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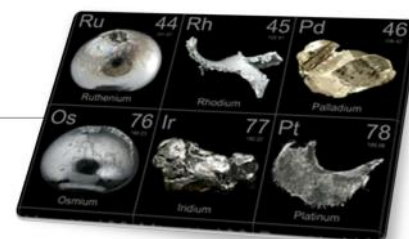
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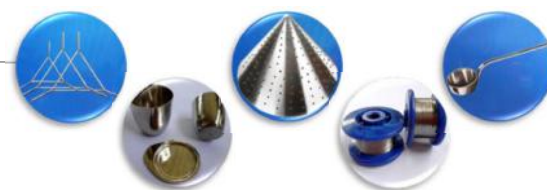
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It is heartening to find the first issue of the journal, "Material and processing" brought out by ASM India National Council has been well received by readers, comprising academia and industries. The number of articles and advertisements spontaneously received from the authors and industry for the current is a testimony to the same. I am sure with the commitment of office bearers and editorial board; the journal will find an eminent position as a platform of knowledge exchange. The journal further showcases the activities of Material Advantage student chapters which will enthuse the student community. The journal will enhance the visibility of ASM and activities in India effectively.

The sustained effort of the office bearers is noteworthy.

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Editorial Message



Mr. Ajith Kumar Sandur
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Dear Readers,

We are absolutely thrilled to receive overwhelming positive response to our inaugural Issue. Your support and encouragement will surely motivate us to come out with better and high - quality contents in all our forthcoming issues.

It is incredibly exciting to see how quality technical articles and features have received tremendous attention and triggered sparks for fruitful engagements. Articles from wide ranging fields have attracted made the Journal worth reading and spreading the message of positive vibes amongst professionals. They are evident from the fact that we have been receiving articles both in quality and quantity beyond our expectations from reputed academia like IITs and industries.

Our editorial board has been quite forthcoming with meaningful suggestions and feedback due to which we were able to bring about first Issue with astounding success. Their continuing dedication has enabled us bring out this next Issue also and will be counting on their efforts for all our future Issues. We have added few more features and will continue to do so thanks to creative shared thoughts from members.

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Thank you for being part of our journey towards spreading wealth of knowledge.

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Correlation of Uniaxial Tensile properties with Sheet Metal Formability for Low Carbon Automotive Steel Sheets

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Abstract

Stretch-flangeability is one of the important formability parameters for steel sheets to be used in the complicated body parts in industries. Stretch-flangeability is generally evaluated by Hole Expansion Ratio (HER) but test for HER evaluation is very time-consuming and require a large amount or number of materials as well as specialized equipment. So practically, it is not possible to determine HER for each steel grade. The finite element study confirms that the stress state in the hole edge region during Hole Expansion Test (HET) is almost the same as that of the uniaxial tensile test. Based on this fact HER of steel sheets can be correlated with uniaxial tensile properties. In this study five commercially produced low carbon automotive steel sheets with varying thickness are evaluated. The results suggest that post uniform elongation (PUE), ultimate tensile strength (UTS), and total elongation (TE) show a good correlation with HER.

Keywords: *Hole expansion ratio; stretch-flangeability; Sheet metal formability; Post uniform elongation; ultimate tensile strength*

1 Introduction

Sheet Metal forming is the process of transforming a flat sheet of metal into a desired shape without fracture or excessive localized thinning [1]. Sheet metal forming is very important aspect in the automotive industry. Many automotive stampings are formed from the steel sheets which have been sheared from the larger coil. The process includes shearing of edge which is formed during the shearing process and stamping process. Traditional formability prediction method such as forming limit diagrams (FLDs) act as a useful guide for the general formability. It gives the maximum deformation limit in different strain condition but doesn't account for the edge cracking. Hole Expansion Ratio (HER) is one of the methods to determine the shear edge formability. It evaluates the stretch-flangeability of the sheet materials which referred to the ability of a material to be formed into a complex shape. HER of the steel sheets is denoted by some numerical value. The higher value indicates that it is easier to convert the steel sheets to desired complex shape materials. Hole expansion properties of the steel sheets are determined by the hole expansion test (HET) which involves the initial square sample usually 100×100 square mm dimension with a 10 mm central hole made of either punching or milling after the punching process. This central hole is expanded by some conical punch until edge cracking through thickness takes place.

HET is a very time-consuming experiment and requires

large amount /or number of materials as well as specialized equipment. This is the reason; it is not possible to determine the formability of each steel sheet in the industries. Finite element analysis confirms that the stress state at the hole edge region during the hole expansion test is the same as that of the uniaxial tensile test [3,4]. Based on the fact it is reasonable to correlate the HER with uniaxial tensile properties.

Many researchers have previously proposed the correlation between the HER and uniaxial tensile properties [2-9]. Paul [4] have investigated the correlation between the HER and uniaxial properties but failed to correlate with each tensile property. Also, in the other study, Kim et al. [2] have investigated that normal anisotropy and width strain show a strong correlation with HER. However, weak correlation can be observed for other properties such as ultimate tensile strength (UTS) and post uniform elongation (PUE). Further, Bhadeshia et al. [5] and Chen et al. [6] have reported that UTS is the only tensile property which correlates with HER whereas De et al. [7] proposed that UTS and Carbon equivalent of steel sheets have the most pronounced effect on the HER. But none of the above studies have provided the unified correlation between two parameters for diverse microstructures and properties. In this study, the punching process has been used for initial hole fabrication which is very common in industries because of the cost-effectiveness. This study investigates the correlation between HER and tensile properties of automotive steel sheets having a wide range of tensile properties. The work aims to determine the factors which have the most pronounced effect on HER and can lead to giving some good insight into the formability of the steel sheets.

2. Experimental details

2.1 Materials

For this study, hot and cold rolled automotive steel sheets with varying thickness produced by an integrated steel plant are used. Five commercially produced low carbon steel sheets, one extra deep drawing (EDD) steel(3.80mm), one HR interstitial-free (IF) steel(4mm), one dual-phase (DP) 600 steel(1.75mm) and two CR interstitial-free (IF) steel sheets with 0.6mm and 0.7mm thickness have been used in this study. Table 1 shows the chemical composition of the all-steel sheets.

Table 1. Chemical composition of all investigated steel sheets

Steel samples	C	Mn	Al	Si	Ni	Ti	Cu	Fe
EDD (HR)	0.051	0.168	0.053	0.019	0.001	0.001	0.006	Bal.
IF(HR)	0.002	0.086	0.047	0.014	0.059	0.059	0.005	Bal.
DP600(CR)	0.084	1.8	–	0.015	0.001	0.001	0.006	Bal.
IF (CR-0.6mm)	0.002	0.075	0.052	0.022	0.055	0.055	0.006	Bal.
IF (CR-0.7mm)	0.002	0.079	0.045	0.018	0.058	0.058	0.006	Bal.

2.2 Microstructural Characterization

A small cross-section of all samples is hot mounted in order to careful handling of the sample for observation of microstructure. Samples are polished by polishing machine (Make: MECAPOL, Model: P 320) and etched by freshly made etchant nital (with 3% HNO₃ solution). Samples are cleaned with acetone before conducting the microstructure observation by an optical microscope (Make: LEICA, Model: DMRX).

2.3 Uniaxial Tensile Testing

Uniaxial tensile testing has been conducted for all steel sheets in order to determine the mechanical properties of steel sheets. To determine the stress-strain curve and plastic strain ratio (r) value, standard rectangular samples are prepared and tested by following the ASTM E8 standard [9] at a crosshead displacement rate of 5 mm/min for each steel in three directions i.e. longitudinal direction, transverse direction and 45° to RD. Normal Anisotropy ($\bar{r}$) has been calculated by using the following equation [10].

$$\bar{r} = \frac{(r_0 + 2r_{45} + r_{90})}{4}$$

2.4 Hole Expansion Test

Hole expansion test (HET) for each steel sheet has been conducted on the 60-tonne hydraulic press according to ISO 16630-2017 (Metallic Materials- sheet and strip-Hole expansion Test) Standard test procedure [11]. A 10 mm central hole in 100X100 square mm steel sheet has been fabricated by the punching process. In HET, the central punched hole has been expanded using a 50 mm diameter conical punch with cone angle of 60°. When cracking through the thickness direction is observed, Travel of the punch is stopped immediately. Punching speed has maintained constant in HET for all the steel sheets. Initial hole diameter d_0 and final hole diameter d_f are measured by taking the average in perpendicular direction. Hole expansion Ratio of the steel sheets is measured by using the following equation.

$$HER(\%) = \left(\frac{d_f - d_0}{d_0} \right) \times 100$$

3. Results and Discussion

The formability is assessed by HER. Automotive steel sheets with ferrite microstructure have been taken because the ferrite phase is generally continuous and provide the excellent ductility (formability) to the steel [12]. Microstructures of all the investigated steel are shown in the Fig. 1 at 500X. In case of the cold-rolled IF steel, a 200X microstructure is also shown in the fig. 1(e) in order to clarify the microstructure. EDD steel [13], hot rolled IF steel, and cold rolled IF steels [14] consists of the fully- ferrite microstructure as shown in the fig. 1(a, b, d, e) whereas DP steel [15] has ferrite and martensite phases in its microstructure as shown in the fig. 1(c). The nano-indentation hardness test has been carried out at 20m N load on DP steel which reveals that light regions of the structure having the hardness of 251 HV represent the ferrite phase while the grey regions having the hardness of 450 HV represent the martensite phase.

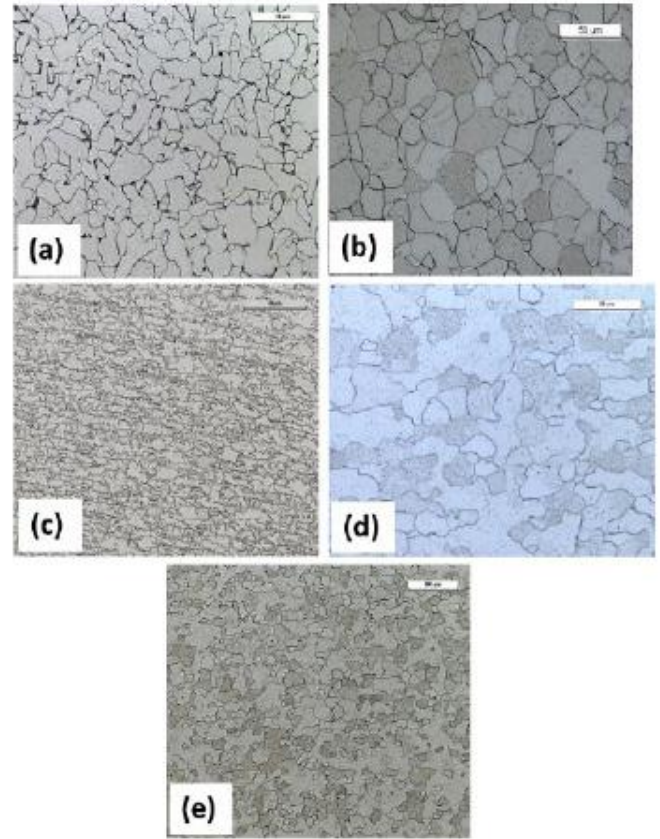


Fig. 1. Optical micrographs of (a) Hot rolled EDD steel (500X), (b) Hot rolled IF steel (500X) (c) Cold rolled dual-Phase steel (500X), and (d) Cold rolled IF steels with 0.6mm thickness (500X) and (e) Cold rolled IF steels with 0.7 mm thickness (200X)

Fig. 2 represents the experimental engineering stress-strain curve for all investigated steel samples. Tensile test results demonstrate good ductility for each sample which is one of essential properties needed for use in automotive parts.

