ISSN 0972-0480 • Vol. 25 No. 10 • October 2022

IIM METAL NEWS

A monthly publication of The Indian Institute of Metals

Crude Steel production by region (Oct)

	Oct 2022 (Mt)	% change Oct 22/21	Jan-Oct 2022 (Mt)	% change Jan-Oct 22/21
Africa	1.4	2.3	12.5	-5.6
Asia and Oceania	107.3	5.8	1,145.3	-2.1
EU (27)	11.3	-17.5	117.1	-9.2
Europe, Other	3.7	-15.8	38.4	-9.8
Middle East	4.0	6.7	36.4	7.7
North America	9.2	-7.7	94.0	-4.7
Russia & other CIS + Ukraine	6.7	-23.7	72.6	-19.0
South America	3.7	-3.2	36.4	-4.5
Total 64 countries	**147.3**	**0.0**	**1,552.7**	**-3.9**

The 64 countries included in this table accounted for approximately 98% of total world crude steel production in 2021. Regions and countries covered by the table:

- **Africa :** Egypt, Libya, South Africa
- **Asia and Oceania :** Australia, China, India, Japan, New Zealand, Pakistan, South Korea, Taiwan (China), Vietnam
- **European Union (27)**
- **Europe, Other :** Bosnia-Herzegovina, Macedonia, Norway, Serbia, Turkey, United Kingdom
- **Middle East :** Iran, Qatar, Saudi Arabia, United Arab Emirates
- **North America :** Canada, Cuba, El Salvador, Guatemala, Mexico, United States
- **Russia & other CIS + Ukraine :** Belarus, Kazakhstan, Moldova, Russia, Ukraine, Uzbekistan
- **South America :** Argentina, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela

Top 10 steel-producing countries

	Oct 2022 (Mt)	% change Oct 22/21	Jan-Oct 2022 (Mt)	% change Jan-Oct 22/21
China	79.8	11.0	860.6	-2.2
India	10.5	2.7	103.8	6.1
Japan	7.3	-10.6	75.2	-6.5
United States	6.7	-8.9	68.1	-4.8
Russia	5.8 e	-11.5	60.4	-6.6
South Korea	5.1	-12.1	55.7	-5.0
Germany	3.1	-14.4	31.4	-6.9
Türkiye	2.9	-17.8	30.2	-10.1
Brazil	2.8 e	-4.5	28.7	-5.2
Iran	2.9	3.5	25.1	9.0

e - estimated. Ranking of top 10 producing countries is based on year-to-date aggregate

Source : worldsteel.org

IIM METAL NEWS

Vol. 25 No. 10 October 2022

E-mail: secretarygeneral.iim@gmail.com, iimmetalnews@yahoo.com
Phone: 033-2367 9768 / 2367 5004
Website: www.iim-india.net
Fax: (033) 2367 5335
Facebook - https://www.facebook.com TheIndianInstituteofMetals/
Instagram - https://www.instagram.com/indianinstituteofmetals/
LinkedIn - https://www.linkedin.com/company/the-indian-institute-of-metals/
Twitter - https://twitter.com/iimetals_india

THE INDIAN INSTITUTE OF METALS

Obituary Dr. J J Irani, Former President, IIM, 1985-86

Late Dr J J Irani
[2nd June 1936 – 31st October 2022]
Former President, The Indian Institute of Metals

With a deeply pained and heavy heart we convey that Dr. J J Irani, Former President (1985-86) and Honorary Member of IIM had left for the heavenly abode. The IIM fraternity deeply mourns his sad demise.

A distinguished metallurgist from Nagpur University with a doctorate from the University of Sheffield, Dr. Jamshed J. Irani started his illustrious career as senior scientific officer in 1963 at the British Iron & Steel Association, Sheffield.

He will be remembered as a visionary leader who led Tata Steel from the forefront during India's economic liberalization in the early 1990s and contributed to the growth and development of the steel industry in India.

Besides Tata Steel and Tata Sons, Dr. Irani also served as a Director of several Tata Group companies, including Tata Motors and Tata Teleservices. He was conferred with the Padma Bhushan in 2007 for his contribution to the industry. He was the recipient of the Lifetime Achievement Award by the Government of India in 2008 as an acknowledgment of his services in the area of metallurgy. Dr. Irani was the pioneer of the quality movement in India.

He enabled Tata Steel to reinvent itself with a focus on quality and customer satisfaction while becoming the lowest-cost steel producer in the world having quality to compete with the best in the international market. After his retirement from services, Dr. Irani continued to contribute his immense knowledge and experience in diverse fields.

As a President of The Indian Institute of Metals during 1985-86, Dr. Irani led from the front. His contributions towards the Institute and the metallurgical fraternity are of huge magnitude through pursuit of quality management in metallurgy and materials science. Dr. Irani envisioned IIM as a global body, and during his tenure he worked towards establishing collaborations between industry and the Institute.

Dr. Irani, also known as the STEEL MAN of INDIA will be profoundly missed by all stakeholders.

Interview Dr. Tata Narasinga Rao, Director (Additional Charge), ARCI

Dr. Tata Narasinga Rao
Director (Additional Charge)
at ARCI

1) Which is the main focus of your laboratory which, we understand, has a special status within DST and has a unique structure?

- Major focus of ARCI is on materials technologies and the mandate of the centre is on translational research, taking the Laboratory research to high Technology Readiness Levels (TRLs) as well as to transfer to Indian Industries.

2) How do you inspire your scientists to focus on innovative research?

- Interaction of Director of the centre with the scientists on one-to-one basis and nurturing the innovative ideas based on the potential
- Freedom to spend 40% of their time on publication-oriented research of their own interest in line with ARCI's mandate.
- Promotion of team work through creating think tank groups with multidisciplinary back ground.
- Incentive schemes
- Opportunities to interact with premier scientists /forums in the respective areas

3) What is ARCI's role towards different advanced manufacturing and new technologies being introduced for manufacturing?

- Identifying the critical technological gaps in the Indian context with respect to potential civilian and strategic sectorsa
- Addressing the gaps based on in-house expertise or through collaborations with technical capabilities in the respective areas
- Initiating new emerging research areas in line with National Technology Missions (e.g.: Energy storage, Hydrogen production, Additive Manufacturing etc.).

4) Which are the different advanced technologies that have been adopted by ARCI and demonstrated?

- Indigenous development of electrode materials (Li-ion, Na-ion, Supercapacitors) & devices for EV and stationary applications
- Development of high temperature materials and manufacturing technologies for improved life, better performance and higher productivity of coal-based power generation plants.
- Development of powders for additive manufacturing, thermal spray coatings and niche applications of powder metallurgy

- Development of technologies for utilisation of indigenously available rare earths and magnets for motor applications
- Indigenous production of low-expansion glass ceramics for application in strategic and civilian sectors

5) Considering the National and International scenario, regarding the adoption of advanced manufacturing, which are the immediate challenges?

- Cost effective alternative energy technologies
- Technologies for zero emissions
- Recycling process for waste like Li-ion batteries

6) How do you benchmark your product technologies?

- Evaluate the technologies with respect to TRL and also Products Readiness Level.
- Target the properties at par with international market leaders

7) Do you organize regular workshop/training programs for the members of ICC?

- Yes, ARCI gives priority to the workshop/training programmes organised by ICC time to time.

8) Have you framed any plan to promote/inspire the lady scientists in your or any of the Indian laboratories such as ARCI?

- No specific plan is in place. However, ARCI is always aware of gender balance and keen to provide opportunities to women scientists in important committees and responsible positions to promote them
- Regular deputation of women scientist for participation in empowerment programmes arranged from time to time.

9) Is there any role of public relationship for the promotion of research?

- For societal applications-based development, public relationship can definitely help and also can attain better visibility.

10) What are your visionary plans for ARCI and how do you see it in National building programmes such as AtmaNirbhar Bharat & International initiatives for zero emissions by 2070 or earlier?

Activities at ARCI are planned with a vision and in-line with both Atma Nirbhar Bharat & international initiatives for zero emissions. For example,

- Indigenisation of electrode materials for EV and stationary applications
- Indigenous development of solar energy materials and systems for solar thermal and photovoltaic applications
- Development of powders for additive manufacturing, thermal spray coatings and other niche applications.
- Indigenous production of low expansion glass ceramics for application in strategic and civilian sectors.
- Progress achieved at ARCI till now indicates that ARCI would be able to make significant contributions towards national building programmes such as AtmaNirbhar Bharat & international initiatives for zero emissions.

Brief Bio of Dr. Tata Narasinga Rao

Dr. Tata Narasinga Rao received his Ph.D. degree in Chemistry from Banaras Hindu University, India in 1994. After having worked at IIT Madras as Research Associate, he moved to The University of Tokyo in 1996 as a JSPS post-doctoral fellow and later became lecturer in the same University in 2001. He joined International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad, India, in 2003 as Senior Scientist, and at present is the Director (Additional Charge) at ARCI. In addition, he is an Adjunct Professor at IIT Hyderabad.

Dr. Rao is known for his translational nanomaterials research. His research contributions in the field of electrochemistry and nanomaterials later led to several technologies at ARCI which made the Institute well-known in the field of nanotechnology in India. Basing on this S&T and R&D, Dr. Rao has published more than 190 research papers and filed/granted more than 20 international and Indian patents, several of which have been translated to technological developments. His publications got more than 16000 citations with an h-index of 51 and the average Impact Factor for his publications of last 5 years is above 5. Apart from these, seven of the technologies developed by his team have been commercialized. His present interest is on emerging fields like supercapacitors, Na-ion batteries, Room temperature Na-S batteries and Li-Sulfur batteries. Other areas of Dr. Rao's research interest include Solar Energy Materials, Photocatalysis, Diamond Electrochemistry, Bio Sensors/Devices. He is a mentor of biomedical working group at ARCI with special focus on additively manufactured biomedical devices and bio-compactable coatings. He has also significantly contributed to UVC-based systems and copper-coated masks for Covid-19 disinfection during recent pandemic. The copper-based masks (under a Nano Mission project) were shown to fight effectively against SARS CoV 2. Several thousands of the self-disinfecting masks were produced and distributed.

He is the recipient of several awards and honors including 'Material Research Society of India (MRSI) Medal -2009'; 'Tokyo University of Science President Award-2014'; 'Academician of Asia Pacific Academy of Materials (APAM)-2015'; 'Technology Day National Award-2016' (received from President of India); Fellow of Telangana & AP Academy of Sciences-2017; and 'Bangalore India Nano Innovation Award-2018'. Recently, Dr. Rao has been selected for 'Materials Science Annual Prize-2022 of MRSI'.

****

Technical Article

A Comprehensive Review on Ti-Alloy Research and Recent Trends

Sujoy Kumar Kar, Trideep Banerjee

Abstract

In this article, an attempt is being made to comprehensively review the diverse aspects across the important and emerging fields related to titanium alloys. Ti-alloys, owing to their high specific strength, excellent corrosion resistance along with their sensitivity to thermo-mechanical treatments find their applications which are otherwise difficult to be compensated by many other conventional alloy systems. This article emphasizes the fundamental aspects of physical and mechanical metallurgy of Ti-alloys, in relation to processing, microstructure evolution, mechanical properties, along with corresponding deformation mechanisms. Some open unanswered questions are also pointed out. In addition, contemporary developments in different manufacturing routes for titanium alloys accompanied with their benefits and concerns have been discussed in light of the simultaneous optimization of parameters and alloy development possibilities. Some sections mentioning the recent cost-effective trends in manufacturing of Ti-alloys and avenues for alloy-development studies have also been discussed.

1. Introduction

Anything that is to be flown should be made of materials of high specific strength; this ensures the desired performance with higher energy efficiency, and reduced cost and emission-related problems. There comes the attractiveness of Ti-alloys, due to their inherent lower density and higher strength (achieved through microstructure engineering), for applications in aerospace sector.

A metallurgist/ material scientist brings out the right set of mechanical properties (yield strength, ductility, fracture toughness, LCF etc.) through microstructural engineering for different alloys of Ti; it is done by variation in thermo-mechanical treatments, which produce variations in size, amount and morphology of various phases that are possible in the alloy system. A brief description of different phases follows.

Ti is an allotropic element, having HCP crystal structure (the α phase) that is stable at room temperature and above, till 882 ^{0}C, beyond which it changes to BCC β phase. The transition temperature is called the β-transus temperature. A significant majority of Ti-alloys is made of various proportions of these two phases, α and β, except those of TiAl-based intermetallic systems and SiC-based Ti-alloy composites.

