packaging& Cement to name a few. Steel is infinitely recyclable and its by-products and waste energies are valuable

resources. Steel is integral to the global circular economy and thus the successful delivery and maintenance of a sustainable future. India is well poised to become a global steel hub. With the recently announced PLI scheme, few gaps, which are mainly in speciality steel, are expected to be closed in few years. Enhanced availability of all types of steel shall open up new downstream and collateral industrial opportunities. India is already among the top few countries in terms

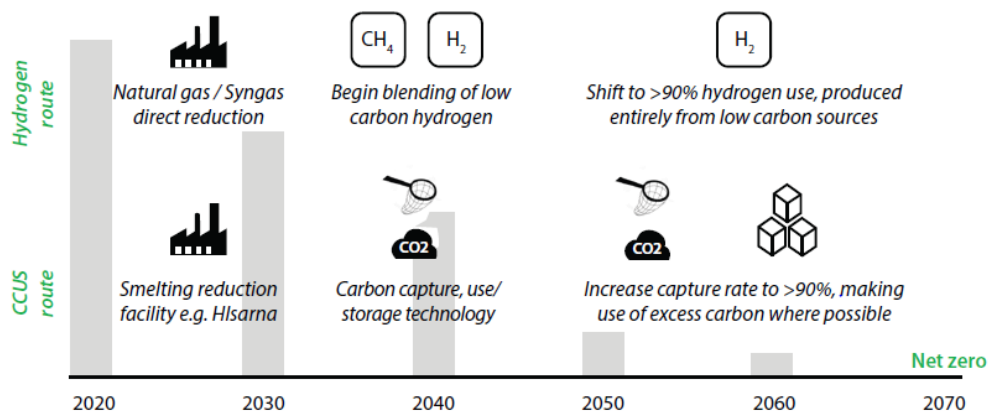


Figure 11: Probable Path for Net Zero in Indian Steel Sector by 2070

of renewable energy capacities and expanding at a rapid pace. Businesses across the globe will have the opportunity to balance their global carbon footprints through investments in India. India is at a crucial juncture of energy transition and with recent announcements of 2070 net-zero goals, it's imperative to focus on reducing energy consumption and associated CO₂ emissions from hard-to-abate sectors such as the steel industry. Moreover, commitment to sustainability and investors around climate action are driving major steel manufacturers and buyers to transition to steel produced from greener routes. Major GHG reduction in Indian Iron & Steel Industry will depend on adoption & scalability of breakthrough technologies including Carbon Capture & use of Hydrogen or any other environment friendly material including Bio-Coke or Natural Gas as a reducing agent. Green steel produced from processes such as green-H₂ DRI process, DRI process coupled with Carbon Capture, Utilization and Storage (CCUS) or direct electrification can lower CO₂ emissions bringing sector in alignment to climate goals, enhance energy security and lower costs. Probable path for Net Zero in Indian Steel Sector by 2070 has been shown in Figure 11.

Its high time to make iron & steel without coal. Innovative intent and Government

policies are going to play a big role in this decarbonization journey of Steel. The steel industry has made significant reductions in greenhouse gas emissions in the past decades by improving energy efficiency and deploying new technologies and practices, resulting in benefits to the environment and economies. Today Sustainability is the new competitive advantage for Corporates & it's very important for Indian Steel Industry to adapt, be actively engaged & strive to move towards a Low Carbon Industry by:

1. Enhancement of iron content & reduction of Alumina in Iron Ores by installation of beneficiation Plant in Mines. This will reduce fuel rate in BF.
2. Reduction of Scope 2 GHG emission by installation of combined Solar & Wind Power Plants at Cooling Ponds of Steel Plants
3. Judicious utilization of Heat & Waste Gas being generated at in Steel Plants for Energy efficiency using LD Gas Holder, TRT, CDQ & Reheating facilities.
4. Injection of Coke Oven Gas, LD Gas, Coal-Bed-Methane & Oxygen enrichment in Blast Furnace to reduce Fuel rate.
5. To enhance the use of Pellets in place of Sinter in BF.

6. Reheating of Sinter using Waste Gaseous.
 7. Logistic Re-engineering such as Hot charging of thin slabs directly to Hot Rolling Mill without the need of Reheating Furnace.
 8. Logistic improvement in SMS&CCS to increase the number of Heats.
 9. Increase percentage of scrap in steel making by recovery of more scrap from slag by using latest technology for scrap recovery.
 10. Energy efficiency in all the process by preventing heat loss by proper selection & utilization of refractory bricks.
 11. Shop wise plan with targets to enhance energy efficiency.
 12. Use of VVVF drives , IE3 Motors & LED lights to enhance Energy efficiency.
 13. Installation of large BF > 4000 m3 volume with operational discipline & stringent techno-economics parameters.
 14. Digital intervention for combustion Control System in BF , SP & Rolling Mills.
 15. Use of data analytics in processes to optimize the energy consumption in processes & feeding of gathered data to other system to optimize that process.
 16. Circular Economy -100% granulation of BF slag, 100% utilization of processed LD Slag, use of sludge for micro-pelletization, use of Mill-Scale & sludge for Briquettes making.
 17. Minimum rejection & Quality Control to avoid reworking and conserve resources.
 18. To enhance volume of production by reduction in break-down by use of Proactive maintenance.
 19. Cultural shift among employees for resource conservation.
 20. Earning Carbon Credits by reducing GHG reduction as per the provision of Energy Conservation Act 2022.
 21. Adoption of latest technology & energy efficient route in up-coming expansion-cum-modernization of Steel Players.
 22. Carbon capture from Flue Gas using Solid observant.
 23. Massive tree plantation for Carbon sequestration.
 24. Installation of one pilot plant for steel making using DRI-EAF route.
 25. Recovery of Hydrogen from Coke Oven Gas using PSA.
 26. Promoting community participation for GHG reduction.
- The profitability & sustainability of Steel Industry will depend on the pragmatic view of Steel Makers and their ability to quickly transform themselves into Energy Efficient organizations with maximum utilization of heat, gaseous & other waste products, to improve productivity in line with the concept of Circular Economy. Sharing of resources & collaborative approach to find a path-breaking less carbon Intensive route for steel making will be key to the future.

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Flat steel products are fundamental to modern manufacturing and construction, serving as crucial materials in a wide array of industries. From automotive components and household appliances to building structures and packaging materials, flat steel's versatility and strength make it indispensable.

The flat steel industry has seen numerous technological advancements that have enhanced product quality and production efficiency. Key developments include:

- Advanced Coating Technologies
- Precision Manufacturing
- High-Strength and Specialty Steels
- Sustainability Initiatives

The advancements in flat steel products have had a profound impact on both industry and society. In the industrial realm, these products have enabled the creation of safer, more efficient, and more durable materials. The automotive industry's use of high-strength steel, for example, has led to safer vehicles with improved fuel efficiency.

On a societal level, the widespread use of flat steel products has contributed to improved living standards. Household appliances and infrastructure developments have enhanced everyday life by providing reliable and durable solutions. Additionally, the impact of flat steel products on the economy cannot be overstated; they support numerous jobs and contribute significantly to global trade.

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