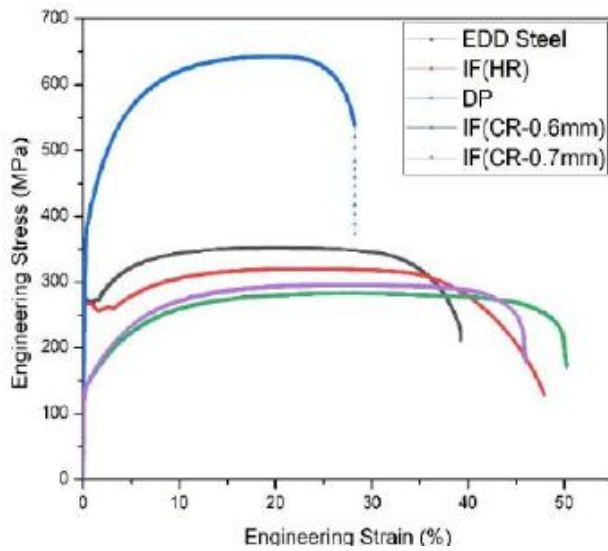


Fig. 2. Engineering stress-strain curve of all investigated steel sheets

Table 2 represents the summary of tensile properties resulted from the tensile test in the rolling direction. Hot rolled IF steel shows the highest total elongation around 49% probably because of the relatively coarser grains ($\sim 17\mu\text{m}$) of the ferrite in its microstructure (fig.1(b)). While the the lowest total elongation can be observed in the dual-phase steel around 28%. Further, it can be also observed that dual-phase steel has the highest strength values among all the steels. This is mainly due to presence of martensite ($\sim 25\%$) and fine grains ($\sim 8\mu\text{m}$) structure in dual-phase steel (Fig.1(c)). Martensite being a hard phase increases the strength of the steel at the same time it reduces total elongation as shown in Table 2 [16].

Table 2. Summary of Tensile properties for all investigated steel sheets

Steel	YS (MPa)	UTS (MPa)	Total elongation (%)	Uniform elongation (%)	Post uniform elongation (%)	n-Value	$\bar{r}$ -Value
EDD (HR)	274.72	351.83	37.79	20.5	17.74	0.17	0.907
IF(HR)	212	270	49.1	22.66	26.4	0.2	0.68
DP600(CR)	378.87	659	27.78	19.58	8.2	0.2	0.905
IF (CR-0.6mm)	131.5	287.7	46.2	27.9	18.3	0.28	2.21
IF (CR-0.7mm)	136.64	302.8	44.87	23.97	20.9	0.27	1.98

HER of all the steel samples are calculated and represented in Table 3. According to that, HR IF steel has the highest HER (213 %) among all the steel. It is because HR IF steel has coarser and homogeneous microstructure (see Fig. 1(b)) than other steels and ferrite being a soft phase undergo high deformation during the forming process. Lowest HER (44%) has been observed in DP600 steel due to micro-damages at the interface of soft (ferrite) and the hard (martensite) phase takes place during the forming process and makes the DP steel more prone to crack and expand [7]. These micro-damages occurs mainly because of the hardness difference between the phases [17]. EDD steel and CR IF steels also show the good hole flanging capacity as they have the HER value more than 100%. It has been observed that steel with single-phase microstructure has higher HER than dual-phase (DP600 steel) or multiphase microstructure [18].

Table 3. Summary of HER for investigated steel sheets

Steel	Average initial hole diameter, mm	Average final hole diameter, mm	Average HER, %
EDD (HR)	10.005	22.6	125.95
IF(HR)	10.005	31.32	213
DP600(CR)	10.012	14.43	44.13
IF (CR-0.6mm)	10.029	22.55	124.83
IF (CR-0.7mm)	10.023	23.34	132.86

It has been attempted to correlate the uniaxial tensile properties with HER of the punched hole in the figs 3 (a-e). The study tries to establish the correlation between HER and tensile properties, although fails to correlate with each tensile property. Which indicates that other parameter such as microstructures of the steels can govern the HER performance [19,20]. Fig. 3 (a) shows the strong linear relation between PUE and HER with the correlation coefficient of 0.96, showing the same trend as published literature [3,4]. According to this study, HER is very closely related to PUE. So, in order to enhance the HER of the steel, PUE of the particular steel should be improved. Fig.3 (b) shows a very good non-linear correlation with total elongation (correlation coefficient 0.80) which indicates a high total elongation of the steel sheet is beneficial for HER performance. Automotive steel sheets with high ductility show the superior press formability [21]. DP600 steel possesses the lowest elongation (TE $\sim 28\%$ and PUE $\sim 8\%$) and has the lowest HER which increases with increasing the elongation as shown in Fig. 3(a) and Fig. 3(b). HER shows the linear correlation with UTS and YS as shown in Fig.3(c) and fig.3(d) with a correlation coefficient of 0.62 and 0.10 respectively. According to that with increasing the UTS and YS of the steel sheets, HER decreases. It has been observed that steel sheets with high strength and inhomogeneous microstructure particularly the martensite are not suited for hole flanging operation [22]. This is the reason in fig.3(c) and fig.3(d), DP600 steel with high strength (YS ~ 380 MPa and UTS ~ 659 MPa), and dual-phase (ferrite and martensite) microstructure has lowest HER and HER increases as the strength of the sheet decreases. Fig.4 (e) shows a weak relation between the ratio of yield strength(YS) to ultimate tensile strength (UTS) with a correlation coefficient of 0.20. The trend line shows that with increasing the YS/UTS ratio, HER of the steel sheets increases. This result is in line with published literature [8]. It can be concluded from data analysis that HER has a prominent correlation with PUE, TE, and UTS.

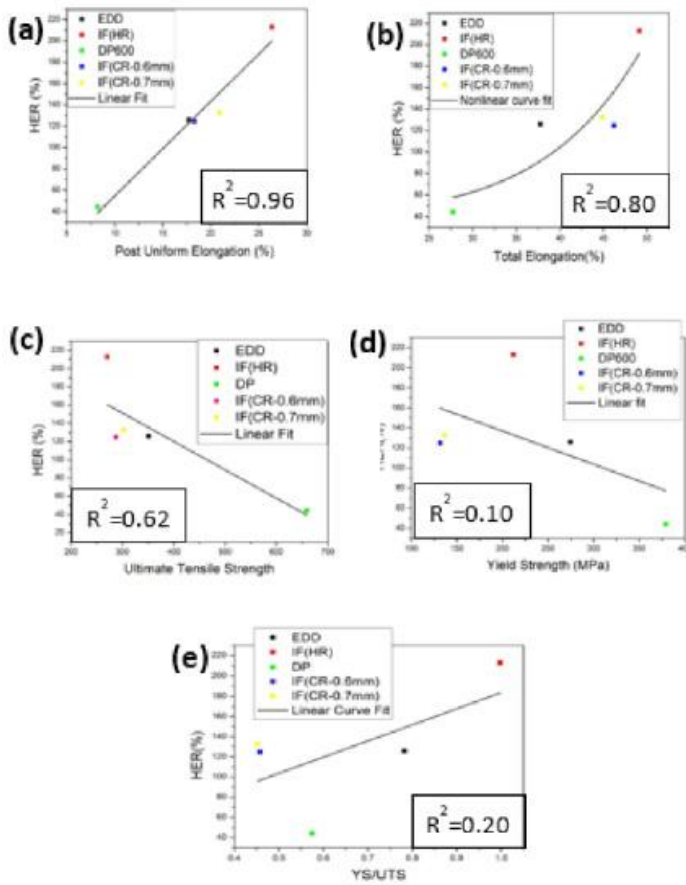


Fig. 3. Correlation of Hole expansion ratio with tensile properties such as (a) Post uniform elongation (b) Total elongation (c) Tensile strength (d) Yield strength (e) YS/UTS Ratio

It can be observed in fig. 4 that there is no specific correlation of HER with strain hardening exponent (n), Normal anisotropy, and uniform elongation. Material with high n -Value generally having lowers the HER. This behavior is observed because during the Hole expansion test, steel sheet with higher n -value increases the resistance to the wall thickness and accelerates the deformation in circumferential direction [23]. In fig.4(a), DP steel with lower n -value should possess the higher HER but due to dual-phase microstructure, it has relatively lowered the HER [18]. In the case of IF(HR) and EDD steel clearly it can be seen that IF(HR) possesses the coarser grain structure ($\sim 17\mu\text{m}$) compared to EDD steel ($\sim 13\mu\text{m}$). This is the reason IF(HR) possesses the highest HER. Generally high normal anisotropy ($\bar{r}$) has the good stretch-flangeability and almost linearly correlated [2,4] but in fig.4(b) hot rolled IF steel and cold rolled IF steel shows the contrast result probably because of the fact that total elongation and strength of the steel sheets which has the positive [2,4,7] and negative correlation [2,4,7,8] with HER respectively. Uniform elongation doesn't show any trend with the HER as shown in fig.4(c) which is in line with the many works of literature [2,4]. It is due to the basic deformation difference between hole expansion and the uniaxial tensile test. The absence of diffuse neck in hole expansion test results far higher hole expansion ratio than the uniform elongation of the material [24]. This mismatch between these two parameters lead to no correlation as shown in fig.4(c).

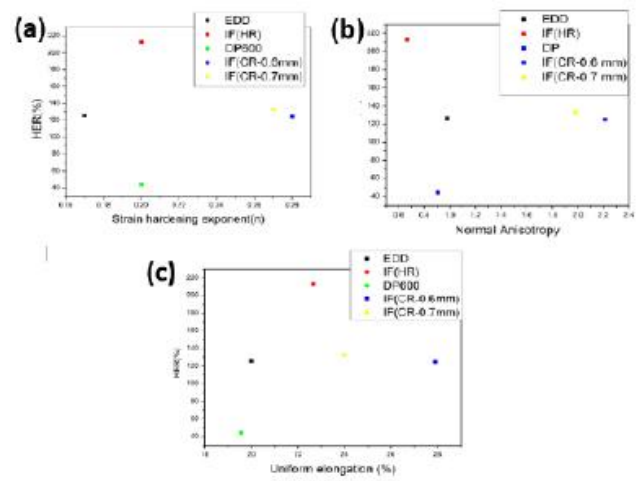


Fig. 4. Correlation of Hole expansion Ratio with (a) strain hardening exponent (b) Normal anisotropy and (c) Uniform elongation

4. Summary

HER mainly depends on the microstructure and tensile properties of the steel sheets. Correlation results suggest that HER has a good correlation with post uniform elongation (PUE), total elongation (TE), and ultimate tensile strength (UTS). Yield Strength and Ratio of yield strength to tensile strength have a very weak correlation with HER. However, Other properties such as strain hardening exponent (n) and normal anisotropy ($\bar{r}$) don't show any correlation with HER. Results indicate that based on the properties such as PUE, UTS, and TE, one can get a fair idea about sheet metal formability.

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Role of Materials on Prevention of Viral Transmission

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Abstract

COVID-19 pandemic has intensified agitation globally about the predominance of practicing the conventional rules to prevent the widespread use of microorganisms. Engineering research and investigation regarding this issue to design a surface that prevents or kills microbe's adherence has been revived. Literature review suggests that there are many research studies available on antibacterial coatings or materials. But inadequate information exists regarding the use of antiviral materials. Although, due to the emergence of new viruses, new materials are added to the literature. The mixture of antiviral and antibacterial chemical entities may be a key player in terms of preventing disease. In this review, the discussion of importance of corona-virus, how it affects humans, and the predominant antiviral and antibacterial materials of various classes such as copper, TiO₂, and silver have been discussed. The material's surface defense mechanisms against pathogen colonies are addressed in-depth, highlighting crucial differences that will decide the parameters and guide the future production of advanced antibacterial and antiviral materials.

Keywords: *corona-virus, sars-cov-2, covid-19, antiviral materials, antimicrobial materials*

1 Introduction

It is unknown how long coronaviruses will survive on various surfaces. However, a stipulated amount of survival time has been estimated or postulated for some materials. Droplets and/or aerosol generated by infected people are thought to be the most common mode of transmission. It is reported that the coronavirus enters at the mouth or nose region, when people usually rub them with the carrier, and goes down deeper into the body. It ends up in the lungs, the spleen, or the intestines. The immune system is there to protect our body, but corona uses it to become dangerous. Coronavirus affects some of our immune cells. This creates a big confusion among the immune cells, whether to attack the infected cell or the healthy cell. Corona infects the immune cells and causes them to overreact and excites them with a bigger problem. In a way, it puts the immune cells into a kind of boxing match and sends much more immune cells than it should [1]. This results in more damage and wastage of cells. Two types of cells, in particular, cause the greatest damage. First, neutrophils, which kill everything, including our cells. As they arrive in huge numbers, they start destroying friends as well as enemies by pumping out enzymes. The other important kind of cells that go into the battlefield is the dangerous T-cells, which usually make infected cells commit controlled suicide as they are also confused and start ordering the healthy cells to kill themselves too. In most cases, the immune system gradually regains control. It kills the infected cells, identifies the viruses that

are trying to infect new cells, and cleans up the battlefield (lungs). If it's a critical case, the protective lining of the lungs will perish and millions of epithelial cells will have died. Bacteria also infect the alveoli (small airbags through which breathing occurs), thus making it tougher to breathe. SARS-CoV-2 (Corona-virus) structure is a spherical shell or a hull around the Genetic material containing DNA and RNA. They also have proteins that are shown as protruding spikes around the surface [1 - 2]. Nanotechnology based treatment is considered one of the critical treatments for infectious diseases caused by viruses and bacteria, both predicted and unforeseen. Antimicrobial agents, generally, are chemical compounds that are either natural or synthesized polymer embedded without or with nanoparticles. Antiviral properties of nanoparticles, in particular, have been well established, and due to their large surface area to volume ratio, they display a significant response even at low concentrations. Their main purpose is to act as an antimicrobial agent, inhibiting or killing pathogenic microbes such as viruses, fungi, and bacteria.