Alloying additions like Al stabilize the α phase, whereas alloying elements like V, Mo, Cr, Fe stabilize the β phase; accordingly, the transition temperature goes up or down, as a function of composition. Extensive solubility of oxygen and nitrogen makes Ti-alloys unusual. These elements stabilize the α-phase to such an extent that α-phase forms directly from the liquid phase in some high oxygen alloys. This causes no or little formation of oxides, or nitrides or sulfides in Ti-alloys, unlike in many other ferrous or non-ferrous alloys. Carbon is another α-stabilizer, but does not have as much solubility as oxygen or nitrogen. Hydrogen is a β-stabilizing element. Boron does not have much solubility in both the α and the β phases. In Boron-containing alloys, α-phase forms through a peritectoid reaction between β phase and TiB phase. Decomposition of β-phase can give phases like ω-phase and martensite, along with the α-phase, as can be seen from figure 1. Depending on the alloy composition that dictates the stabilities of these various phases, Ti- alloys are classified into different categories namely, α or near α-alloys, α+β alloys, age-hardenable high strength β-alloys and β-alloys.

Structural components of aircrafts are largely made of high strength βTi alloys, mainly because of their

IIT Kharagpur

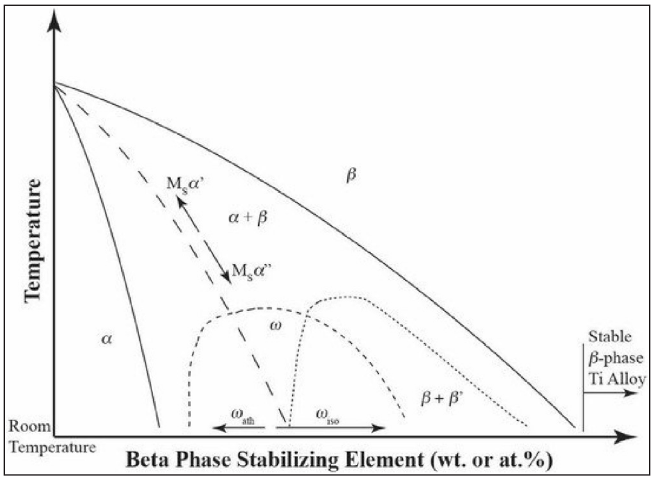


Fig. 1 : A schematic of a pseudo-binary isomorphous phase diagram [1].

superior combination of strength and fracture toughness. In fact, the largest forged component of a commercial aircraft, the landing gear component that connects the landing wheels to the cockpit is now-a-days made of high strength βTi alloys like Ti-5Al-5Mo-5V-3Cr. In an aero-engine, the front fan earlier used to be made of Ti-alloys, which is currently being made of composite materials. Inside an aero-engine, components prior to the combustion chamber experience a temperature less than 350 ^{0}C, and there, the Ti-alloys are preferably used. High temperature capabilities of Ti-alloys are limited by burn resistance, oxidation and by the approach to the β-transus (rather than the melting point), as the β-phase, having more open structure, exhibits higher diffusivity. The high solubility of oxygen in titanium also is another factor that limits the long-term thermal exposure in application as it forms high volume fraction of brittle α-phase on the surface. The compressor section of an aero-engine is made of α+β Ti alloy, Ti-6Al-4V. Such α+β Ti-alloys show a range of combinations of strength, fracture toughness, and moderate temperature properties, that make them attractive to be used in wide applications in aerospace sector. βTi alloys find another big application in bio-medical field. This is due to their bio-compatibility, corrosion resistance and their relatively low stiffness, comparable to that of bones. For bone replacement, βTi alloys are used for their comparable stiffness with bone, which helps equal load distribution between the replaced part and the existing bones. αTi alloys are used where corrosion resistance is of more concern, rather than strength; such application includes heat exchangers in industries. Even with such attractive applications for Ti-alloys, the major barrier to its full-fledged application in wider areas is its cost, which mainly comes from the cost of its extraction which involves reduction of Ti-rich oxides and chlorides. Though alternative extraction routes have been researched in laboratory levels, scaling up has remained a problem and is still an open area of research.

In this backdrop, we shall now discuss various aspects of research in Ti-alloys, that have been going on through many decades as well as the recent trends. Conventional research areas are classified here into Thermo-mechanical processing, Microstructure and its evolution, Properties as a function of microstructure and composition. Recent advancements in Ti-research are also subsequently discussed; these consist of various aspects of Additive (AM) and powder metallurgy (PM) manufacturing processes, like alloy design through exploration of new compositional regimes, porous Ti alloys, and related microstructure and properties.

1.1. Thermo-mechanical processing

Ti-alloys are thermo-mechanically processed in the β-phase field or in the α+β phase field. The common practice for all Ti-alloys after melting and homogenizing the ingot is to work in the β-phase field to break the cast structure, followed by initial recrystallization of β-grains by heating in the β-phase field. Subsequently, it is also worked through the β-transus temperature to maintain the fine β-grain structure. This is followed by working in the α+β

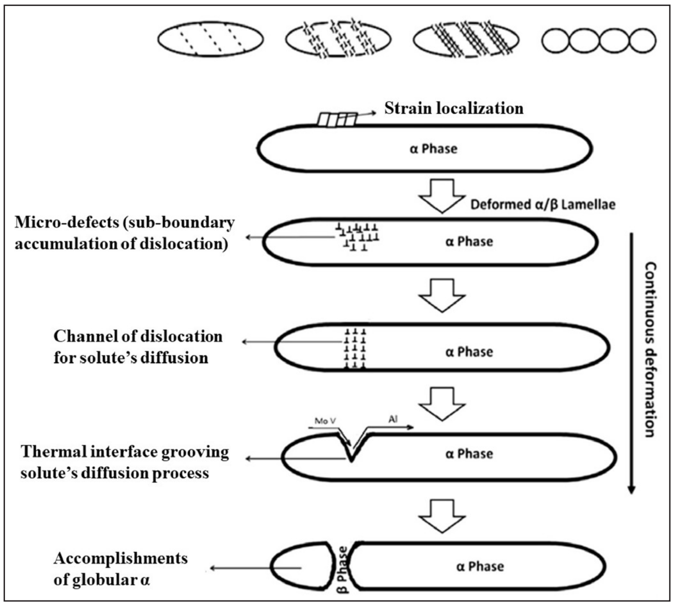


Fig. 2 : Schematic showing globularization mechanisms during α+β recrystallization [2].

phase field, coupled with annealing treatment in the α+β phase field, for α-alloys to have controlled α-grain size and texture, and for the α+β or metastable β-alloys to obtain recrystallized globular α in the resulting bimodal microstructure. During this subtransus thermo-mechanical treatment, both α laths breakdown and their recovery and recrystallization and recrystallization of the β-phase occur as shown schematically in figure 2. Although, it has been found that α lath globularization process depends on the amount of strain, the initial lath size and orientation; however, no quantitative physics-based model has yet been developed for this process.

Microstructure and texture evolution during such processes involve evolutions of deformation texture and recrystallization texture of individual phases, as well as transformation texture for the forward and the reverse transformations between the β and the α-phases. Texture evolution is guided by the Burger's Orientation Relationship (BOR) between the α and the β-phases (BOR is described in the following section). A thorough understanding of the evolutions of microstructure and texture is necessary to correlate the processing with the material's plasticity and fracture behavior.

1.2. Evolution of phases and Microstructure

During solidification, usually β-phase is the primary solid phase. Higher content of β-stabilizing elements causes segregation during solidification. Better melt practices should be employed, facilitated by improved solidification models, to tackle the problems of segregation. Boron addition has been found to refine the solidification structure to a large extent. The reason sometimes is ascribed to constitutional supercooling; continuous formation of β grains in undercooled liquid leads to refinement. Addition of Boron results into breakdown or complete removal of grain boundary α (GB α). It renders better cohesive strength of grain boundaries and provides thermal stability against grain coarsening.

During cooling from the β-phase, α-phase first forms on the prior β-grain boundaries, then inside grains. It is difficult to avoid GB-α and it affects fracture toughness and other mechanical properties by providing an easy path for crack growth. As a result, these properties depend on the grain boundary α thickness. α- phase maintains a Burger's Orientation Relationship (OR) with the β-phase $(0002)_\alpha \| \{110\}_\beta$ and $\langle 2\bar{1}\bar{1}0\rangle_\alpha \| \langle 111\rangle_\beta$. There are 12 possibilities of α-orientations maintaining such OR, which are called different variants of α. GB-α maintains OR with grain of one of its sides as shown in figure 4. α inside grains primarily forms in Widmanstatten morphology (lath or needle shape). Between two α-laths there is a rib of β-phase. Similarly-oriented α-laths with β-ribs in between them form a colony. Sometimes, a cluster of different variants of α forms, giving a basketweave morphology in place of colony.

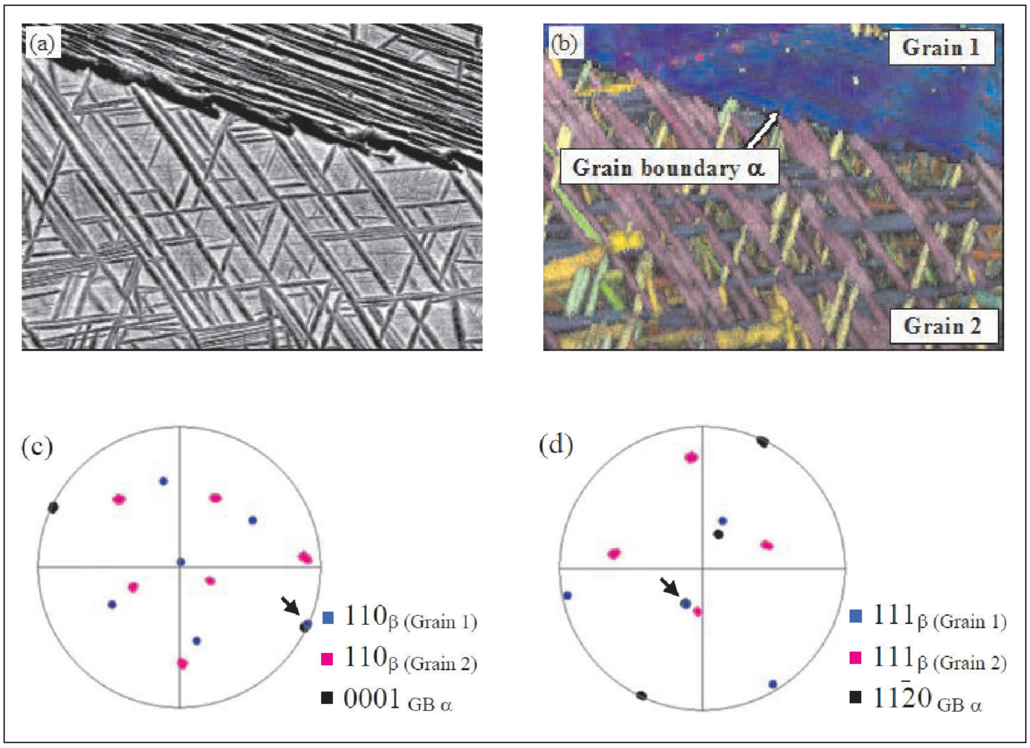


Fig. 3 : Colony grows in that side of the grain, β of which has the Burgers Orientation Relationship with the grain boundary α.[3]

Basketweave microstructure preferentially forms at lower transformation temperature, that realizes under fast cooling for α-stabilizing element rich alloys or during isothermal ageing of β-stabilizing element rich alloys which can be seen in the CCT plot in Fig. 4. Some aspects of formation of colony vs. basketweave morphology are still of research interest. The reason behind maintaining identical variant among α-laths nucleated independently inside grains is still not clear; however, it is ascribed to a negative interaction energy that exists between two identical crystallographic variants oriented parallel to each other. In metastable β-alloys, under low undercooling condition, triangular arrangements of individual α-variants form. This arrangement is ascribed to self-accommodated variant distributions that minimizes elastic interactions; however, it might also be a result of a statistical consequence of random nucleation of the 12 crystallographic variants; this aspect is not completely clear.

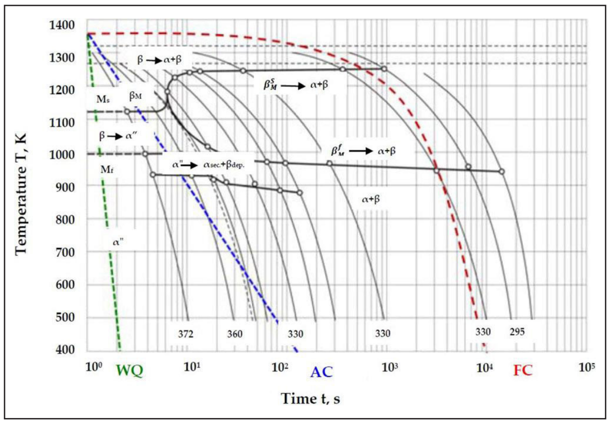


Fig. 4 : CCT diagram for Ti-6Al-4Valloy showing cooling curves of three different cooling methods [4].

Hot working followed by recrystallization treatment (below β-transus) ensures some of the α-laths to recrystallize yielding equiaxed morphology, resulting in a bimodal microstructure, where the α-phase inside grains remains in both lath as well as globular morphology. Bimodal microstructure gives good ductility.

On quenching of α or α+β Ti alloys, two types of matrensite can form depending on the composition; while in β-lean alloys, HCP martensite α′ forms, in β-rich alloys, orthorhombic martensite α″ forms. Upon quenching of βTi alloys, ω-phase forms from the β phase by a displacive mechanism involving various degrees of collapse of alternate pairs of {111} β-planes to an intermediate position; partial collapse gives trigonal symmetry, whereas complete collapse results in a hexagonal symmetry. Alloys have been mapped into different stability areas for the β decomposition products, martensite vs. ω, in the plot of Bo vs. Md, shown in Fig. 5, where Bo is the covalent bond strength of Ti with any other metal and Md is the d orbital energy level of the alloying element. However, the effects of alloying element for various such β-decomposition products are not fully understood. For example, although the elements Al, Zr, Sn and O are known not to stabilize the β-phase, still they have been shown to retard the ω transformation and decrease the Martensitic start temperature (M_s). Interface movements in marternsitic transformation in a β-matrix containing ω-phase are also less understood.

Understanding the Ti-alloy microstructure in three-dimension has been the focus of many recent researches. With the advent of advanced characterization tools like dual beam FIB, it is now possible to image different sections through ion milling, and then three dimensionally reconstruct the microstructure from the individual images. 3-D quantification of microstructure is also of recent research focus, with the use of advanced image analysis software, like MIPAR. Fig. 6 illustrates the sequential manner in which 3-D reconstruction can be done using FIB-SEM and MIPAR image reconstruction module.

Simulation of microstructure evolution in Ti-alloys needs valid thermodynamic and kinetic databases. Although there are some commercially available databases, their description should be continuously upgraded for the databases to be valid for new alloys.

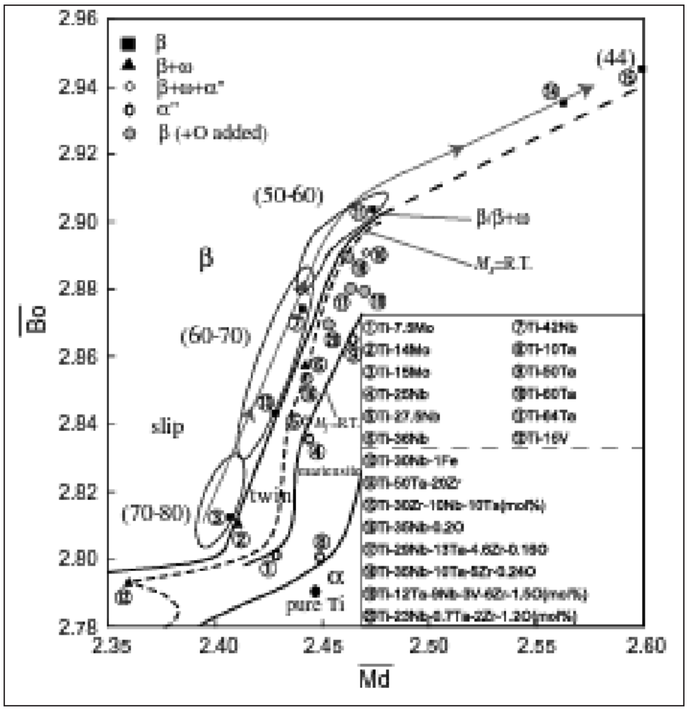


Fig. 5 : Extended 2.40 Bo 2.45 Md 2.50 2.55 Md diagram in which the β/ β+ω phase boundary is shown together with the boundaries for Ms = RT and for Mf =RT[5].

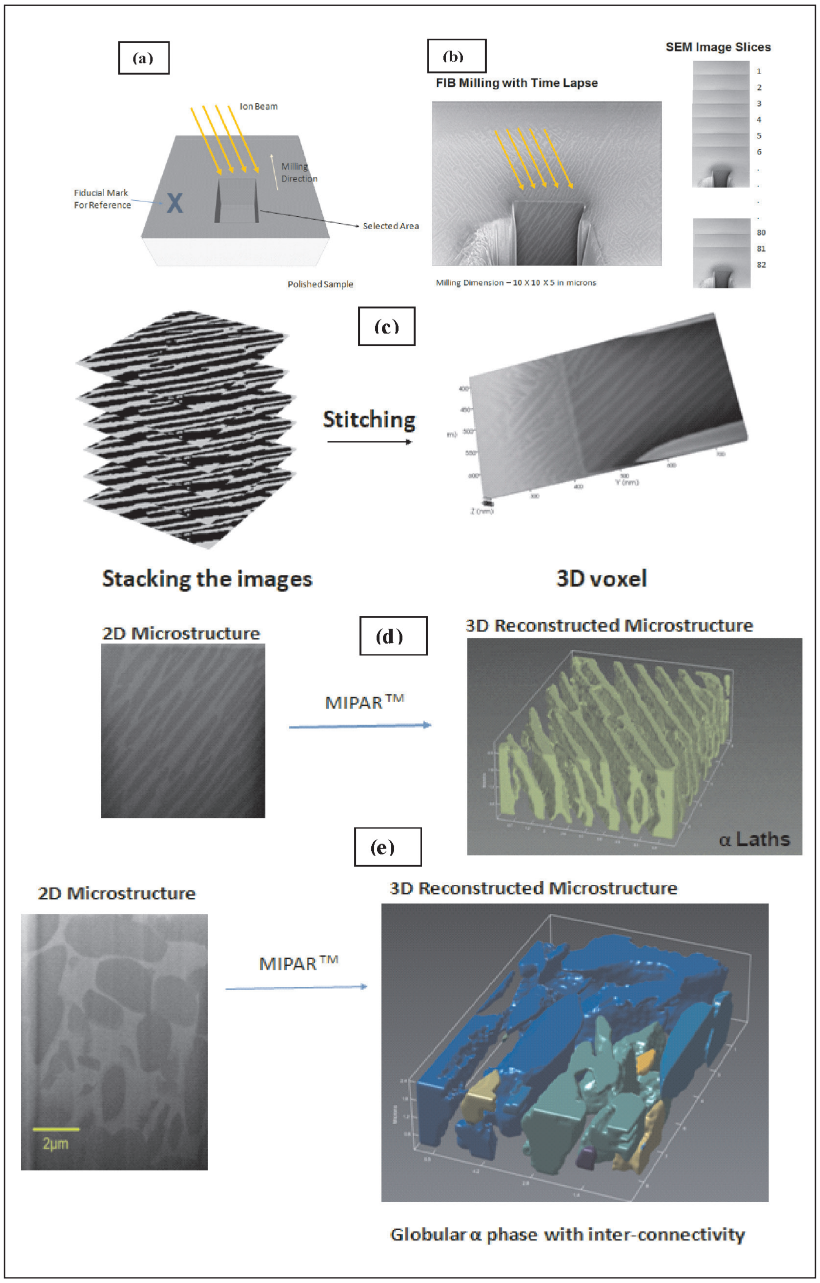


Fig. 6 : (a) FIB-SEM for 3D-data acquisition; (b) FIB milling with time lapse; (c) Reconstruction of 3D Microstructure; (d) 2D and 3D microstructure image of β annealed sample; (e) 2D and 3D microstructure image of Bimodal sample.

2. Properties as a function of microstructure and composition

2.1 Modulus, strength and flow stress

In αTi-alloys, there is anisotropy in the Young's modulus, being higher in the 'c' direction as compared to the 'a' direction; however, as the temperature approaches the β-transus temperature, anisotropy decreases. These alloys also exhibit high anisotropy in plastic deformation behavior. Tanaka and Conrad [5] showed that the 'a' slip is the easiest in the prism plane; but with increasing interstitial or Al content, basal or pyramidal slip also gets activated. α-grains having orientations that do not allow 'a' slip, usually deform by twinning on pyramidal planes. Plasticity in pure Ti depends on a combined effect of 'a' slip and twinning. Interstitials, such as O, along with substitutional elements like Al, Sn, Zr harden the α-phase. Interstitials cause dynamic strain ageing too. Al and O are found to suppress twinning, to favor planar slip, and to activate non-basal 'c+a' slip. Since 'c+a' slip has significantly higher critical resolved shear stress (CRSS) than 'a' slip, grains along 'c' become much stronger. This phenomenon is utilized in sheet metal forming of αTi-alloys; formability is significantly improved by making the sheet metal textured, so that most of grains' 'c' direction is perpendicular to the sheet, so that the through thickness strengthening gives less chance of excessive thinning during forming process. Some open research areas in mechanical behavior of α-Ti-alloys include the effect of alloying elements on core spreading of 'a' dislocations and subsequent effect on plasticity, combined effect of grain size, strain rate and alloying on twinning.

Highly stabilized β-Ti-alloys are mainly used for bio-implant applications, where modulus is the key property, and the aim is to have an alloy with low modulus. With decreasing electron/ atom (e/a) ratio, the modulus decreases; however, the β-phase instability to form martensite and/ or ω increases. Alloying strategy for bio-implant application (i.e., for low modulus) should be such that these decompositions get suppressed below room temperature with the lowest possible e/a ratio[6], [7]. Additionally, effects of Zr, Sn and O on suppressing martensite and ω transformation should also be taken into consideration for alloy design[8], [9] . The main plastic deformation mode in the β-phase is slip, and most often planar slip is observed in presence of coherent nano ω particles.

Strength in the α+β Ti-alloy primarily comes from the resistance to dislocation movement at the interfaces. α-phase accommodates the initial strain through slip as the β becomes harder being plastically confined by the surrounding laths and high concentrations of partitioned solutes in transformed β. In high strength β-alloys, where the β-phase has more continuity and the plastic constraint is removed, the β phase becomes softer of the two and slip initiates in it. Slip transfer depends on a variety of factors, like: i) Difference in length of Burger vectors of the two phases; (ii) Change in values of modulus between the two phases; (iii) Distance between obstacles to dislocation and the nearest interface determining dislocation build-up at interface; and (iv) reciprocity between glissile dislocations and geometrically necessary dislocations at the interface. Finer the α-laths, more are the numbers of α/β-interfaces; hence, more would be the yield strength. Consequently, control of α-phase size, morphology and distribution of its orientation variants are of fundamental importance in determining the properties of α+β titanium alloys. In case of basketweave microstructure, slip transfer across the α/β-interfaces is even more complicated. Microstructural features that determine the yield strength are thickness of α-laths, volume fraction (vf) of α, colony size, vf of colony vs. basketweave microstructure, etc.

Strength and ductility in bimodal microstructure depend on some additional features like size and volume fraction of globular α, along with the lath thickness and colony size in the transformed β-region (laths of α/β). In bimodal structure, slip initiates in the globular α-particles. Hence, in bimodal microstructure the yield strength does not significantly depend on the transformed β-constituent; however, post-yield flow stress at higher strain becomes strongly dependent of the transformed β-constituent.

2.2 Ductility

Usually, Ti-alloys under normal loading fails through ductile mode. Fracture initiates by formation of micro-voids at interphase interfaces, which are usual sites for strain incompatibility. Those sites include sides of GB α, or globular α or α-laths. Because of usual low work-hardening rate in Ti-alloys, easier void growth is promoted, resulting in ductile fracture at relatively low strains. Very low ductility fracture scan also arises from conditions that promote planar slip and severe strain localization. Such cases can happen in the α-phase by presence of oxygen and aluminum contents beyond critical levels that promote short-range order in this phase. In the β-phase, such strain localization can happen because of the presence of high volume-fractions of ω phase and extremely fine α-particles in β.

2.3 Fracture Toughness

Fracture toughness is usually related to the tortuosity of crack paths and depends on features like thickness and continuity of GB-α, aspect ratio of α-laths, prior β-grain size etc.

Ti-alloys usually show an opposite trend between fracture toughness and tensile ductility. Therefore, a given microstructure can only attain excellence in either of these two properties.