The main objective of the current article is to study about the role of free radical, Reactive Oxygen species (ROS) and photocatalytic properties on the viral growth. Based on the effectiveness of these parameters on viral growth, the study aims to recommend antiviral surfaces or materials in the health care facility in the current and future scenario.

2.1 Copper

The antimicrobial properties of copper are due to its ionic nature. When a foreign organism, such as a bacterium or virus, comes into contact with copper or one of its alloys, the virus recognizes copper ions as an essential nutrient and starts to consume them. The ionic dose becomes lethal as more and more copper ions penetrate the viral cell [3 - 4]. The influx of ions destabilizes the cell's electrical micro-current, recognized as the transmembrane potential, and essentially short-circuits the viral membrane, making these amounts of copper toxic to the viral cell. This compromises the membrane's integrity, allowing more copper ions to enter the cell. This has a major impact on the cell's ability to metabolize and, as a result, kills it by destroying its DNA and RNA. The list of microbes it can destroy is truly amazing, including coronavirus, norovirus, E. coli, MRSA, and certain antibiotic-resistant infection strains. There are three mechanisms that have been postulated by which copper surfaces affect microbes or viruses. i) Membrane Depolarization, ii) ROS generation, iii) Contact Killing. It can be inferred that copper in the form of native copper is more effective as compared to alloy. Brass may be more effective than bronze. The different established mechanism and hypothesis has been discussed below.

2.1.1 Membrane Depolarization

Membrane Depolarization is the most commonly proposed mechanism that is for copper to act as an antibacterial and antiviral agent by killing the microbes. Generally, there is a potential difference of 100-200 milli-volt between the outside and the inside of the cell. This difference is induced by the cell membrane. The inner membrane has less negative potential. This potential difference is reduced by the copper ions by binding to the bacterial or viral cells which are charged negatively in both inner and outer cell membranes giving rise to membrane depolarization as shown in the Fig. 1. This causes a rupture or a leak in the membrane when the potential difference between the two membranes becomes zero [3-5]. This mechanism is widely found in the gram-negative and gram-positive bacteria where copper ions are bound to carboxylic groups, and peptidoglycans.

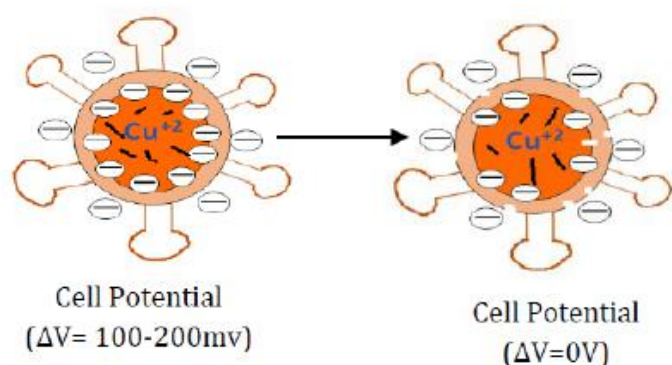
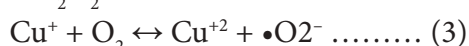
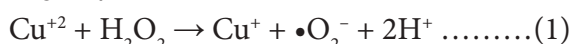


Fig. 1. Diagrammatical representation of the Membrane depolarization

2.1.2 ROS Based Hypothesis and Antimicrobial Mechanism

Although there are various antimicrobial materials and different mechanisms to tackle different viruses, there are some common features among nanoparticles that are to be addressed. One common feature is that there is an interaction of ROS such as superoxide ($\cdot\text{O}_2^-$), hydrogen peroxide (H_2O_2), and hydroxyl radicals ($\cdot\text{OH}$) with the virus. As a result, the DNA or RNA inside the virus is ruptured. First, let us look at how these reactive oxygen species are formed. During mitochondrial electron transport [6], the majority of reactive oxygen species are generated as by-products. Furthermore, ROS are produced as required intermediates in metal-catalyzed oxidation reactions as shown below. 2 unpaired electrons lie in different shells in the outer electron shell of atomic oxygen. Oxygen is vulnerable to formation of radicals due to its electronic structure. Hydroxyl ion, Hydroxyl radicals, Hydrogen peroxide, Superoxide, and nitric oxide are the ROS in general. These are synthesized by adding electrons which thereby causes a sequential reduction. The formation of the ROS in metal-catalyzed oxidation reaction is shown in following sequential reactions.



One of the most commonly used markers of free radical development, which is a measure or a marker of oxidative stress, is lipid peroxidation. Free radicals also attack unsaturated fatty acids, which are generally found in cellular membranes [7]. In certain reactions, a hydrogen moiety is captured by a free radical in order to generate unsaturated carbon which eventually forms water in a chain reaction. This results in a fatty acid unpaired electron, allowing it to capture oxygen and form a peroxy radical. Carbonyl compounds such as MDA are formed due to the instability of lipid peroxides. This involves a chain of reactions and finally forming malondialdehyde. This oxidative stress further ruptures DNA and RNA inside the cell and eventually, the cell dies. ROS prevent the viral growth on the surface by damaging the cellular membrane, disrupting the respiratory system and inhibiting the network signal of the viruses. Schematic representation of the ROS generation and its application in prevention of viral growth has been shown in the Fig. 2.

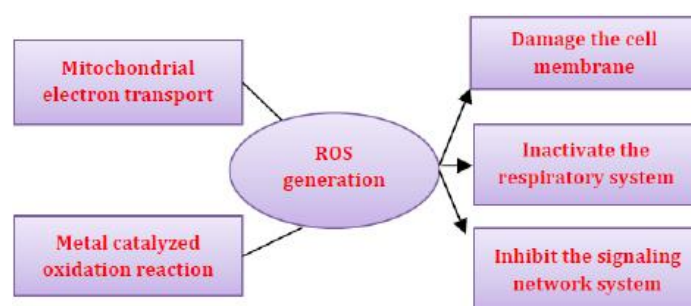


Fig. 1. Schematic representation of the ROS based antimicrobial properties

2.1.3 Contact Killing

Metallic copper or alloyed Copper surfaces are well known for a mechanism called contact killing under non-wet as well as moist/wet condition[8-11]. Direct hand contact on the surface is related to the non-wet condition whereas sneezing and coughing resembles the application of microbes through wet condition. Killing kinetic of microbes on the non-wet surface is relatively high due to the liquid surface between the microbes and surface which protects the microbes[12]. Copper has a free electron in its outer orbital shell which enable the copper to take part in oxidation-reduction reactions easily. This is the reason, rapid dissolution of copper ion from copper surface takes place. These ions blast the pathogen like an onslaught of missiles, preventing cell respiration and punching holes in the cell membrane or viral coating and creating free radicals that accelerate the kill, especially on dry surfaces. Most importantly, the ions seek and destroy the DNA [9] and RNA [13] inside a bacteria or virus, preventing the mutations. Stepwise the possible series of events during the contact killing by the metallic copper/alloyed copper surface (Fig. 3)

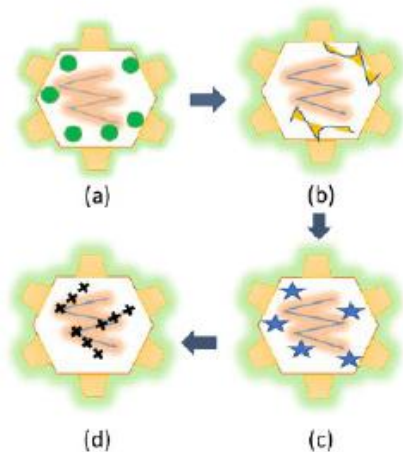


Fig. 1. Stepwise possible series of events during the contact killing on copper surface (a) dissolution of copper ions from copper surface causing cell damage (b) Cell membrane ruptures due to copper ions (c) Copper induce the formation of free radicals (ROS) (d) RNA and DNA destroyed by ROS subsequently degrades genomic materials which prevents mutations of virus.

2.2 TiO₂

TiO₂ Nano-particles have photocatalytic properties, which controls the microbial growth as shown in some study [14-15]. These photocatalytic properties enable the excitation of electron from the valance bond to conduction band under the enough UV exposure and generates the electron-hole pair. This is the reason TiO₂ has a wide bandgap of 3.2eV. These hole-electron pairs react in various ways on the surface and generate the ROS such as O₂•⁻ and OH• radicals. Photogenerated ROS attacks by different mechanisms to microorganisms (virus/fungi/bacteria). On one track, the cell membrane can be damaged, while on another, it can react to and disrupt the cell wall [16]. Some researchers also found that the signaling system and the respiratory system of the virus have been inactivated [8 and 16]. Application of TiO₂ Surface as antiviral surface with regard to interaction nature with bacteria/virus surfaces due to its nano-scopic characteristics. TiO₂ nanoparticles change surfacearea- to-volume ratios to maximize ROS interaction. whereas the cell membrane and wall rupture by intracellular oxidative damage is supplemented by the small size of nanoparticles

2.3 Silver₂

Ag and its oxide (Ag₂O) Nanoparticles are also used in healing of wounds, engineering of tissues, food packaging, water disinfection, and dentistry. According to various studies, during the interaction between microorganisms and Ag nanoparticles, Ag⁺ ions interfere with the cell wall peptidoglycan of bacteria, causing structural variation, which contributes to increased membrane permeability and cell death. By combining with proteins of bacteria via available sulfhydryl groups, Ag nanomaterials often help to prevent DNA replication. DNA replication capacity is lost as a result of destructive interaction with bacterial DNA

and Ag₂O. Ag nanoparticles have been shown to have a substantially stronger antiviral response to HIV-1 (98%) than Au nanoparticles (6–20%). As a result, we can see that Ag is a valuable and promising antimicrobial solution for a variety of microbes, and the process with resultant antimicrobial activity varies depending on the Ag-based content.

2.4 Hypothetical Material

It has been established that ROS plays an important role to fight against viral transmission. Furthermore, free electron is having some role in that mechanism. Research indicates that high conductor like copper as semiconductor in the form of quantum dot are effective to prevent transmission and treatment. Considering predominate role of free electron and photocatalytic effect of Cu and TiO₂ respectively authors recommend Cu-TiO₂ nanocomposites as a material of choice to prevent transmission of COVID-19 virus. It will generate free electron and or ROS and effect virus growth considering virus as also charged particle. Some research on the Cu deposited TiO₂ thin films [17] and Cu-TiO₂ nanofibers [18] on the surface under visible light with weak UV illumination (1μW/cm²) which corresponds to UV intensity of indoor light in general has been done. Research suggests Photocatalytic process causes the partial decomposition of the outer cell membrane while copper ions penetrate into cytoplasmic membrane resulting in complete loss cell's integrity [17]. Although, study has been done E. coli and bacteriophage f2 strain rather than corona virus. Cu-TiO₂ films or nanocomposites also possesses the deodorizing and self-cleaning properties besides its antiviral properties. One more important consideration regarding the usage of Cu-TiO₂ nanocomposites are its properties such as density and Hardness. Density decreases and hardness increases with increasing the TiO₂ particle [19]. Thus, these outstanding properties of the Cu-TiO₂ nanocomposites are best suited to being used in present and future at health care facility considering the current scenario of COVID-19 Pandemic in order to prevent virus infection. Although, its proper efficacy against COVID-19 virus is still unknown and investigation are immediately needed to be started in this regard.