2.4 Creep

Creep of the α-phase is better than those of the β, because of the intrinsically lower diffusivities in its close packed structure. Nevertheless, the α- phase can accumulate relatively large plastic strains at ambient temperatures under constant loading conditions below its yield stress. Primary creep strains in titanium are quite high, leading to significant strain accumulation even at room temperature. This room temperature creep sensitivity of Ti-alloys makes them very sensitive to dwell fatigue. However, there is a high variability in the primary creep strain which is a problem for designing rotating parts with tight clearances between them and the static surroundings, as in aero-engines. Steady state creep is believed to be controlled by deformation processes in the α-phase. Sliding at the interfaces of α/β and α/α has often been reported as contributing to creep strains[10],[11]; as a result, equiaxed α and very fine α-laths show low creep resistance which decreases with vf of equiaxed α. Si in solid solution imparts creep resistance due to dynamic strain ageing. Trace levels of Fe and Ni are known to lower the creep resistance.

2.5 Fatigue

In bimodal structure, fatigue deformation and crack initiation usually occur in the primary α-particles. Ti-alloys show strong sensitivity to dwell fatigue, even at ambient temperature. It has led to uncontained disc failures in aero-engines in the past. Texture and hard α-orientations play an important role towards this sensitivity to dwell; and crack initiation usually happens in hard α grains in sub surface. Whereas, in case of fatigue with no dwell, crack nucleation usually happens on surface. Hydrogen also might have a damaging contribution to dwell fatigue; it should be investigated in detail.

2.6 Property model as a function of microstructure

There are varieties of microstructural features, with distinct morphology and size, that collectively dictate mechanical properties. Experimentally one cannot vary each of the different microstructural features independently of the others. Neural network-based approach [12] can extract trends in mechanical behavior as a function of different structural constituents from quantified microstructural features that are simultaneously varied. Fig. 7 and Fig. 8 show examples of these trends in strength and toughness extracted from such analyses. Detailed crystal plasticity analysis is also being used to understand thermo-mechanical response of two-phase titanium alloys. Modelling and simulation help to reduce the time and cost of qualifying materials for a given application. Good models however require sound physical understanding of the phenomena that govern the materials behavior.

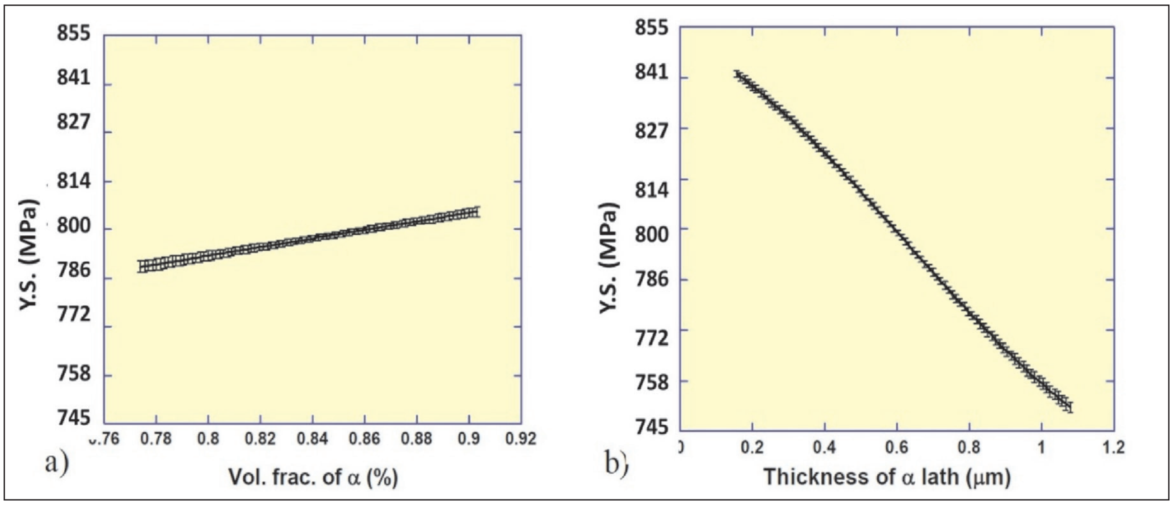


Fig. 7 : Trend plots of variation in yield strength (Y.S) with (a) vf of α, (b) thickness of α-lath, keeping other microstructural features constant [12].

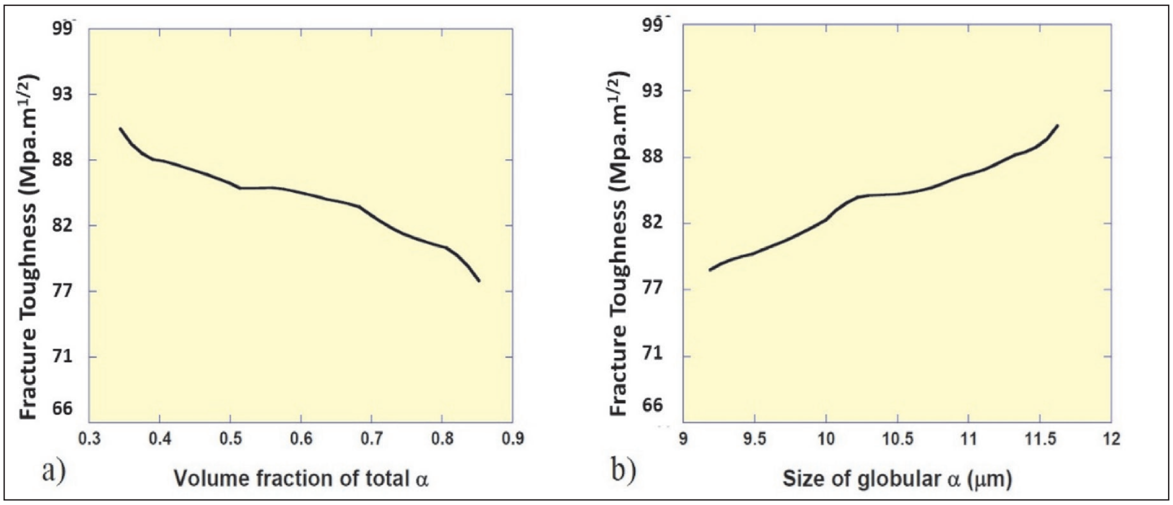


Fig. 8 : Trend plots of variation in fracture toughness of bimodal microstructure, with (a) vf of total α, (b) size of globular α, keeping other microstructural features constant [13].

3. Additive manufacturing processes

The applications of titanium alloys are restricted by the difficulty and high cost involving conventional manufacturing processes. Using additive manufacturing (AM) process, one can manufacture metallic components in near net shape. Some recent research progress in AM of titanium alloys is briefly described here.

The complexities associated with AM contribute to both the advantages and the drawbacks in AM of Ti-alloys. The process intricacies observed in AM techniques are mainly related to the complex thermal history experienced by consecutive layers together with the steep thermal gradients and high cooling rates. The steep thermal gradients decrease the propensity for constitutional supercooling-induced nucleation ahead of the solidification front, as a result of which long columnar grains form[14], [15]. The high cooling rate experienced in AM on one hand gives rise to high residual stresses and distortion while on the other hand enables AM techniques to stabilize metastable phases in β-Ti alloys and provides better strengthening owing to martensite formations in CP-Ti alloys or α+β Ti-alloys[16], [17]. The thermal cycling experienced by adjacent layers may decompose the metastable phases and sometimes results in recovery and recrystallization of α' and α-laths.

The process constraints in AM demand simultaneous development of suitable alloys. For example, for manufacturing metastable β-components, the alloys should be made highly hardenable for resisting any effect of thermal cycling. An alloying criterion which determines the potential to promote degree of constitutional supercooling is growth restriction factor, Q. Fe was found to increase the Q-factor when added up to 3% in Ti-6Al-4V premixed powder and yields equiaxed solidified grain instead of coarse columnar grains in Ti-6Al-4V premix without Fe, which can be seen in Fig. 9. Mo in the premix induces cellular solidification in place of columnar as it makes the columnar front instable and drives the solidification front towards the centre of the melt pool[18], [19]. Thus, with synergistic development of AM involving optimization of the process variables and concurrent alloy development can bring brighter future for near net shape additive manufacturing of Ti-alloys at low cost.

4. Powder metallurgy - Issues and solutions

The substantial alloy development studies in the field of powder metallurgy (PM) of Ti-alloys allows cheap but reliable ways to alleviate the existing technological and production cost related barriers. PM techniques can be uniquely steered to obtain the desired properties. In case of PM of Ti-alloys, two major challenges frequently encountered are residual porosity and interstitial impurities, mostly oxygen, picked-up in dissolved forms. These directly influence the mechanical properties of the PM-made Ti-alloys. Sintering of Ti-alloys under high vacuum

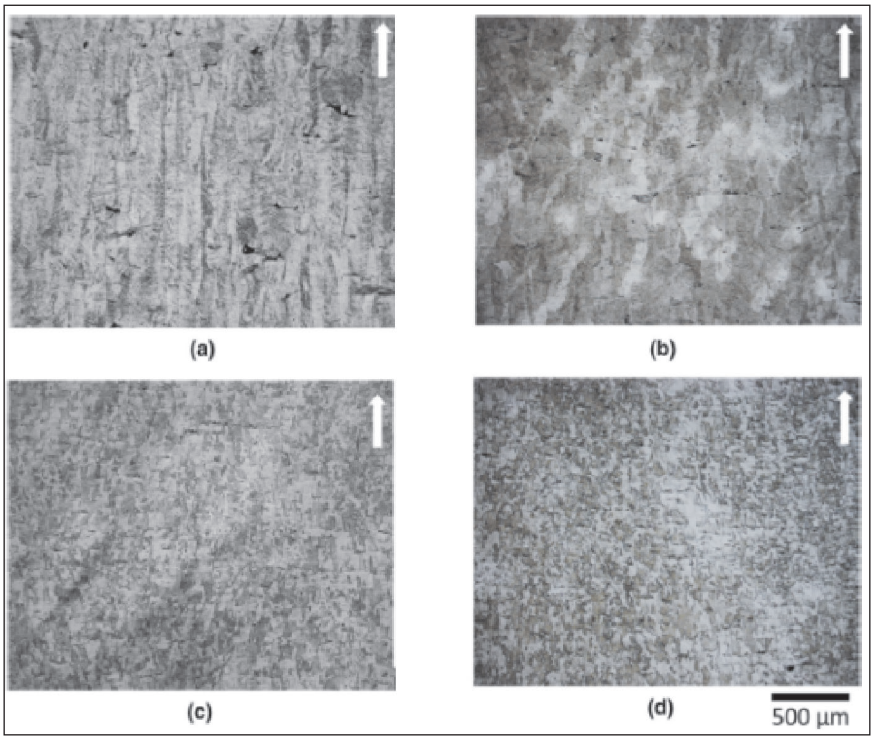


Fig. 9 : Optical micrographs of as-built samples revealing the microstructure: (a) Ti6Al4V, (b) (Ti6Al4V)-2Fe, (c) (Ti6Al4V)-3Fe, and (d) (Ti6Al4V)-4Fe. White arrows show the build direction. [20]

or with very high Ar gas partial pressures alleviate both the issues of impurity entrapment and residual porosity to some acceptable level [21]. However, long sintering time and high temperature requirements increase the cost of the PM approaches for Ti-alloys. In order to increase the economic viability of the PM routes, certain additions of low cost alloying elements like Fe, Al, Co, Si etc. are introduced; these alloying elements scavenge the impurities and increase the sintered densities of the products[22]–[25]. In PM route, a remarkable benefit is the ease of alloy modification. One can obtain a desired composition of base alloy with simple adjustments in the blending of powders. Among the different ways of alloy powder blending, elemental powder mixing provides the easiness but, tends to suffer from poor mechanical properties [26]. Pre-alloying of powder, on the other hand, provides increased sintered densities with a little restriction on alloying flexibilities[27].

Sintering tends to depend a lot on the metal-powder particle-size distribution, where, obtaining fine distribution of metallic powder by optimizing the colloidal chemistry is of prime importance [28]. In recent studies, Ti-alloy-based bulk metallic glasses and nano-structured Ti-alloys were reported to attain properties at par with high performance materials [23]. Amorphous Ti-powders obtained through mechanical alloying, after being subjected to spark plasma sintering, are found to yield sintered densities comparable to those of bulk Ti-alloys. Categorically, there are two ways to distinguish the sintering aids for Ti-alloys: First, the elements which increase the self-diffusion of Ti and thereby help in enhancement of densification on sintering. This kind of elements mostly includes the transition metals and phosphorous which specifically decreases the solidus temperature of the mixture. The second kind of alloying elements as sintering aids forms a liquid or semi-liquid state at sintering temperatures. This liquid phase then enables rapid mass transport among the consolidated agglomerates. In certain cases, two metastable precipitates form a liquid through a eutectic reaction between them, thereby facilitating local densification[23]. However, the presence of the liquid phase brings with it some typical issues related to shape distortion, solid-liquid segregation and rapid grain growth, which add to the cost owing to further processing requirements.

4.1 Effect of alloying additions on PM of Ti-alloys

Fe addition in Ti-powders exhibits higher Ti-self-diffusivity and also decreases densification time (Fig. 6). This is due to the Ti-Fe eutectic at 1081 ^{0}C that forms a transient liquid phase at the sintering temperature. Owing to the addition of Fe, the strength tends to increase while ductility deteriorates, mainly due to formation of Ti-Fe intermetallics [24]. Size of Fe-particles in the powder mixture affects the size of residual porosities in the sintered product. Fe-particles below 10-20 microns enhance densification of Ti-alloys by increasing the self-diffusion of Ti-atoms which results in homogenous microstructures and strengths comparable to those of bulk Ti-products[29], [30]. On the other hand, coarse Fe-particles increase the porosity. Also, presence of coarse Fe-particles leads to coarse β-Ti grains, further hampering the mechanical properties. Possible mechanisms for pore formation include Fe-diffusion in Ti, and the exothermic reaction of Ti-Fe intermetallic liquid and its simultaneous solidification [30].

In the studies involving powder blending of Ti-alloy with Ni-powders or with pre-alloyed Ti, it was found that Ni largely enhances the densification of Ti-alloys on sintering (Fig. 7)[27], [31], [32]. However, formation of intermetallics like TiNi and Ti_2Ni renders poor ductility to the sintered material.

Blending of Si with Ti-powders improves densification and mechanical properties, when added in a limited quantity. Si, somewhat like Ni, gives rise to transient liquid forming intermetallics and helps in densification. Furthermore, the intermetallics formation in case of Si-addition takes place at grain boundaries or lath boundaries, thus pinning the boundaries at elevated temperatures. However, Si-addition beyond 1 wt% results in coarse precipitates or GB network resulting into ductility deterioration [33], [34].

Rare earth elements like Yttrium, Erbium, Gadolinium, and Neodymium when added in elemental powder or in the form of their hydrides, silicides and borides show the potential of oxygen-scavenging at high sintering temperatures [33], [35]. Some heavy metals like Nb and Ce also show a similar tendency (Fig. 10). Besides elements, TiB and Ti-based silicates are also capable of removing oxygen or other interstitials from the PM Ti-matrix.

5. Ti with porous structures

Porous Ti, over a range of pore sizes ranging from 100-400 µm, is used in bio-implant application, because of efficient bone in-growth process, see Fig.11. Elastic modulus which is one of the most important mechanical properties for bio-implants, depends on the relative density (RD) of a porous material which in case of Ti-alloys, which can be seen in Fig. 13, and also on the relative fraction of open vs. closed pores. Under compressive load, at low RD-values, only bending of the pore-walls takes place as the main deformation signature, whereas increased RD-values result in more simple compression and extension of walls of open pores[37].

Monotonic compression behavior of porous Ti is quite poor as compared to the bulk Ti. The stages through which the pores-containing materials

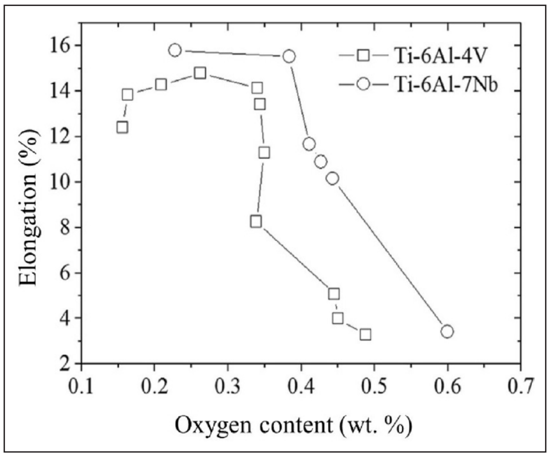


Fig. 10 : Elongation reduction by the increase of oxygen content in Ti–6Al–4V [36].

degrade can be seen in the Fig. 12a. Primarily, the strain path crosses the first transient to the plateau region after accumulation of a little strain. Until the strain remains with the second stage, i.e. the plateau region, the material takes the maximum of the total strain which remains low compared to that of the bulk. Once it reaches the tertiary region, the material fails rapidly.

Porous Ti-alloys show poor compression-fatigue property [38]. Porosity, surface finish and residual stresses are found to be the prime deterrents in lowering of fatigue endurance limits [39].

In spite of all challenges sustaining with development of porous Ti-components and their performances, some intelligent choices regarding combination of pore sizes, their respective fractions and the techniques to fabricate can provide remarkable performance in the application of the porous Ti-alloys.

Summary

An alloy system as versatile as titanium alloys can serve several applications apart from their presently prevalent fields of aerospace, gas turbine, bio-medical implants, chemical industries and automobile applications where Ti-alloys are being extensively used in their different variants, are being extensively used. This article has given a comprehensive picture of Ti-alloy metallurgy, covering various aspects of processing, microstructure and properties. New advances in manufacturing through additive and powder metallurgy routes are enabling exploration of new alloy space in this system. The potential of

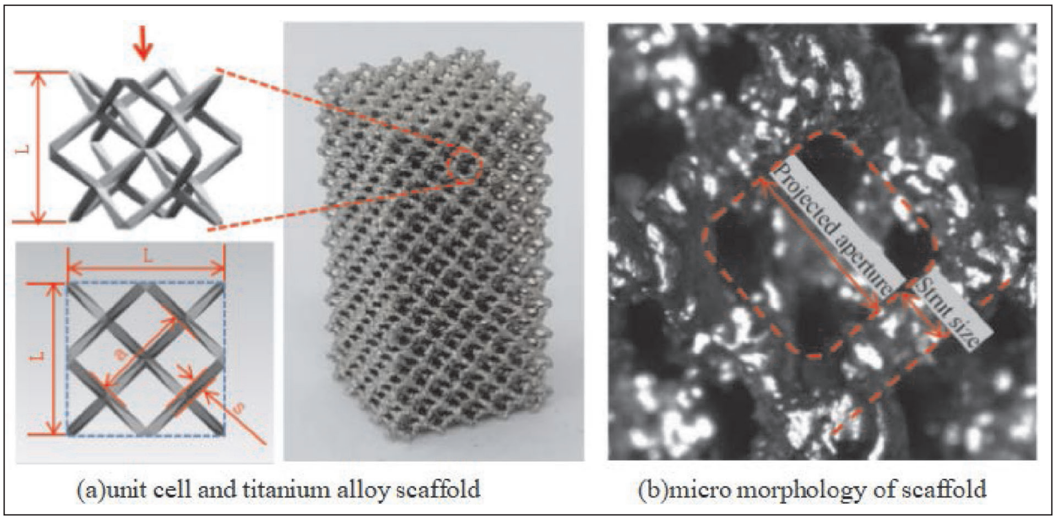


Fig. 11 : Titanium alloy scaffold built by unit cell: (a) Unit cell and titanium alloy scaffold, (b) Micro morphology of scaffold. [37]

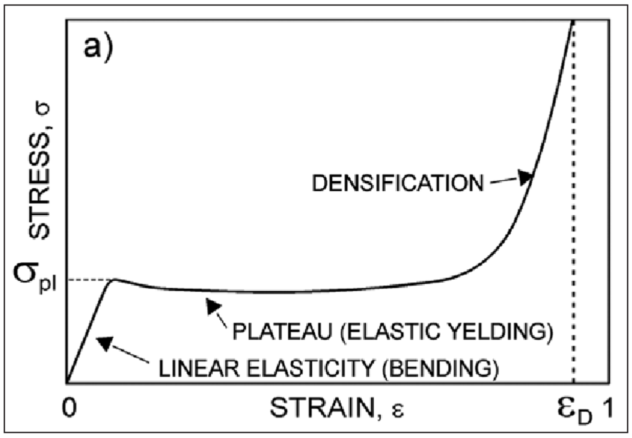


Fig. 12 : Compression stress–strain schematic curves for a common metallic foam: An elastic-plastic. [40]

Ti-alloys to serve even greater demand for materials can be achieved through collective and simultaneous technological progress, involving fundamental scientific understanding enabled by simulation of processing, microstructure and properties.

References

[1] R. P. Kolli and A. Devaraj, “A Review of Metastable Beta Titanium Alloys,” *Met. 2018 Vol 8 Page 506,* vol. 8, no. 7, p. 506, Jun. 2018, doi: 10.3390/MET8070506.

[2] J. Zhang, H. Li, and M. Zhan, “Review on globularization of titanium alloy with lamellar colony,” *Manuf. Rev.,* vol. 7, p. 18, 2020, doi: 10.1051/mfreview/2020015.

[3] E. Lee, R. Banerjee, S. Kar, D. Bhattacharyya, and H. L. Fraser, “Selection of α variants during microstructural evolution in α/β titanium alloys,” *Philos. Mag.,* vol. 87, no. 24, pp. 3615–3627, Aug. 2007, doi: 10.1080/14786430701373672.

[4] J. Sieniawski *et al.*, “Microstructure and Mechanical Properties of High Strength Two-Phase Titanium Alloys,” *Titan. Alloys - Adv. Prop. Control,* May 2013, doi: 10.5772/56197.

[5] T. Tanaka and H. Conrad, “Deformation kinetics for $\{10\bar{1}0\}\langle 11\bar{2}0\rangle$ slip in titanium single crystals below 0.4Tm,” *Acta Metall.,* vol. 20, no. 8, pp. 1019–1029, Aug. 1972, doi: 10.1016/0001-6160(72)90136-8.

[6] M. Tane *et al.*, “Low Young’s modulus of Ti–Nb–Ta–Zr alloys caused by softening in shear moduli c′ and c44 near lower limit of body-centered cubic phase stability,” *Acta Mater.*, vol. 58, no. 20, pp. 6790–6798, Dec. 2010, doi: 10.1016/j.actamat.2010.09.007.

[7] M. Tane *et al.*, “Low Young’s modulus in Ti–Nb–Ta–Zr–O alloys: Cold working and oxygen effects,” *Acta Mater.,* vol. 59, no. 18, pp. 6975–6988, Oct. 2011, doi: 10.1016/j.actamat.2011.07.050.

[8] Y. W. Zhang *et al.*, “Elastic properties of Ti–24Nb–4Zr–8Sn single crystals with bcc crystal structure,” *Acta Mater.*, vol. 59, no. 8, pp. 3081–3090, May 2011, doi: 10.1016/j.actamat.2011.01.048.

[9] S.-H. Lee, M. Todai, M. Tane, K. Hagihara, H. Nakajima, and T. Nakano, “Biocompatible low Young’s modulus achieved by strong crystallographic elastic anisotropy in Ti–15Mo–5Zr–3Al alloy single crystal,” *J. Mech. Behav. Biomed. Mater.*, vol. 14, pp. 48–54, Oct. 2012, doi: 10.1016/j.jmbbm.2012.05.005.

[10] *Titanium.* Berlin, Heidelberg: Springer Berlin Heidelberg, 2007. doi: 10.1007/978-3-540-73036-1.

[11] S. Ankem, H. Margolin, C. Greene, B. Neuberger, and P. Oberson, “Mechanical properties of alloys consisting of two ductile phases,” *Prog. Mater. Sci.*, vol. 51, no. 5, pp. 632–709, Jul. 2006, doi: 10.1016/j.pmatsci.2005.10.003.

[12] S. Kar *et al.*, “Modeling the tensile properties in β-processed α/β Ti alloys,” *Metall. Mater. Trans. A*, vol. 37, no. 3, pp. 559–566, Mar. 2006, doi: 10.1007/s11661-006-0028-8.

[13] S. Kar, “MODELING OF MECHANICAL PROPERTIES IN ALPHA/ BETA-TITANIUM ALLOYS,” Ph.D. thesis, Ohio State University, U.S.A, Center for the Accelerated Maturation of Materials (CAMM), Material Science and Technology, 2005.

[14] A. Prasad *et al.*, “Towards understanding grain nucleation under Additive Manufacturing solidification conditions,” *Acta Mater.*, vol. 195, pp. 392–403, Aug. 2020, doi: 10.1016/J.ACTAMAT.2020.05.012.

[15] D. H. Stjohn, M. Qian, M. A. Easton, and P. Cao, “The Interdependence Theory: The relationship between grain formation and nucleant selection,” *Acta Mater.*, vol. 59, no. 12, pp. 4907–4921, Jul. 2011, doi: 10.1016/J.ACTAMAT.2011.04.035.