3. Will coating of copper at health care facility will be beneficial: Data Based Study

In India, the prevalence of hospital-acquired infections is 14.7 percent, which means that approximately 15 people out of every 100 are affected by the hospital climate. And nearly every 37 in 1000 people are hospitalized in India with over a quarter of the older population [20]. This means that installing copper in hospitals could prevent tens of thousands of infections per year. Increasing the use of copper in our public spaces and hospitals will be a step backward, as copper was previously used much more commonly. Handrails, doorknobs, elevator keys, public benches, and many more frequently touched surfaces can be replaced or coated with copper.

The major reason is due to the high upfront costs [21], hospitals are hesitant to use copper and take this life-

saving measure. Copper was phased out of hospitals in the first place. It's due to our own vanity and an affinity for other materials like plastics, stainless steel, and aluminum. Copper door knobs, railings, and beds were replaced with other similar materials.

According to US statistics, installing copper on just 10% of a hospital's highest-risk surfaces costs about \$50,000. The costs are much higher in India because of the amount scaling to the hospitals. The theory is that looking at costs in this manner is a bad idea. The total cost of healthcare-acquired infections on an annual basis is truly staggering. In the United States, about 99,000 people die each year as a result of health-care-associated infections, with treatment costs totaling nearly 35 billion dollars. This suggests that the total cost of treating a hospital-acquired infection is nearly \$30,000 [4]. This number rises much higher in India, where the population and infection rate are both higher [20]. However, it was discovered that installing copper to only 10% of the surfaces in one hospital over a year resulted in over 15 fewer infections. Even if we use the lowest cost for treating a healthcare-acquired infection, the savings from the copper installation are almost \$400,000 (savings of over 13 times). With these figures, it's fair to say that if the copper percentage was raised above 10%, the savings will be much greater, and most importantly, more patient lives would be saved [4]. Small changes such as copper door handles and copper bed frames, for example, have been shown to measurably reduce the rates of healthcare-acquired infections in hospital environments. Although copper, like all other elements, is a finite resource, it is unlikely that we will run out of it anytime soon. According to the International Copper Association (ICA), the world's copper reserves are currently at 830 million tonnes. According to our current use, this supply should last around 50 years. But copper, practically, is one of the most recycled products on the planet, so we'll be able to use it for a long time. Also, even though copper oxidizes and turns green, it retains its antimicrobial properties. Another problem is that households generally don't find copper attractive, it loses its coloration over time but never loses its antimicrobial property. Although, the world is in crisis, and people should not be thinking in the direction of attractiveness, rather think in the direction of safety.

Authors suggest the use of very thin nano copper coating to take care of cost. Nano copper is having better surface properties and may be better kinetics with reference to generation of ROS. Further, the contact killing mechanism will be effective on that surface. TiO₂ nano-coating may be tried also considering photocatalytic properties.

4. Conclusions

Considering the above review, Authors have found that using the Copper, TiO₂ and Ag₂O nanoparticles in public places, most touched surfaces and health care facility prevent the risk of infection from the microbes. Considering the properties of the Cu and TiO₂ nanoparticles against the microbes, Authors also recommend the hypothetical Cu-TiO₂ nanocomposites to be considered for research and investigation against COVID-19 to combine the effect of Cu and TiO₂ particles in order to tackle the current pandemic

as well as for future applications.

Conflict of interest

All authors listed declares that they have no conflict of interest.

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Grain Boundaries: Structure to Engineering- A review

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Abstract

Grain boundaries (GBs) are interfaces that separate adjacent grains in a polycrystalline material and play a crucial role in determining the overall properties of crystalline materials. The structure and crystallography of GBs determine their energy and properties. Grain boundary engineering (GBE) is aimed at manipulating and optimizing the characteristics of grain boundaries to enhance material properties. GBE aims to increase the fraction of special grain boundaries with relatively lower energy while reducing the contiguity of random high-energy boundaries. Special grain boundaries often exhibit unique properties that can improve the material's resistance to intergranular degradation. In this work, we review the grain boundary crystallography, structure, and energy and the role of GBE on intergranular degradation (such as weld heat-affected zone (HAZ) liquation cracking and steam oxidation) of high-temperature materials.

Keywords: Grain boundaries, Structure to Engineering, polycrystalline material, Heat-affected zone

1.0 Introduction

Metals, alloys, and ceramics are predominantly used in their crystalline form in engineering applications. The properties of crystalline materials depend strongly on the deviation from an ideal crystal lattice, i.e., intrinsic crystal defects. Crystal defects, with various spatial dimensions, include the crucial two-dimensional planar grain/phase boundaries. Thermomechanical processing is widely employed to engineer the defect density and distribution and customize the required material properties.

1.1 Grain boundary crystallography

The description of grain boundary crystallography requires eight parameters: five macroscopic degrees of freedom (DOFs) and three microscopic DOFs. Among the five macroscopic DOFs, three parameters define the orientation relationship between adjacent grains, typically expressed as Euler angles (ϕ_1, ϕ, ϕ_2), Miller indices $\{hkl\} \langle uvw \rangle$, or an angle (θ)-axis $\langle UVW \rangle$ pair in Rodrigues-Frank space. Two additional parameters precisely define the spatial orientation of the grain boundary plane, specifically the boundary inclination, expressed through the normalized crystallographic normal vector ($n = (n_1, n_2, n_3)$) with respect to one of the adjacent grains. Alongside the macroscopic parameters, three independent values of the microscopic translational vector ($t = (t_1, t_2, t_3)$) characterize the location of the grain boundary plane. Intrinsic properties of grain boundaries,

i.e., mobility and energy, are intimately connected to these eight parameters. While external factors can affect the five macroscopic parameters, the translational vector t is determined by minimizing the total energy of the crystal [1-3].

1.2 Grain boundary structure and energy

Atoms at the core of the grain boundary deviate from regular crystal positions compared to the interior. The arrangement of atoms at GBs is well-established as crystal-like, supported by theoretical and experimental evidence of anisotropic behaviour. Two atomic structure groups emerge: low-angle grain boundaries and high-angle grain boundaries. Using a lattice dislocation model, the energy of low-angle grain boundaries was found to vary linearly with the misorientation angle (θ) up to approximately 15° as the number of dislocations increases linearly with θ . However, for θ values larger than 15° referred to as high-angle grain boundaries (HAGBs), the lattice dislocation model becomes invalid due to the overlap of dislocation cores, leading to the loss of their identity as individual lattice defects. Significant efforts have been made to develop a simple geometrical model for specifying singular (special) character grain boundaries. Kronberg and Wilson [4] proposed the coincidence-site lattice (CSL) model by assuming that grain boundary energy is minimized when there is a high coincidence of atomic positions in both adjoining grains, leading to fewer broken bonds across the boundary. It considers two grains misoriented by a chosen angle (θ) around a selected axis (o). In the superposition of these crystals, certain atomic sites coincide, termed coincidence sites, distributed regularly throughout the superimposition and forming a superlattice known as the coincidence-site lattice (CSL). The density of coincidence sites, represented by the reciprocal value ' Σ ', is a key parameter characterizing the CSL [5] and is defined as the number of coincident sites in an elementary cell divided by the total number of lattice sites in that cell. Grain boundaries with low Σ values exhibit special behaviour [6,7]. While Σ serves as a widely accepted geometric criterion for identifying special grain boundaries, it solely reflects the mutual misorientation of two adjoining crystals. Experiments show that $\Sigma 3$ characterizes singular twin grain boundaries in both bcc and fcc structures. Despite its limited information on grain boundary orientation or atomic structure changes, the CSL approach is widely used to characterize individual boundaries and their networks [2].

1.3 What is grain boundary engineering (GBE)

Watanabe [6] introduced “Grain Boundary Design”, later evolved into “Grain Boundary Engineering (GBE),” to enhance the properties of polycrystalline brass, emphasizing an increased fraction of CSL boundaries for improved resistance to intergranular fracture. GBE has been widely applied to enhance the intergranular stress corrosion resistance of FCC materials in aggressive environments [6]. The fundamental principle of GBE is to optimize the grain boundary character distribution (GBCD) by increasing the proportion of low Σ ($\Sigma \leq 29$) boundaries [8]. GBE is extensively applied to low-to-medium stacking fault energy (SFE) materials, focusing on enhancing the fraction of $\Sigma 3$ boundaries and its variants (e.g., $\Sigma 9$ and $\Sigma 27$) [8]. The primary objective is to improve properties associated with $\Sigma 3$ boundaries, as they preferentially terminate on low-index planes. Higher order $\Sigma 9$ and $\Sigma 27$ boundaries play a geometric role in reconfiguring the grain boundary network, eventually disrupting random HAGB connectivity.

1.4 GBE processing

GBE microstructure has been realized through various processing approaches, such as applying magnetic field or mechanical stress during annealing, laser surface melting followed by annealing, and thermo-mechanical processing (TMP). Amongst all these approaches, TMP is the most effective and widely employed as it is well suited for scaling up to industrial processing. GBE is accomplished through a series of iterative thermomechanical treatments involving deformation and annealing. GBE is most widely employed in low and medium stacking fault energy FCC materials wherein multiple twinning processes are achieved easily [8].

Generally, the processing of GBE is classified into strain annealing and strain recrystallization. Strain annealing is characterized by low strains of 5-10%, as low as possible not to initiate recrystallization. It is followed by annealing at high temperatures for a short duration or a relatively low temperature for longer durations [8]. This process, though, enhances the fraction of special boundaries in the material; it comes with an increase in grain size, which is found detrimental in certain applications. When the material is deformed, the grains fragment, leading to an increased fraction of HAGBs and a decrease in special boundaries fraction. This microstructure with increased stored energy due to the deformation increases grain boundary migration rate during subsequent annealing, and chances of multiple twinning are enhanced. Strain recrystallization involves straining the material by 15-30%, followed by annealing above the recrystallization temperature for a very short duration. The recrystallization temperature for a material is a function of the prior applied strain. New strain-free grains nucleate and grow during recrystallization, increasing the special boundaries fraction while maintaining a lower grain size. This is often considered suitable for commercialization owing to its shorter annealing times. During the straining part of GBE processing, dislocation pile-up occurs at the twins existing in the un-deformed microstructure. The pile-up of

dislocations at the twin boundary causes an increase in internal stress, which acts as the driving force for grain growth or recrystallization, during which the twins could interact with other boundaries and increase the fraction of the low Σ special boundaries.

1.5 Quantification of GBE microstructure

1.5.1 Fraction of low Σ CSL or special boundaries

Evaluating the optimization effect of GBCD often relies on the proportion of special twin boundaries, quantified through both fraction and density measures [9-10]. The fraction is defined as the ratio of the total length of all $\Sigma 3n$ twin boundaries to the total length of all high-angle grain boundaries. The density corresponds to the total length of $\Sigma 3n$ twin boundaries per unit area. According to the CSL model, grain boundaries are categorised into low-angle grain boundaries (LAGBs) or $\Sigma 1$ grain boundaries, low- Σ CSL boundaries ($1 < \Sigma \leq 29$), also known as special twin boundaries, and high- Σ CSL boundaries ($\Sigma > 29$), referred to as random HAGBs [11-12]. Studies indicate that low- Σ CSL boundaries, with lower free energy than HAGBs, exhibit superior resistance to intergranular degradation [13].

The rotation axis $\langle uvw \rangle$ and rotation angle θ of low- Σ CSL boundaries can be characterized using the electron back-scattered diffraction (EBSD) technique (Table 1). For identifying the CSL boundary, the Brandon criterion ($\Delta\theta_{\max} = 15^\circ \Sigma^{-1/2}$) [14] is most widely used. However, recent research has suggested that the Bradon criterion is very lenient, and a more restrictive criterion, such as Palumbo–Aust standard ($\Delta\theta_{\max} = 15^\circ \Sigma^{-5/6}$), is being suggested to be used to identify CSL GBs [15].

Table 1. List of low- Σ CSL boundaries ($\Sigma \leq 29$) and their corresponding rotation axes $\langle uvw \rangle$ and angles θ in cubic crystal system [16-17].