[16] H. Attar, M. J. Bermingham, S. Ehtemam-Haghighi, A. Dehghan-Manshadi, D. Kent, and M. S. Dargusch, “Evaluation of the mechanical and wear properties of titanium produced by three different additive manufacturing methods for biomedical application,” *Mater. Sci. Eng. A,* vol. 760, pp. 339–345, Jul. 2019, doi: 10.1016/J.MSEA.2019.06.024.

[17] T. Ahmed and H. J. Rack, “Phase transformations during cooling in α+β titanium alloys,” *Mater. Sci. Eng. A*, vol. 243, no. 1–2, pp. 206–211, Mar. 1998, doi: 10.1016/S0921-5093(97)00802-2.

[18] B. Vrancken, L. Thijs, J. P. Kruth, and J. V. Humbeeck, “Microstructure and mechanical properties of a novel β titanium metallic composite by selective laser melting,” *Acta Mater.*, vol. 68, pp. 150–158, Apr. 2014, doi: 10.1016/J.ACTAMAT.2014.01.018.

[19] F. Huber, T. Papke, C. Scheitler, L. Hanrieder, M. Merklein, and M. Schmidt, “In Situ Formation of a Metastable β-Ti Alloy by Laser Powder Bed Fusion (L-PBF) of Vanadium and Iron Modified Ti-6Al-4V,” *Met. 2018 Vol 8 Page 1067*, vol. 8, no. 12, p. 1067, Dec. 2018, doi: 10.3390/MET8121067.

[20] M. Simonelli et al., “The Influence of Iron in Minimizing the Microstructural Anisotropy of Ti-6Al-4V Produced by Laser Powder-Bed Fusion,” *Metall. Mater. Trans. Phys. Metall. Mater. Sci.*, vol. 51, no. 5, pp. 2444–2459, May 2020, doi: 10.1007/S11661-020-05692-6/TABLES/5.

[21] O. M. Ivasishin, D. G. Savvakin, F. H. (Sam) Froes, and K. A. Bondareva, “Synthesis of Alloy Ti — 6Al — 4V with Low Residual Porosity by a Powder Metallurgy Method,” *Powder Metall. Met.*

Ceram., vol. 41, no. 7/8, pp. 382–390, 2002, doi: 10.1023/A:1021117126537.

[22] M. Qian, Y. F. Yang, M. Yan, and S. D. Luo, "Design of Low Cost High Performance Powder Metallurgy Titanium Alloys: Some Basic Considerations," *Key Eng. Mater.*, vol. 520, pp. 24–29, 2012, doi: 10.4028/WWW.SCIENTIFIC.NET/KEM.520.24.

[23] L. H. Liu et al., "A new insight into high-strength Ti62Nb12.2Fe13.6Co6.4Al5.8 alloys with bimodal microstructure fabricated by semi-solid sintering," *Sci. Rep. 2016 61*, vol. 6, no. 1, pp. 1–7, Mar. 2016, doi: 10.1038/srep23467.

[24] P. G. Esteban, L. Bolzoni, E. M. Ruiz-Navas, and E. Gordo, "PM processing and characterisation of Ti–7Fe low cost titanium alloys," *https://doi.org/10.1179/174329009X457063,*vol. 54, no. 3, pp. 242–252, Jul. 2013, doi: 10.1179/174329009X457063.

[25] H. R. Ogden and R. I. Jaffee, "THE EFFECTS OF CARBON, OXYGEN, AND NITROGEN ON THE MECHANICAL PROPERTIES OF TITANIUM AND TITANIUM ALLOYS," Oct. 1955, doi: 10.2172/4370612.

[26] H. Wang, Z. Fang, and P. Sun, "A critical review of mechanical properties of powder metallurgy titanium," *Int. J. Powder Metall.*, vol. 46, pp. 45–57, Sep. 2010.

[27] I. M. Robertson and G. B. Schaffer, "Review of densification of titanium based powder systems in press and sinter processing," *http://dx.doi.org/10.1179/174329009X434293*,vol. 53, no. 2, pp. 146–162, Jun. 2013, doi: 10.1179/174329009X434293.

[28] R. G. Neves, B. Ferrari, A. J. Sanchez-Herencia, and E. Gordo, "Colloidal approach for the design of Ti powders sinterable at low temperature," *Mater. Lett.*, vol. 107, pp. 75–78, Sep. 2013, doi: 10.1016/J.MATLET.2013.05.015.

[29] P. G. Esteban, E. M. Ruiz-Navas, and E. Gordo, "Influence of Fe content and particle size the on the processing and mechanical properties of low-cost Ti–xFe alloys," *Mater. Sci. Eng. A*, vol. 527, no. 21–22, pp. 5664–5669, Aug. 2010, doi: 10.1016/j.msea.2010.05.026.

[30] J. O'Flynn and S. F. Corbin, "The influence of iron powder size on pore formation, densification and homogenization during blended elemental sintering of Ti–2.5Fe," *J. Alloys Compd.*, vol. 618, pp. 437–448, Jan. 2015, doi: 10.1016/J.JALLCOM.2014.08.134.

[31] Y. Liu, L. F. Chen, H. P. Tang, C. T. Liu, B. Liu, and B. Y. Huang, "Design of powder metallurgy titanium alloys and composites," *Mater. Sci. Eng*. A, vol. 418, no. 1–2, pp. 25–35, 2006, doi: 10.1016/j.msea.2005.10.057.

[32] Y. Xia, G. B. Schaffer, and M. Qian, "The effect of a small addition of nickel on the sintering, sintered microstructure, and mechanical properties of Ti–45Al–5Nb–0.2C–0.2B alloy," *J. Alloys Compd.*, vol. 578, pp. 195–201, Nov. 2013, doi: 10.1016/J.JALLCOM.2013.05.104.

[33] Y. F. Yang, S. D. Luo, G. B. Schaffer, and M. Qian, "Impurity scavenging, microstructural refinement and mechanical properties of powder metallurgy titanium and titanium alloys by a small addition of cerium silicide," *Mater. Sci. Eng. A*, vol. 573, pp. 166–174, Jun. 2013, doi: 10.1016/J.MSEA.2013.02.042.

[34] Y. Xia, P. Yu, G. B. Schaffer, and M. Qian, "Cobalt-doped Ti–48Al–2Cr–2Nb alloy fabricated by cold compaction and pressureless sintering," *Mater. Sci. Eng. A*, vol. 574, pp. 176–185, Jul. 2013, doi: 10.1016/j.msea.2013.03.023.

[35] Y. F. Yang, S. D. Luo, and M. Qian, "The effect of lanthanum boride on the sintering, sintered microstructure and mechanical properties of titanium and titanium alloys," *Mater. Sci. Eng. A*, vol. 618, pp. 447–455, Nov. 2014, doi: 10.1016/J.MSEA.2014.08.080.

[36] T. Ebel, O. M. Ferri, W. Limberg, M. Oehring, F. Pyczak, and F. P. Schimansky, "Metal Injection Moulding of Titanium and Titanium-Aluminides," *Key Eng. Mater.*, vol. 520, pp. 153–160, 2012, doi: 10.4028/WWW.SCIENTIFIC.NET/KEM.520.153.

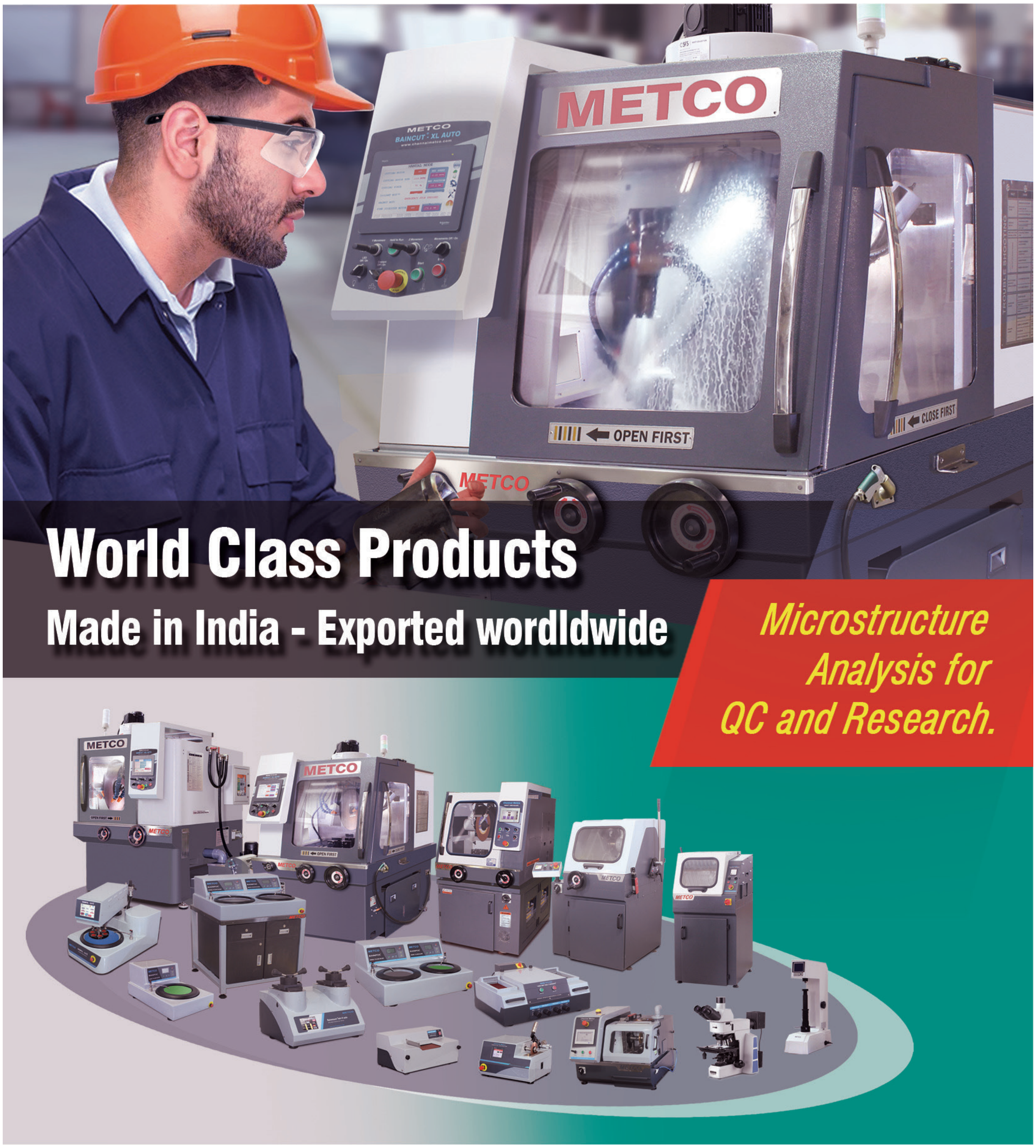
[37] C. Zhang et al., "Mechanical behavior of a titanium alloy scaffold mimicking trabecular structure," *J. Orthop. Surg.*, vol. 15, no. 1, p. 40, Dec. 2020, doi: 10.1186/s13018-019-1489-y.

[38] S. A. Yavari et al., "Fatigue behavior of porous biomaterials manufactured using selective laser melting," *Mater. Sci. Eng. C*, vol. 33, no. 8, pp. 4849–4858, Dec. 2013, doi: 10.1016/J.MSEC.2013.08.006.

[39] P. Edwards and M. Ramulu, "Fatigue performance evaluation of selective laser melted Ti–6Al–4V," *Mater. Sci. Eng. A*, vol. 598, pp. 327–337, Mar. 2014, doi: 10.1016/J.MSEA.2014.01.041.

[40] L. J. Gibson and M. F. Ashby, "Cellular solids: Structure and properties, second edition," *Cell. Solids Struct. Prop. Second Ed.*, pp. 1–510, Jan. 2014, doi: 10.1017/CBO9781139878326.

****


METCO
OPEN FIRST
CLOSE FIRST
World Class Products
Made in India - Exported worldldwide
Microstructure
Analysis for
QC and Research.

रक्षा अनुसंधान एवं विकास संगठन
रक्षा मंत्रालय, भारत सरकार
DEFENCE RESEARCH & DEVELOPMENT ORGANISATION
Ministry of Defence, Government of India

Aeronautics Research & Development Board

Vision

Make India technologically strong by establishing world class cutting edge aeronautical science and technology base to provide our Defence, Space and Civil Aviation sectors a decisive edge by equipping them with internationally competitive systems and solutions.