Σ	θ	$\langle uvw \rangle$	Σ	θ	$\langle uvw \rangle$
1	0°	$\langle 111 \rangle$	19a	26.5°	$\langle 311 \rangle$
3	60°	$\langle 111 \rangle$	19b	46.8°	$\langle 100 \rangle$
5	36.9°	$\langle 100 \rangle$	21a	21.8°	$\langle 331 \rangle$
7	38.2°	$\langle 111 \rangle$	21b	44.4°	$\langle 211 \rangle$
9	38.9°	$\langle 110 \rangle$	23	40.5°	$\langle 311 \rangle$
11	50.5°	$\langle 110 \rangle$	25a	16.3°	$\langle 100 \rangle$
13a	22.6°	$\langle 100 \rangle$	25b	51.7°	$\langle 331 \rangle$
13b	27.8°	$\langle 111 \rangle$	27a	31.6°	$\langle 110 \rangle$
15	48.2°	$\langle 210 \rangle$	27b	35.4°	$\langle 210 \rangle$
17a	28.1°	$\langle 100 \rangle$	29	46.3°	$\langle 100 \rangle$
17b	61.9°	$\langle 221 \rangle$			

In optimizing GBCD, it's crucial to consider whether low- Σ CSL boundaries effectively disrupt the connectivity of random grain boundaries. Lehockey et al. [18] demonstrated that enhancing intergranular failure resistance is possible only when low- Σ CSL grain boundaries interrupt the connectivity of the random boundary network. Current methods for characterizing network connectivity include triple junction character distribution, grain cluster analysis, percolation theory, and fractal analysis.



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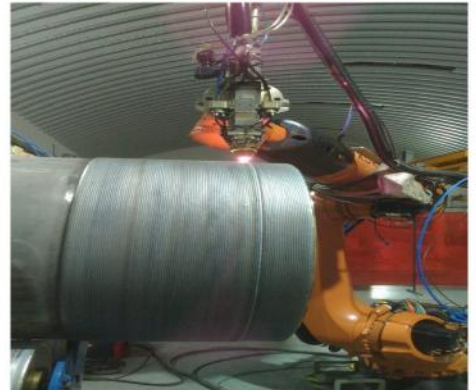
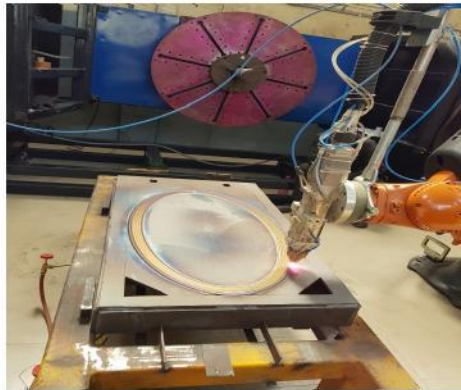
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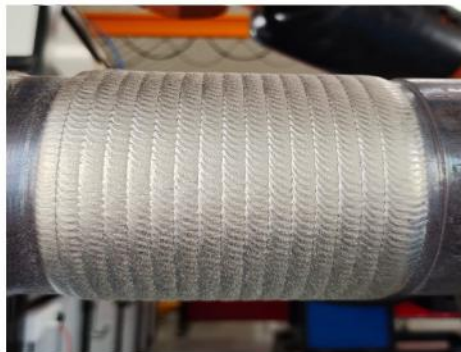
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1.5.2 Triple junction character distribution

The classification of triple junctions (TJs) based on the number of low- Σ CSL boundaries includes four distinct types: three random boundaries (0-CSL), one special and two random boundaries (1-CSL), two special boundaries and one random boundary (2-CSL), and three special boundaries (3-CSL).

1.5.3 Grain cluster/ Twin-related domain (TRD)

A grain cluster, also known as the twin-related domain (TRD), contains grains with a $\Sigma 3n$ orientation relationship among themselves. The internal structure of a grain cluster consists of $\Sigma 3$ twin boundaries and their geometrically related twin boundaries ($\Sigma 9$, $\Sigma 27$), while the outer grain comprises random HAGBs. The formation of a grain cluster is attributed to multiple twinning, involving iterative twinning operations starting from a single nucleus during recrystallization.

1.5.4 Percolation theory

Percolation theory, a stochastic geometric probability model, quantifies random boundary network connectivity and predicts material failure probability. It is frequently used to assess intergranular crack arrest probability at triple junctions and evaluate the influence of optimized GBCD through GBE on material resistance to intergranular cracks [19-20]. Three percolation models are proposed and typically employed to estimate the intergranular crack arrest probability at TJs.

Enhancing the resistance against intergranular failure in polycrystalline materials poses significant challenges in various industries, notably in addressing issues like liquation cracking, high-cycle fatigue, creep, intergranular corrosion (IGC), intergranular stress corrosion cracking (IGSCC), and intergranular segregation/ precipitation. These challenges are particularly pronounced in austenitic stainless steels and nickel-based alloys, considered the most promising structural materials for nuclear power and chemical plants. These industries demand the utmost safety and reliable operation, especially following the tragic accidents in nuclear power plants.

Over recent years, multiple researchers have conducted comprehensive investigations into the influence of GBE on intergranular failure in polycrystalline materials.

Here, we provide a brief overview of the research efforts undertaken by our group, briefly investigating the impact of GBE on mitigating intergranular failure. Specifically, our focus lies on weld heat-affected zone (HAZ) liquation cracking and hot corrosion in austenitic stainless steel and nickel-based alloys.

2.0 Effect of GBE on weld heat affected zone (HAZ) liquation cracking of austenitic stainless steel

Weld heat-affected zone (HAZ) liquation cracking poses a significant hurdle in fusion welding. This occurrence is marked by the development of liquid films along grain boundaries, typically initiated by the segregation of impurities and/or constitutional liquation arising from

the localized eutectic melting of second-phase particles. We present below the role of GBE on liquation cracking in a Ti stabilised austenitic stainless steel taken from our work [21]. A 6 mm thick plate of austenitic stainless steel (AISI 316Ti) was used as an as-received (AR) sample. A small strip of the AR sample was sectioned off and subjected to cold rolling (5% thickness reduction), and subsequent annealing at 1373 K for 0.5 h resulted in a higher fraction Σ CSL fraction (GBE sample). The liquation cracking was assessed using the longitudinal Varestraint tests conducted on AR and GBE samples, utilizing two augmented strain levels (2 and 4%). The welding parameters used in this work were shown elsewhere [21]. The assessment included evaluating the total number of cracks, maximum crack length (MCL), and total crack length (TCL). Samples obtained from the top surface of the Varestraint test regions were additionally prepared for EBSD examination. Bead-on-plate welds were produced on AR and GBE samples using the same welding parameters as previously specified. These welds were then subjected to microstructural analysis across different regions. The grain boundary maps of AR and GBE samples are shown in Figure. 1a and b, respectively. The HAGBs are well-connected in the AR sample (see inset of Fig. 1a). However, in the GBE sample, CSL boundaries notably disrupt their connectivity (indicated by grey ($\Sigma 3$), red ($\Sigma 9$), and green ($\Sigma 27$) lines). This disruption is evident in the marked regions (see Fig. 1b; black arrow from 1 to 7).

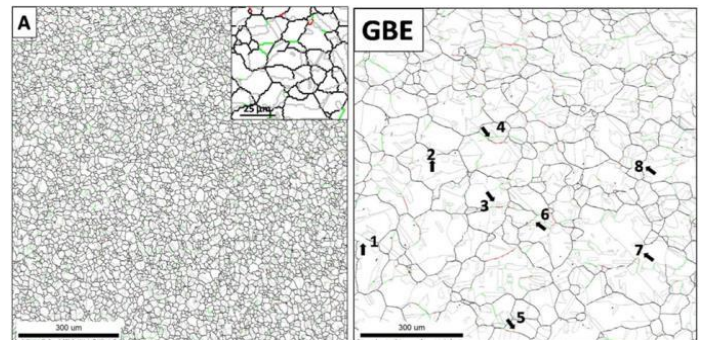


Fig.1. CSL map showing type and distribution of grain boundaries in (A) AR and (B) GBE material, $\Sigma 3$ (grey), $\Sigma 9$ (red), $\Sigma 27$ (green) and HAGBs (black) [21].

The average grain size of the AR and GBE samples considering with and without twins as grain boundaries was 6 μm and 16 μm , and 10 μm and 36 μm , respectively (see Fig.1). Other than CSL boundaries, GBE characterization also involves essential parameters like TRDs and TJs [22-24]. The TRDs represent large clusters of grains interconnected through twin misorientations [25], each TRD linked to another via HAGBs. The TRDs are commonly characterized by their average size and the average number of twins per TRD [24]. The size of TRDs in the GBE sample is $(66 \pm 3 \mu\text{m})$, representing an increase of approximately 40% compared to the TRD size observed in the AR sample $(47 \pm 3.3 \mu\text{m})$. Additionally, the GBE sample exhibits a notably higher average number of twins per TRD, measuring (16.8 ± 1.8) . This value is approximately eight times greater than the average number of twins per TRD observed in the AR sample (2.3 ± 0.1) . The considerable increase in TRD size and the elevated average number of twins per grain in the microstructure can be attributed to the multiple

twinning events during grain boundary migration. Figure 2 shows the interfacial microstructure of the AR and GBE samples, showing the fusion zone, HAZ and base metal (BM). The re-solidified liquated grain boundary lengths in the AR and GBE samples were nearly 100 μm and 50 μm , respectively. Elemental mapping of liquated and re-solidified boundaries revealed the presence of Ti, Mo, and S (Fig. 3). However, due to the closely matched L α and K α energies of Mo and S, the maps in Fig. 3 do not definitively confirm S segregation to the grain boundaries. Additionally, C was not detected in the liquated regions. Still, the simultaneous presence of Mo and Ti in these regions suggests the constitutional liquation of (Ti, Mo) carbides/carbosulfides.

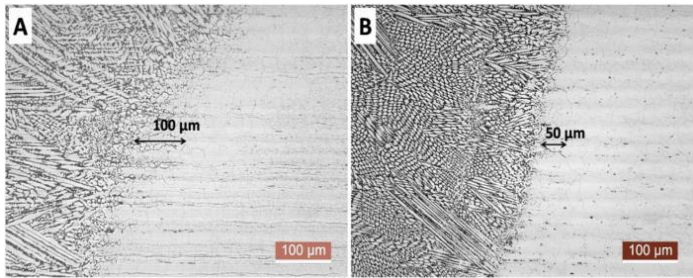


Fig.2. Optical micrographs of fusion boundary showing HAZ liquation in A) AR and B) GBE conditions [21].

Diffusion and solute element segregation occur slower along CSL boundaries than random HAGBs, as reported in [16]. This phenomenon reduces element segregation in GBE material. Studies have indicated that a higher fraction of low Σ CSL boundaries contributes to decreased segregation, enhancing the material's resistance to liquation cracking, as highlighted in [26-27].

Fig. 4a and b depict the typical microstructures of Varestraint-tested samples subjected to 4% augmented strain, revealing liquation cracks in AR and GBE samples, respectively. TCL, MCL, and the number of cracks were measured to assess the material's cracking susceptibility. Table 2 summarises the results obtained from longitudinal Varestraint tests performed at 2% and 4% strain levels. The findings indicate that, in both 2% and 4% strain samples, the AR material exhibited a higher total number of cracks, TCL, and MCL than the GBE sample.

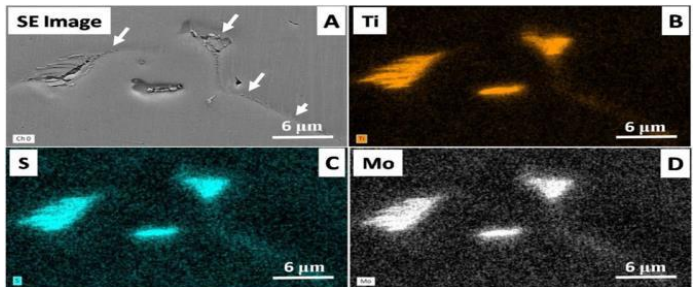


Fig. 3. a) SEM image of liquated grain boundary (marked with arrows) in AR sample and (b-d) Ti, S and Mo elemental X-ray maps of the same region indicating segregation at the liquated and re-solidified grain boundary [21].

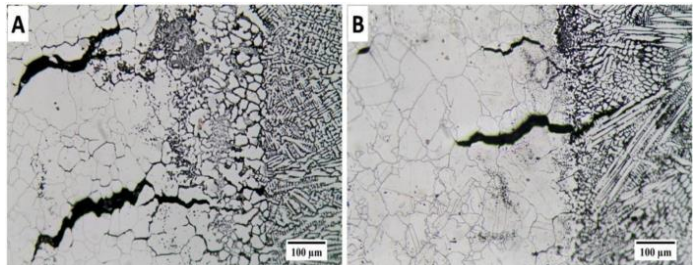


Fig. 4. Optical micrographs of 4% Varestraint tested samples showing liquation cracks in a) AR and b) GBE material [21].

Table 2. Liquation cracking susceptibility parameters obtained from longitudinal Varestraint test.

Strain (%)	Sample	TCL (mm)	MCL (mm)	Total number of cracks
2%	AR	4.62	0.54	16
	GBE	2.11	0.29	9
4%	AR	11.75	1.02	32
	GBE	8.3	0.91	24

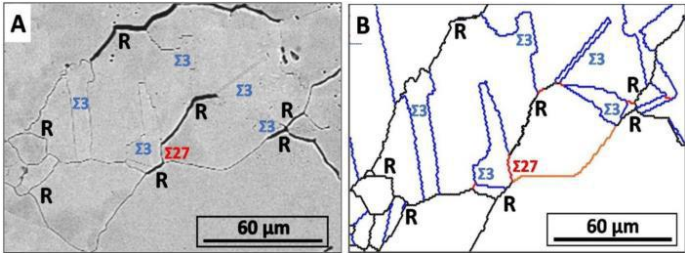


Fig. 5. a) SEM micrograph showing arrested liquation cracks at 1-CSL and 2-CSL triple junctions in 4% Varestraint tested sample, and b) CSL map of the same region where the boundary character is marked [21].

Following Varestraint tests, the microstructural analysis revealed changes similar to autogenous weld samples [21]. The AR sample has a finer grain size than the GBE sample (Fig.1). Contrary to conventional expectations linking finer grains to enhanced resistance against liquation, the current study reveals that the GBE sample, despite having a coarser grain size, demonstrated smaller liquated lengths compared to AR sample. This unexpected result is attributed to the higher fraction of special boundaries in the HAZ of the GBE sample [21]. Although grain sizes in the HAZ of AR and GBE samples are comparable considering twins, the GBE sample displayed superior resistance to liquation cracking. This resistance is linked to the higher fraction of CSL boundaries, primarily $\Sigma 3$ twin boundaries, in the HAZ GBE sample. Prior research on GBE samples supports the notion that special boundaries offer greater resistance to cracking than random HAGBs [27-28]. The increased susceptibility to liquation cracking in AR samples can be attributed to (i) a lower fraction of CSL boundaries in the weld HAZ [16] and (ii) a higher number of carbide particles on the grain boundaries. Fig. 5a and b show that cracks were primarily initiated along random HAGBs but were arrested at 1-CSL and 2-CSL TJs. Gertsman et al. [28] confirmed that triple points with n-CSL ($0 < n \leq 3$) boundaries enhance cracking resistance. In the GBE sample, 90% of observed triple points involve 1-CSL, 2-CSL, and 3-CSL boundaries, compared to 77% in AR material (Fig. 1). The lower number of TJs in the AR sample due to larger grain size may contribute to a lower probability of arresting cracks [16,28].

3.0 Influence of GBE on high-temperature steam oxidation behaviour of IN617 alloy

Ni-based alloys find widespread application in high-temperature environments across aerospace, nuclear, chemical, and power industries, owing to their exceptional high-temperature mechanical properties.

However, exposure to oxidizing conditions at elevated temperatures can significantly degrade their mechanical performance. Oxidation resistance enhancement is typically achieved by altering alloy chemistry [29] or applying protective coatings [30]. The degradation processes involve the depletion of alloying elements from the material or the ingress of reactive elements from the environment, both facilitated by diffusion through RHAGBs. To improve oxidation and corrosion resistance, disrupting the connectivity of RHAGB networks by increasing the fraction of low-energy grain boundaries proves effective [31-32]. The detailed GBE processing of IN617 alloy was discussed elsewhere [33]. The role of GBE on isothermal and cyclic oxidation under steam at 1273 K which were reported in [33] are presented below.

In Fig. 6, cross-sectional images of isothermally oxidized AR and GBE samples (a and c) are accompanied by EDS maps illustrating oxygen distribution (b and d). Notably, the twin boundary beneath the external oxide layer (marked by the arrow in Fig. 6) remains unchanged through internal oxidation, while neighbouring RHABs undergo internal oxidation. In both AR and GBE samples undergoing isothermal and cyclic oxidation treatments, the oxide scale thickness is non-uniform, attributed to the initial oxide layer growth in regions where grain boundaries intersect the surface, resulting in a thicker layer.

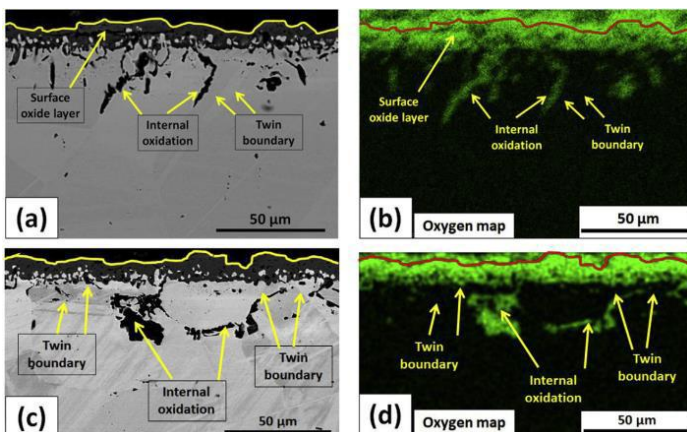


Fig.6. SEM image of a cross-section of a) AR sample and c) GBE sample subjected to isothermal oxidation at 1273 K for 480h. EDS maps showing oxygen distribution in b) AR and d) GBE samples following isothermal oxidation at 1273 K for 480 h [33].”

In Figs. 7 and 8, EDS maps of Al, Cr, Co, Mn, Ni, and O for AR and GBE conditions under cyclic oxidation are shown. The surface oxide scale exhibits a convex feature at the grain boundary intersection (Fig. 7). This is due to faster Cr diffusion along the grain boundary than the matrix, resulting in a thicker oxide layer at the grain boundary [34]. Disrupting the RHAGBs network with Σ 3 and its higher-order variants will decrease Cr depletion during oxidation

The external oxide layer is rich in Cr, O, and Mn, indicating the presence of oxides of Cr and Mn. In internal oxidation, Al_2O_3 is present, and depletion of Ni and Co occurs in both the external oxide scale and internal oxidized regions (see Figs. 7 and 8). Regions rich in Ti and O indicate the formation of TiO_2 .

In alloy 617, GBE specimens exhibit smaller grain sizes than AR samples. Clusters of fine-grained regions are observed in the GBE sample, likely contributing to higher growth stresses and variations in stress distribution, leading to spallation compared to AR samples [33].

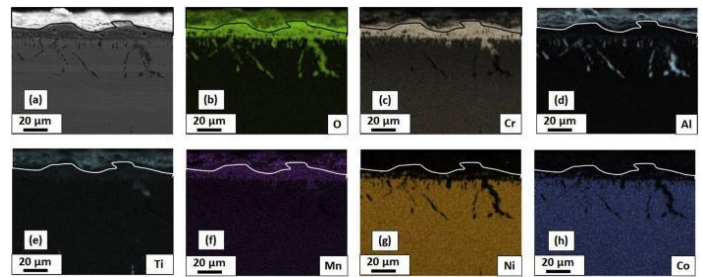


Fig.7 SEM cross-sectional image of (a) GBE sample subjected to cyclic oxidation at 1273 K for 480 h in air with 20% water vapour and b, c, d, e, f, g and h show EDS elemental distribution maps of O, Cr, Al, Ti, Mn, Ni and Co respectively from the region in (a) [33].

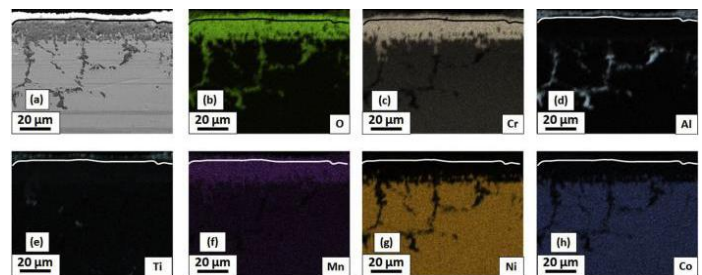


Fig. 8. SEM cross-sectional image of (a) GBE sample subjected to cyclic oxidation at 1273 K for 480 h in air with 20% water vapour and b, c, d, e, f, g and h show EDS elemental distribution maps of O, Cr, Al, Ti, Mn, Ni and Co respectively from the region in (a) [33].

4.0 Summary

In this review, the role of structure and crystallography of grain boundaries on their energy and properties were briefly discussed. The concept of a coincident lattice model for GBs was presented and its application to grain boundary engineering (GBE) was elucidated. The parameters employed to quantify the GBE microstructure and the processing methods applied to achieve a GBE microstructure were presented. The beneficial role of GBE microstructure on weld heat-affected zone (HAZ) liquation cracking and steam oxidation in a Ti austenitic stainless steel and Ni base superalloy is demonstrated.”

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Calculation of inclusion paths during secondary steelmaking using FactSage

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Abstract

The production of clean steel can save cost as well as improve the quality. It requires a detailed understanding of the metallurgical phenomena as well as challenges associated with the production. Hence, the plant practice and theoretical understanding goes hand-in-hand to achieve this goal. This article describes the computational methods developed using FactSage that can calculate predict steel cleanliness during the ladle refining process. Such a tool can be of great help to understand and optimize the process such that the amount and composition of non-metallic inclusions are within an acceptable range. Furthermore, the tool can be used to optimize addition of alloying elements and argon stirring practices.

Keywords: Steel refining, slag, inclusion, calcium treatment, alumina, spinel

1.0 Introduction

Non-metallic inclusions are integral to steel products due to the nature of production process. Very small inclusions of certain compositions such as AlN are useful in controlling microstructure. For example, Cheng et al. [1] reported pinning of the ferrite grain boundaries by 10-100 nm size AlN inclusions in a drawing quality special aluminium-killed steel. Inclusions of intermediate size (0.1 μm – 10 μm) are generally harmless. However, larger size inclusions are undesirable in most of the high-quality steels. Inclusion composition and shape are of great importance as well. Inclusions that are liquid at the steelmaking temperature are typically round and considered less harmful than the solid irregular inclusions. Hence, steelmakers take a great deal of effort to carefully optimize the process to control composition, number and morphology of inclusions and their distributions [2-4]. In addition to industrial practices, academic researchers have developed special tools and techniques to study inclusion behaviour in laboratories [5-8]. In addition to experimental work, there have been significant effort to calculate inclusion composition through various models. Inclusion stability diagram is one-such tool. Several researchers have developed kinetic models to predict inclusion composition during steel refining [9-11]. These modelling tools utilize thermodynamic tools such as FactSage [12] to calculate interfacial equilibria at the steel-slag and steel-inclusion interfaces. Moreover, these models are capable of considering important processing conditions such as stirring, ferro-alloy addition, arcing. The results of these model are often in close agreement with the plant observations.

Endogenous inclusions are generated due to deoxidation

but its composition and amount keeps evolving during processing. For example, alumina inclusions generated during the process may transform to spinel inclusions [13]. Further, Ren et al. reported changes in composition of oxide inclusions during heat treatment as well for stainless steel samples [14].

This article summarizes few applications of FactSage to calculate inclusion paths during secondary steel refining. These examples also demonstrate that inclusion composition is linked to evolution of steel chemistry during the process.

2.0 Calculation of equilibrium inclusion composition

2.1 Method

Alumina inclusions form due to deoxidation of steel by adding aluminium. However, the deoxidation product is often not in equilibrium with the slag i.e. the activities of oxides present in the slag is not the same as that in the deoxidation products. Hence, there is a driving force for change in composition of inclusions.