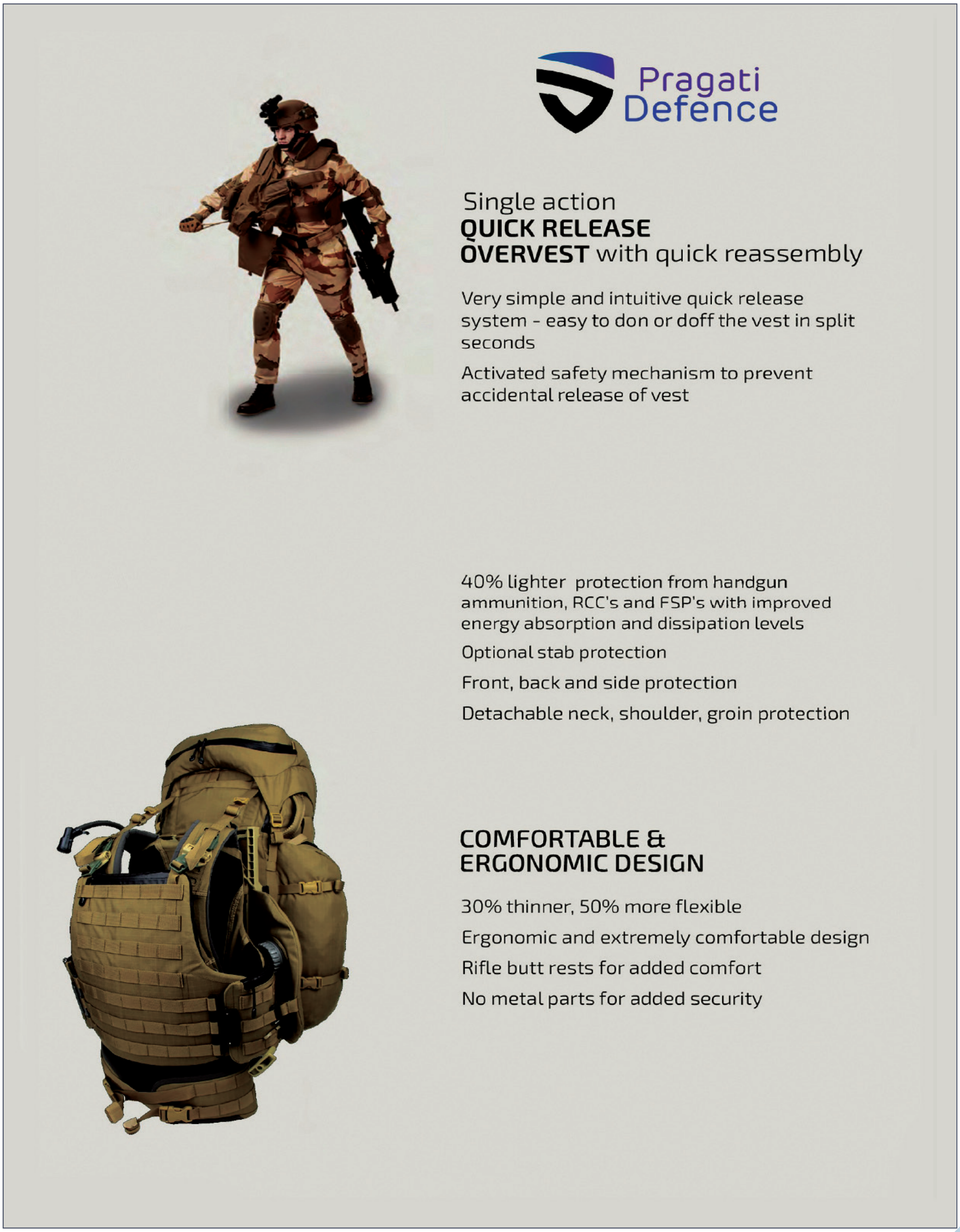
Mission

To encourage and fund basic and applied research in pertinent scientific disciplines directly relevant to our aeronautical systems needed for future by enabling and supporting emerging talents, particularly in academic and research institutions to create and evolve a potential knowledge-base system applicable to future aeronautics needs of the country.

Charter

- To formulate research, design and development programmes in aeronautics and allied sciences, keeping in view future needs of the country specifically with respect to aircraft, helicopter, missiles and all other airborne vehicles.
- To implement such programmes through appropriate institutions and individuals by sponsoring research, design and development projects, creating/ improving infrastructure facilities deemed necessary, while ensuring that they are suitably monitored.
- To promote in all possible ways such educational and training programmes as may be considered necessary for ensuring that adequate manpower of requisite quality becomes available to various aeronautical organizations in the country.
- To promote all relevant R&D activities in the country through appropriate scientific meetings, provisions of support for participation of Indian and foreign scientists in such meetings, conduct of relevant competitions as well as other training and visiting programmes within India and abroad as may fall within the scope of the programmes mentioned at sub para (a) above.
- Dissemination of appropriate technical information through journals and documents, encouragement of individual and collective efforts and nurturing of young talent by institutions with suitable awards, scholarships etc. Organization of necessary centralized services related documentation, software, data-link etc. and in all such other ways that the Board may determine from time to time.

Panels & Chairman	
Aerodynamics Panel **Dr S Pandian** Prof. Vikram Sarabhai Distinguished Professor & Ex- Director & DS, SHAR	**Propulsion Panel** **Dr V Ramanujachari** National Centre for Combustion Research & Development (NCCRD), IIT Madras, Chennai
Aerospace Resources Panel **Dr N Eswara Prasad** OS & Ex-Director, DMSRDE (DRDO), Knp.-13	**UNMANNED AERO SYSTEMS PANEL** **Shri PS Krishnan** DS & Ex-Director, ADE, Bangalore-560075
Materials & Manufacturing Panel **Dr DK Das, Scientist H** Group Head (DSG), DMRL (DRDO) Hyd. - 58	**Structures Panel** **Dr Makarand Joshi** Scientist G, R&DE (E), DRDO, Pune-411015
GTMAP **Prof. Amol A Gokhale, IITB, Chairman**	**Systems / Systems Engineering Panel** **Shri APVS Prasad** Scientist H, CE, CEMILAC, DRDO, Bangalore


Pragati Defence
Single action
QUICK RELEASE
OVERVEST with quick reassembly
Very simple and intuitive quick release system - easy to don or doff the vest in split seconds
Activated safety mechanism to prevent accidental release of vest
40% lighter protection from handgun ammunition, RCC's and FSP's with improved energy absorption and dissipation levels
Optional stab protection
Front, back and side protection
Detachable neck, shoulder, groin protection
COMFORTABLE & ERGONOMIC DESIGN
30% thinner, 50% more flexible
Ergonomic and extremely comfortable design
Rifle butt rests for added comfort
No metal parts for added security


ADITYA BIRLA
HINDALCO
Accelerating towards a
#GreenerStrongerSmarter future
Hindalco is proud to be recognised as the World's Most
Sustainable Aluminium Company* again this year
*Dow Jones Sustainable Indices 2020 & 2021


We make
the best,
even better.
JSW – A conglomerate
worth $13 Billion believes in
transformation to make
a better world every day
It takes a strong will to be ranked among India's top business houses. But it was stronger dreams and ambition that made us venture into the core sectors of Steel, Energy, Cement and Infrastructure. Our strength, state-of-the art technology and excellence in execution have helped us grow and that has helped India grow multi-fold. By harbouring dreams of transformation, focusing on sustainability and a philosophy; to give back to the country, the JSW Group is making a better world every day.
Steel | Energy | Infrastructure | Cement | Paints
Realty | Ventures | Foundation | Sports
www.jsw.in
JSW
Better Everyday

News Updates Domestic

JSW, Japan's JFE plan to invest $1 billion in specialty steel

JSW Steel and its partner Japan's JFE Steel will soon be taking a call on a billion-dollar investment to jointly set up a specialty steel manufacturing facility in India that would help the country reduce its import reliance for the high-end alloy, a top executive said.

A feasibility study commissioned by the two companies last year for manufacturing grain oriented electrical steel in India was close to completion and they would be ready to take a call on the project by December, according to Seshagiri Rao, joint managing director of JSW Steel. "It is a highly specialised steel and is 100% imported into India today," he said. "It has a huge market in India that is fast growing." The project will be implemented at the Vijayanagar complex of JSW Steel in Karnataka.

Grain-oriented electrical steel is used to make energy efficient transformers, generators and motors. It will receive the highest level of support under the government's Rs 6,322-crore production-linked incentives (PLI) scheme. Japan is a leading exporter of electrical steel.

JFE Steel - the second-largest steelmaker in Japan - is a 15% shareholder in JSW Steel through its European subsidiary. It has long been a technology partner for the Indian steelmaker. An alliance with the Japanese steelmaker helped JSW break into the lucrative automotive steel market and today the company is one of the largest suppliers of steel to Indian automakers.

The Economic Times

Govt sets up two advisory committees to iron out challenges in steel industry

The government has set up two advisory committees to iron out the challenges in the steel industry to achieve the target of 300 million tonne of production capacity by 2030. Members of the steel industry, associations, academia, and senior retired government officials are members of the two separate committees formed for integrated steel plants (ISPs) and the secondary steel sector, according to a steel ministry document.

"The Ministry of Steel has constituted two advisory committees, one each for the ISPs and the secondary sector. These committees take cognizance of the issues being faced by the sector and deliberate on the ways and means to mitigate them so as to achieve a targeted crude steel production capacity of 300 Mt by 2030-31, as envisaged in the National Steel Policy 2017," it added.

Several meetings of the advisory committee on ISPs and the secondary sector have been held since their formation.

The ministry is extensively engaged with all concerned stakeholders and has been holding consultations with them to develop and finalise the contours of 'Vision 2047' for the sector, it noted.

The Economic Times

Tata Steel board approves merger of 7 Tata group metal companies with itself in mega consolidation drive

Tata Steel board has approved the scheme of amalgamation between seven of its group companies and itself, as per the company's exchange filing. The decision was taken at a board meeting of the company, the exchange filing said. The company has withdrawn the earlier merger scheme of Tata Metaliks and Tata Steel Long Products. As per the new amalgamation plan, all the Metal companies of the Tata group including Tata Metaliks, TRF, Tata Steel Mining, Indian Steel & Wire Pdts, S&T Mining, Tata Steel Long Pdts, and Tinplate will be merged into Tata Steel. Of the seven companies to be merged into Tata Steel, four are listed on the exchanges, while the rest are unlisted.

The scheme of amalgamation was reviewed and recommended to the board by the committee of independent directors and the audit committee. Explaining the rationale behind the merger scheme, Tata Steel said in the filing that the resources of the merged entities can be pooled to unlock the opportunity for creating shareholder value. Besides citing other synergies, it also highlighted that the mergers will result in utilisation of each other's facilities in a more efficient manner. Marketing and distribution networks of all entities can collaborate.

The mega-merger plan would require the approval of shareholders of all the seven Tata group companies as well as those of Tata Steel, regulatory bodies and stock exchanges. It is worth mentioning that under the leadership of N Chandrasekaran, the Tata group has been trying to consolidate its businesses that share common synergies. Earlier this year, the group announced the merger of its subsidiaries Tata Consumer and Tata Coffee. Some recent reports said that the Tatas are also planning to consolidate airline companies – Air Asia India and Vistara – under the Air India brand by 2024.

Financial Express

****

Chapter Activities

Bhubaneswar, Varanasi, Hyderabad, Delhi, Rourkela, Kalpakkam

Bhubaneswar Chapter

IIM Bhubaneswar Chapter organised the following events recently :

1) A joint webinar series on "Advances in Materials Science and Engineering (AMSE) 2022" seminar by IIM Bhubaneswar Chapter in association with INYAS Kolkata Bhubaneswar chapter was organised on 24th August, 2022 through online mode. This was comprised of two lectures. Prof. Mallar Ray, School of Engineering and Sciences, Tec de Monterrey, Av. Eugenio Garza Sada 2501 Sur, Tecnologico, Monterrey, NL delivered his lecture on the title "A Journey to the World of Amorphous Carbon Nanostructures". The 2nd speaker of the day was Mr. Nipun Sharma, PMRF Scholar Nano sensors Research Group, Indian Institutes of Technology Jodhpur and he delivered the lecture on the title "Functionalization of AlGaN/GaN HEMT for Heavy Metal Ion Sensing".

2) The AGM 2022 of IIM Bhubaneswar Chapter was held on 26th August 2022 at SS Bhatnagar Hall, CSIR-IMMT, Bhubaneswar. The chief guest of the meeting was Prof. Deba Kumar Tripathy, Faculty (Ex) IIT Kharagpur, who delivered lecture on Polymer nanocomposites-processing and applications. The IIM Bhubaneswar chapter award was jointly given to Dr. B.K. Jena and Dr. Y.S. Choudhary, CSIR-IMMT Bhubaneswar. S.K. Tamotia award was given to Dr. A.K. Chaubey, CSIR-IMMT Bhubaneswar. The meeting was concluded with dinner at IMMT Guest house. About 50 members had participated.