The Equilib module of FactSage can be used to calculate equilibrium inclusion composition using following steps:

- Calculate equilibrium between initial steel and slag considering overall composition and amount of both phases.
- Add expected total oxygen to the steel and equilibrate it again. The resultant non-metallic composition can be considered as the composition of the inclusions in equilibrium with the slag as well as steel.

The calculation is demonstrated by considering initial steel and slag compositions described in Table 1 and Table 2 respectively. The amount of steel and slag considered for these calculations are 180 tonnes and 3 tonnes respectively.

Table 1. Initial steel composition

[%Al]	[%O]	[%S]	[%Si]	[%Mn]	[%C]
0.09	0.008	0.02	0.02	0.15	0.05

Table 2. Initial slag composition

%CaO	%Al ₂ O ₃	%SiO ₂	%MgO	%FeO	%MnO
60	27	4	8	0.5	0.5

2.2 Equilibrated inclusion composition

The calculation procedure described in section 2.1 was used to first calculate the equilibrium steel composition. Equilibrium calculation was performed using Equilib module in FactSage 8.3; FTmisc, FToxid and FactPS databases were used for this and all other calculations described in this article. The result is shown in Table 3. The results clearly show the desulfurization assisted by the presence of aluminium and low level of FeO and MnO in the slag.

Table 3. Steel composition equilibrated with slag

[%Al]	[%O]	[%S]	[%Si]	[%Mn]	[%C]
0.029	0.0006	0.0005	0.048	0.157	0.05

The steel composition mentioned in Table 3 was equilibrated with total oxygen = 10 ppm. It should be noted that the additional oxygen amount is needed to create inclusions as the amount mentioned in Table 3 is the dissolved oxygen. The equilibrium calculation shows the formation of 4.9 ppm of spinel ($MgAl_2O_4$) and 1.8 ppm of MgO inclusions. The activity of MgO is very close to unity which is similar to the aMgO in the slag.

3.0 Evolution of inclusion composition

3.1 Method

The inclusion composition described in the previous section is not commonly observed as complete equilibrium is not achieved during the steel refining process. Due to high temperature of the process, chemical equilibrium at the interface is achieved however the overall rate of transformation of inclusions is limited by the mass transport in steel and slag. Therefore, kinetic models have been developed that can predict changes in steel, slag and inclusion composition with time. In such models, the system size for the chemical equilibrium calculation by FactSage is defined by utilizing mass transfer coefficients in both phases. The mass from a phase participating in the equilibrium reaction is calculated as $mAp\Delta t$, where m is mass transfer coefficient, A is the planar interfacial area, ρ is the density of that phase and Δt is the time step size. The approach is popularly known as Effective Equilibrium Reaction Zone approach. Such kinetic models can also consider operating conditions such as argon flow rate and temperature as well as alloying additions. In this work, result from a simplified model is presented to demonstrate the application of this approach.

Initial steel and slag compositions were taken as described in Table 1 and Table 2. The mass transfer coefficient in the steel and slag phase were taken as 0.002 m/s and 0.0002 m/s respectively. It should be noted that the rate of inclusion flotation is implicitly covered by considering the mass transport of liquid steel to the steel – slag interface. Inclusions are considered to be in complete equilibrium with instantaneous composition of steel in each time step. Ladle diameter at the steel – slag interface was taken as 4 m.

The model was implemented by writing macro code which facilitates interaction between MS-Excel and

Equilib module of FactSage i.e. allow reading inputs from MS-Excel, performing equilibrium calculation in FactSage and writing output back in MS-Excel.

3.2 Evolution of steel, slag and inclusion composition

Fig. 1 and Fig. 2 show the calculated compositions of steel and slag with time. It is evident that the aluminium in steel is continuously consumed for desulfurization of steel and reduction of silica from the slag. Such a calculation can be used to find the time required for target desulfurization. For example, if the target sulphur level is 40 ppm, 29 minutes would be enough. As expected, FeO and MnO concentrations in the slag also decrease rapidly.

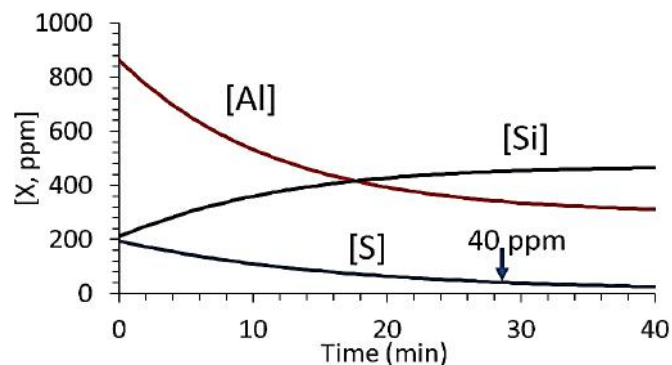


Fig. 1. Evolution of steel composition

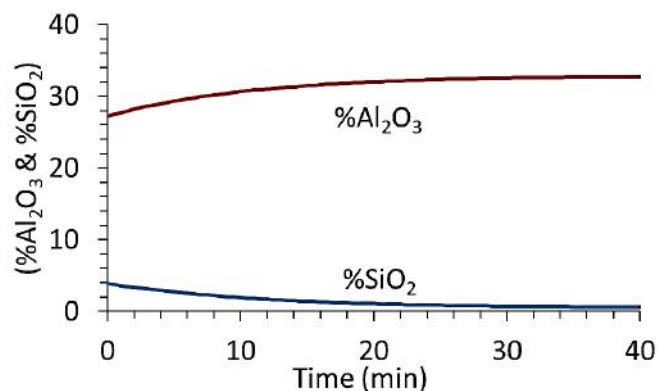


Fig. 2. Evolution of slag composition

Inclusion evolution is shown in Fig. 3 to Fig. 5 shows the change in the molar ratio of Mg/Al present in the inclusion with time. The transformation of alumina to spinel inclusions is clearly seen to progress continuously. The compositional transformation is arrested when the inclusion composition reaches in a single-phase region of the phase diagram, see Fig. 4 from right to left at 1600°C. It can be clearly seen that there is no formation of MgO inclusions indicating that the complete equilibrium between steel and slag is not achieved.

It should be noted that the rate and extent of transformation also depends on the amount of inclusion present in steel. For these calculations, the amount of inclusion in steel can be seen from Fig. 5. Further the Mg pick-up in inclusions is closely followed by the extent of desulfurization as shown in Fig. 6. It is evident that the requirement of deep desulfurization would lead to the transformation of alumina inclusions to spinel inclusions.

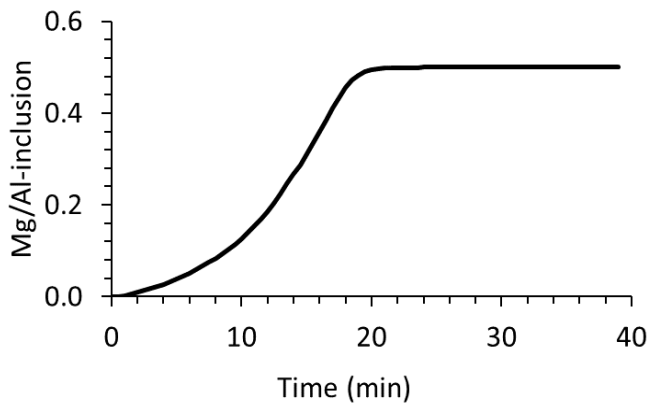


Fig. 3. Evolution of inclusion composition

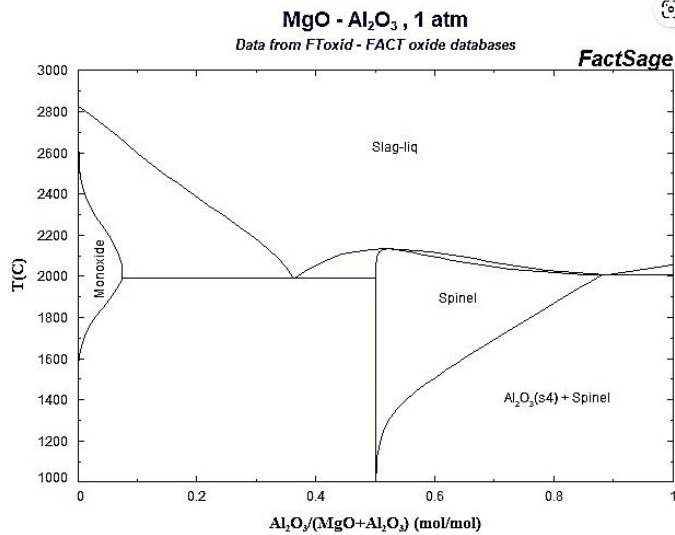


Fig. 4. Al₂O₃ – MgO phase diagram (Bale et al., 2016)

Fig. 5. Total oxygen in steel with time

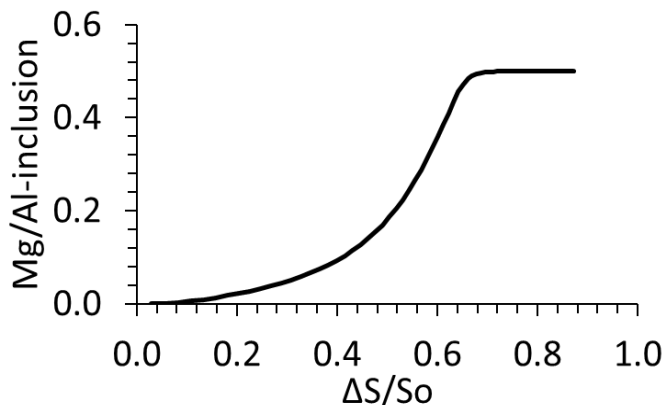
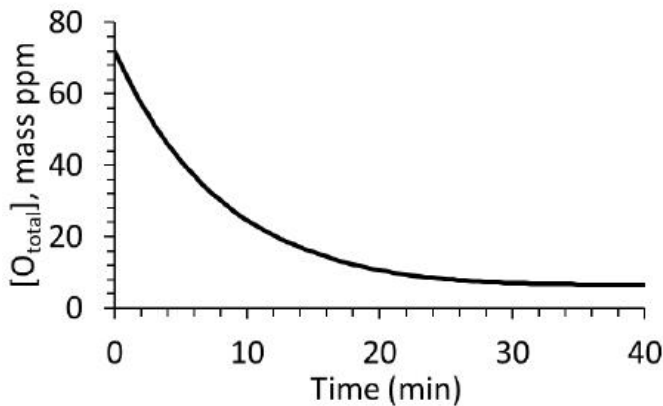


Fig. 6. Inclusion composition with the extent of desulfurization

4.0 Calcium treatment calculation

The solid alumina or spinel inclusions are often treated by calcium addition to form liquid inclusions which are considered less harmful. The clogging tendencies are reduced and spherical shape of the liquid inclusions are preferred over irregular shaped solid inclusions from mechanical properties perspective during processing and applications.

4.1 Calculation method

The delivery of calcium to liquid steel is not modelled in this work. The amount of calcium required for successful modification is calculated by performing equilibrium calculations. The required amount also depends on the time at which calcium is injected. To perform these calculations using FactSage, the instantaneous steel compositions at 10, 20 and 30 minutes were taken from the kinetic calculations described in the previous section. These are listed in Table 4.

Table 4. Calculated steel composition at 10, 20 and 30 min

Time	[%Al]	[O _{tot}] _{ppm}	[S] _{ppm}	[%Si]	[%Mn]
10	0.053	24.6	111	0.036	0.155
20	0.039	10.63	64.4	0.043	0.156
30	0.034	7	38.7	0.045	0.156

Appropriate amounts of calcium were added and the equilibrium inclusion compositions were calculated following the calculation procedure described in section 2.1.