3) The Executive Council (EC) meeting was held on 8th September, 2022. The outgoing members of previous EC Dr. Nilima Dash and Dr. Palishree Prusty briefed their journey. Mr. Shubhra Bajpai, former honorary secretary of this chapter was felicitated for his remarkable work by the Chairman and Secretary of the Chapter.

Mr. Shubhra Bajpai (middle), previous honorary secretary of this chapter was felicitated for his remarkable work by the Chairman Dr. H.K. Tripathy (left) and Secretary Dr. Ajit Panigrahi (right), IIM-Bhubaneswar chapter.

Varanasi Chapter

The Annual General Meeting of IIM Varanasi Chapter held on august 16, 2022 at the Conference Hall, Dept. of Metallurgical Engineering, IIT (BHU), Varanasi. The Chairperson, Dr. Vikas Jindal, welcomed the members present and briefly highlighted the various activities organized by the chapter. The Hon. Secretary, Dr. Ashok Kumar Mondal presented the annual report for 2021-2022. Mr. Debraj Soni will act as convener of the student-affiliated chapter of the IIM Varanasi Chapter. The new EC members for 2022-23 were selected :

Chairman → Dr. Vikas Jindal

Secretary → Dr. Ashok Kumar Mondal

Treasurer → Dr. Surya Deo Yadav

Hyderabad Chapter

XXIX Tamhankar Memorial Lecture by Dr Samir V Kamat

The Tamhankar Memorial Lecture is organised every year by the IIM Hyderabad Chapter to pay tributes to the unique contributions made by Dr. R V Tamhankar in establishing and nurturing two important institutions in the country viz. Defence Metallurgical Research Laboratory (DMRL) and Mishra Dhatu Nigam Limited (MIDHANI). This year the Memorial Lecture was held at DMRL on August 25, 2022. Dr. Samir V Kamat, Distinguished Scientist, Director General (Naval Systems & Materials), DRDO & President, The Indian Institute of Metals has delivered the lecture on "Naval Systems and Technologies". He has given a broad overview of the advanced systems and technologies along with work going on in the Naval Laboratories of DRDO. He has emphasised that India has the capability and potential to become Atma Nirbhar in Naval Systems and Technologies.


Felicitation to Dr. Samir V Kamat by IIM Hyderabad Chapter

Delhi Chapter

MMMM 2022

The MMMM 2022 event consisting of International Conference and Exhibition was held at Pragati Maidan, New Delhi during 25-27 August 2022. The event was held in collaboration with HYVE (formerly International Trade Exhibitions India Pvt. Ltd). The event was inaugurated by Hon'ble Minister of Civil Aviation and Steel, Shri Jyotiraditya M. Scindia. The Theme of the Conference was Resource Efficiency and Circular Economy in Mineral & Metal Sectors". The Conference consisted of the Inaugural Session, Panel Discussion, eight Technical Sessions and a Valedictory Session.

Hon'ble Minister of Civil Aviation and Steel, Shri Jyotiraditya M.Scindia addressing

The Conference brought together leading technocrats, researchers, designers, consultants, academicians, researchers, and students to exchange and share their views and experiences on this important emerging topic 'Resource Efficiency & Circular Economy In Mineral & Metal Sectors'. The Conference provided an interdisciplinary platform which was attended by not only engineers, technologists and scientists in mineral and metal sectors, but also road construction materials specialists, agriculture scientists, recycling specialists and energy specialists.

In this two and half days of conference, there were 42 presentations, 21 from Industries, 9 from internationally reputed technology and equipment suppliers, 6 from national labs. and 6 from design and consultancy organization. The event brought together more than 200 delegates.

Experts in Minerals and Metals Sector participated in Panel Discussion, which was presided over by Ms Ruchika Chaudhry Govil, Addl Secretary, Min of Steel.

40 papers were presented in the Conference under 8 technical sessions. The papers touched upon the subjects relating to the following:

(a) Resource Efficiency and Circular Economy in Metal Sector

The Dignitaries are on the dais @ MMMM 2022

(b) Decarbonisation and Green Steel Production

(c) Manufactures and Exhibitors Presentation

(d) Utilization of Slag and Co-Products

(e) Utilization of Lean Grade Ores

(f) Energy and Environment

(g) New Technology

(h) Industry View on Resource Efficiency and Circular Economy

The Conference was attended by about 200 delegates.

The Valedictory Session of the Conference was presided over by Shri Parmjeet Singh, Addl. Industrial Adviser, Ministry of Steel on 27.8.2022.

Awards were distributed to the selected exhibitors. Mementoes were also given away to the sponsors of the Conference.

Rourkela Student Affiliate Chapter

IIM Rourkela Student Affiliate Chapter organised an orientation program on 8th September, 2022. The major agenda of the program is to promote the activities of IIM Rourkela Student Chapter, process of becoming member of IIM, benefits of IIM membership etc. Prof. Bankim Chandra Ray, Vice-Chairman, IIM Rourkela Chapter, Prof. Anindya Basu, Head of the Department, Metallurgical and Materials Engineering, National Institute of Technology Rourkela, Prof. Rajesh Kumar Prusty, Jt. Secretary, IIM Rourkela Chapter, Prof. Ajit Behera, Jt. Treasurer, IIM Rourkela Chapter, Prof. Anshuman Patra, Faculty Advisor, IIM Rourkela Student Chapter attended the event and discuss various activities of IIM Rourkela Chapter. Certificates were awarded to the student committee of IIM Rourkela Chapter for the session 2021-22 by Prof. Bankim Chandra Ray. The program was co-ordinated by Prof. Anshuman Patra. Students seemed to be quite excited and showed their enthusiasm to be a part of the IIM. Many students from B.Tech, and Ph.D participated in the event.

Glimpses of the event held on 8th September, 2022

Kalpakkam Chapter

30th Prof. Brahm Prakash Memorial Materials Quiz (BPMMQ 2022)

IIM Kalpakkam Chapter conducted the **30th Prof. Brahm Prakash Memorial Materials Quiz (BPMMQ)** at Indira Gandhi Centre for Atomic Research, Kalpakkam during September 9-10, 2022. A total of thirty one teams comprising of sixty two students of class XI and XII accompanied by escorts and office bearers from sixteen chapters across India participated in this flagship programme.

On September 9th, 2022, the Metal Camp programme commenced with welcome address delivered by Dr. M. Vasudevan, Chairman, IIM Kalpakkam chapter and special address by Dr. R. Divakar, Chairman, BPMMQ-2022. A video film "FBTR Breeds Success" highlighting the milestones of flagship research reactor at Kalpakkam was screened. This was followed by a visit to the facilities at Kalpakkam namely Fast Breeder Test Reactor (FBTR), Madras Atomic Power Station (MAPS) and the Prototype Fast Breeder Reactor (PFBR).

On September 10th, 2022, the preliminary rounds of quiz programme commenced in six parallel sessions. The winner and runner of each session contested in semi-final round held in two parallel sessions. The souvenir BPMMQ 2022 Digest was released on this occasion by Shri. S. Raghupathy, Distinguished Scientist, Director RD&TG. This was followed by **Prof. Brahm Prakash Memorial Lecture 2022,** delivered by **Dr. Samir V. Kamat,** Secretary, Department of Defence R&D, Chairman, DRDO and President IIM on the topic **"Rare Earth Metals and Rare Earth Permanent Magnets: Challenges and Opportunities".** The speaker presented a global and Indian perspective of the rare earth metals, its ore resources, exploration cum mining and production statistics. He has lucidly explained the development, challenges involved in the manufacturing and applications of Samarium-Cobalt and Neodymium based magnets in defence laboratories.

Dr. Samir V. Kamat, Secretary, Defence R&D and Chairman, DRDO delivering BPMMQ 2022 Lecture

Dr. Sumanth C. Raman Quiz Master, conducting BPMMQ 2022 Grand Finale

Chief guests, distributing the prizes to winners and runners of BPMMQ 2022

Dr. Sumanth C. Raman, a renowned sport quiz master from Chennai conducted the Grand finale of BPMMQ 2022 comprising of total of six teams (three from each semi-final round). The Finale comprised of eight rounds including google doodle, video, visual, dumb charades, cross word and rapid fire rounds. The winner of BPMMQ 2022 was **Kolkata Team – A** comprising of Mr. Arjoe Basak and Mr. Prateek Kumar Behera of Delhi Public School, Ruby Park, Kolkata. **Mumbai Team** comprising of Mr. Suketu Patni and Mr. Jairam Suresh Ayyar of Delhi Public School, Navi Mumbai won the second place.

The essay cum elocution contest for the quiz participants was also well received this year. The topics were (i) "Role of Silicon in the Modern World" (ii) "Power train Materials for Electric Mobility" and (iii) "Metal Additive Manufacturing in Propulsion System". A total of twenty essays were received and six best essays were selected for elocution contest. Mr. Jairam Suresh Ayyar of Delhi Public School, Navi Mumbai, was the winner of Essay/Elocution contest and the two runners up position was awarded to Mr. Suketu Patni of Delhi Public School, Navi Mumbai and Mr. A. Aashish Kumar of AECS, Anupuram.

The Winner and Runner teams of the Quiz and the elocution contest were awarded with prizes by chief guests Dr. Samir V. Kamat and Shri. S. Raghupathy. The event was successfully conducted with generous financial supports from several well-wishers and promoters of science, including The IIM, Kolkata; IGCAR, Kalpakkam; JSW Centre, Mumbai; DRDO, New Delhi; ARCI, Hyderabad; NFC, Hyderabad; MIDHANI, Hyderabad; NPCIL, Mumbai; MAPS, Kalpakkam; HWB, Mumbai and several leading firms dealing with metallurgical equipment and services. Shri. E. Vetrivendan, Convener BPMMQ 2022 proposed a vote of thanks.

****

Member in the News Prof. Kamanio Chattopadhyay

Prof. Kamanio Chattopadhyay, FASc, FNASc, FNAE, FNA, FIIM, Honorary Professor, Department of Materials Engineering, Former Chair, Mechanical Sciences Division, Convenor, Interdisciplinary Center for Energy Research, Indian Institute of Science, Bangalore and former President of The Indian Institute of Metals attended the 1st International Session of JIMM held on September 22nd and 23rd, 2022. Prof. Chattopadhyay delivered the Lecture on "New Pathways for Developing High-Temperature Aluminium Alloys: The Indian Experiences" which was well accepted by the audience.

****

Advertisers' Index	
Name of the Organisations	*Page Nos.*
Tata Steel Ltd	**Cover**
Chennai Metco Pvt Ltd	**23**
ARP/AR&DB, DMSRDE	**24**
Pragati Defence Systems Pvt Ltd	**25**
Hindalco Industries Ltd	**26**
PTC Industries Limited	**27**
JSW Steel Ltd	**28**
Rashtriya Ispat Nigam Ltd	**3rd Cover**


राष्ट्रीय इस्पात निगम लिमिटेड
RASHTRIYA ISPAT NIGAM LIMITED
(A Government of India Enterprise)
Visakhapatnam Steel Plant
ISO 9001:2015, ISO 14001, ISO 50001, ISO 27001 & OHSAS 18001 Certified Company
VIZAG STEEL Pride of Steel
Azadi Ka Amrit Mahotsav
आत्मनिर्भर भारत में
सहयोगी आर आई एन एल - वाइजाग स्टील
वाइजाग टी एम टी रीबार
एफ ई 550 डी
आई एस : 1786 - 2008 के अनुरूप
अधिक
मजबूती
सुरक्षा
बचत
अब आर आई एन एल - वाइजाग स्टील का
गुणवत्तापूर्ण उत्पाद
आसानी से अपनी देहरी पर पायें
आर आई एन एल ई-सुविधा वेब आधारित पोर्टल के माध्यम से ऑनलाइन आर्डर करें
RINL eSuvidha
आसान
पारदर्शी
सक्षम तरीके से
हमारे 2 टायर वितरण प्रणाली के माध्यम से तूतीकोरिन एवं रायगड़ा के डिस्ट्रिब्यूटर्स सहित 24 क्षेत्रों में डिस्ट्रिब्यूटरों एवं डीलरों का विशाल तंत्र
@RINL VIZAG STEEL
@RINL_VSP
r.i.n.l
RINL DUGDUGI
www.vizagsteel.com


STEEL FACTS
Fabric dust filters in steel plants typically have a collection efficiency rate of more than
99%
even when particle size is very small.
worldsteel.org