4.2 Calcium requirement

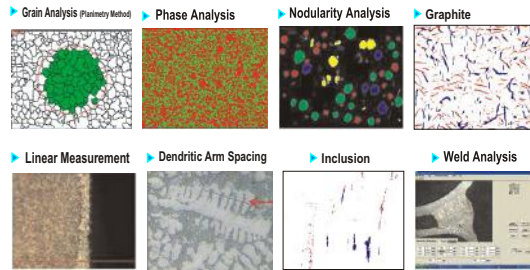
Fig. 7 to 9 show the effect of calcium addition on the phase fractions in inclusions if calcium treatments are performed at 10, 20 and 30 minutes. Dashed lines in this Fig. 7 to 9 show the range of calcium required to achieve 50% liquid fraction in the inclusion which is needed to achieve shape modification. It is clearly seen that the calcium addition narrows a lot with time. For calcium treatment at 10 minutes, 8 – 48 ppm calcium, at 20 minutes 2 – 16 ppm calcium and at 30 minutes only 1 – 5 ppm calcium are needed. Hence, the calcium addition at a later time would require more precise addition but at early times, the required amount can be optimized to save on the cost of the addition. The significant change in the calcium requirement is due to 'exponential' decrease in inclusion amount with time as shown in Fig. 9. Of course, the amount would change with steelmaking practices such as stirring rate and the extent of interaction between steel and slag.

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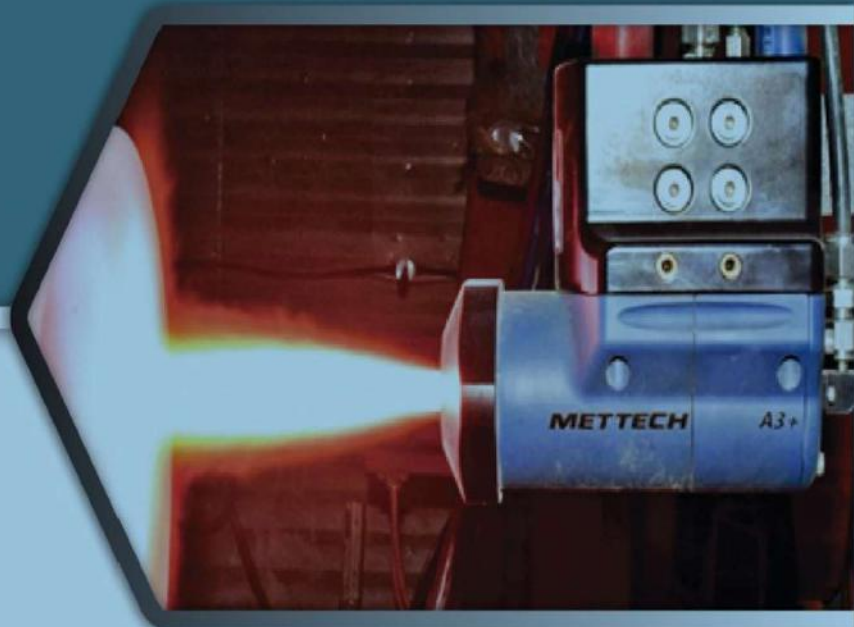
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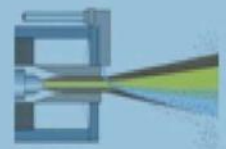
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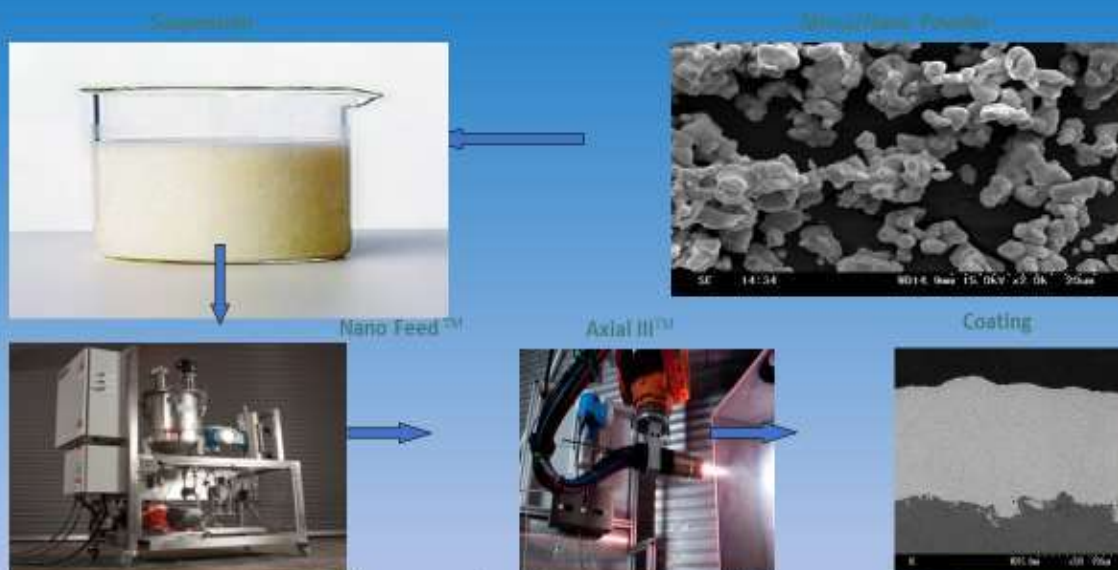
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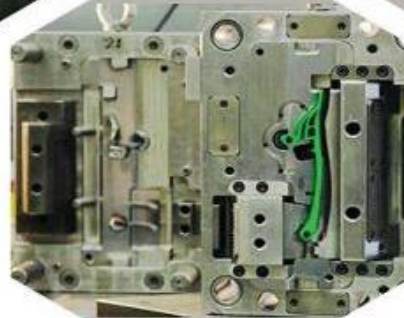


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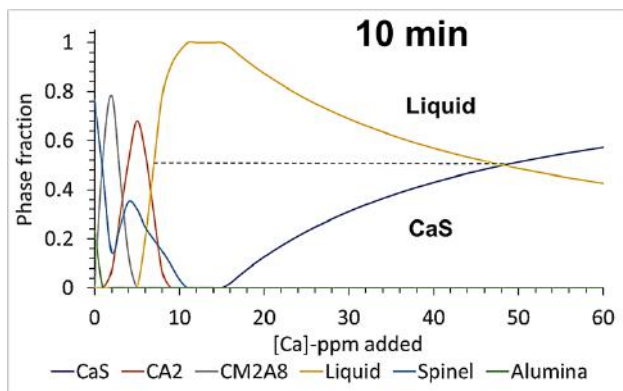


Fig. 7. Calculated inclusion composition for calcium treatment at 10 min

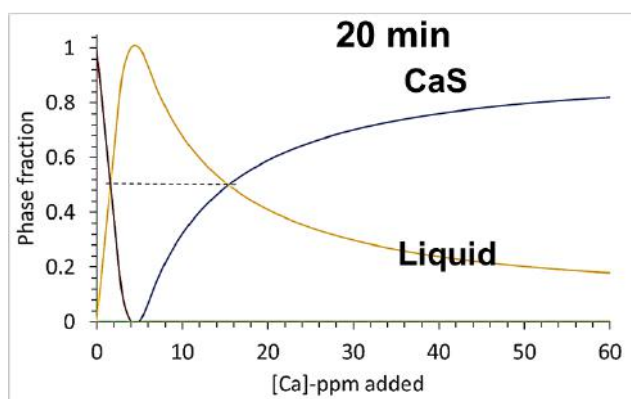


Fig. 8. Calculated inclusion composition for calcium treatment at 20 min

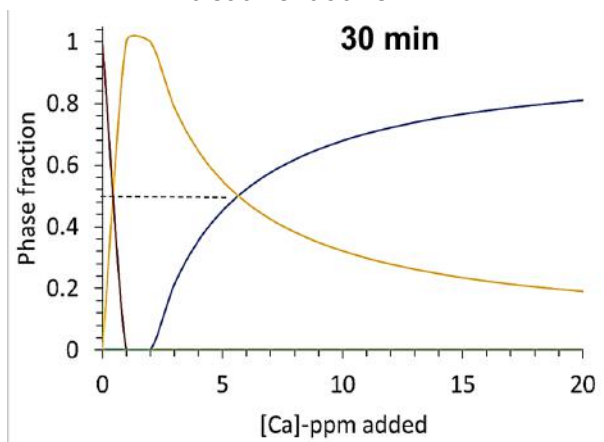


Fig. 9. Calculated inclusion composition for calcium treatment at 30 min

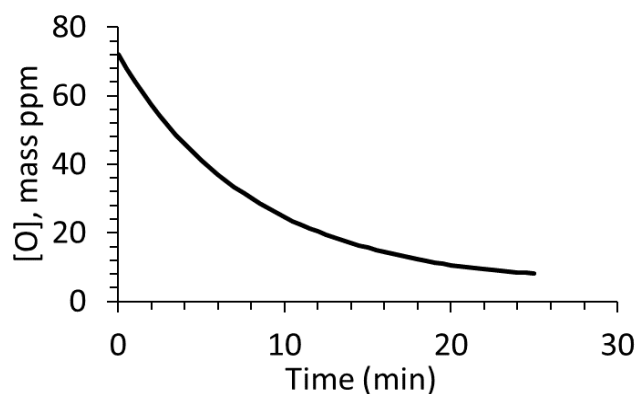


Fig. 10. Total oxygen in steel with time

Conclusion

FactSage is used to calculate inclusion composition during steel refining. The calculation shows that the equilibrium inclusion composition for the equilibrium between reducing slag saturated with MgO and Al-killed steel is spinel ($\text{MgAl}_2\text{O}_4 + \text{MgO}$). However, MgO inclusions are rarely observed as steel-slag complete equilibrium is not achieved during the process. Kinetic calculations showed formation of spinel inclusion only which is typically observed under these conditions. The computational tool developed here is also used to calculate the calcium required to modify alumina/spinel inclusions. The calcium requirement window is shown to shrink significantly from the treatment time of 10 minutes (8-48 ppm) to 30 minutes (1-5 ppm) under these calculation conditions. The calcium requirement depends on the amount and composition of inclusions present in the melt at that time.

The tool may also be used to optimize alloying additions and stirring practices to develop a cost-effective production of high-quality steels.

Acknowledgements

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High temperature deformation characteristics, processing maps and microstructural development of Ti-900 alloy

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Abstract

"The study delves into the high temperature deformation characteristics of the Ti-900 alloy (Ti-6.5Al-3.2Mo-1.8Zr-0.25Si), employing an isothermal high temperature compression test across temperatures ranging from 850°C to 1050°C and strain rates spanning from 0.001 s⁻¹ to 10 s⁻¹. The investigation focuses on the impact of deformation rates and temperature on flow stress. Processing maps are generated, and kinetic analyses are examined to gain insights into the deformability of this novel titanium alloy under diverse conditions of temperature and strain rates. The results suggest that the alloy demonstrates its best processing performance between temperatures of 880°C to 950°C and strain rates ranging from 0.001 s⁻¹ to 0.01 s⁻¹, with peak efficiency noted at 900°C and 0.001 s⁻¹. The kinetic rate equation discloses that the apparent activation energy to deform within the $\alpha+\beta$ region is 531 kJ/mol. The effect of strain rate sensitivity exponent on plastic deformation is studied. Additionally, the study scrutinizes the formation of post-deformation microstructures elaborately. Bimodal microstructures are observed at 950°C temperature and low strain rates. Deformation at high strain rate (10 s⁻¹) shows instability, shear, and crack.

Keywords: Titanium alloy, High temperature deformation, Kinetic analysis, Processing map, Microstructure"

1. Introduction

Titanium alloys find extensive applications in the aerospace and biomedical fields due to their outstanding attributes, such as an impressive strength-to-weight ratio and resistance to corrosion, fatigue, and creep. The Ti-900 alloy, an $\alpha+\beta$ titanium alloy developed recently, is specifically designed for aerospace applications. However, the hot deformation characteristics of this alloy remain unexplored and await systematic investigation. It is crucial to establish these characteristics to optimize the hot working parameters essential for successful alloy forging. In hot working processes, the utilization of flow behaviour, processing maps, and kinetic analysis aids in optimizing deformation conditions by visually illustrating the correlations among variables such as strain, temperature and strain rate. Microstructural and mechanical responses of titanium alloys in high-temperature deformation are sensitive to strain rate and temperature [1-4]. The optimal processing window for commonly used titanium alloy like Ti-6Al-4V alloy ($\alpha+\beta$ titanium alloy) with bimodal microstructure is 870°C and 0.001 s⁻¹ [5]. Different processing efficiency, activation energy and deformation mechanisms (i.e., DRV/DRX/flow softening) can be observed at different temperatures and strain rate regimes. Dynamic recrystallization (DRX) is the

main deformation mechanism for Ti64 alloy with equiaxed microstructure processed in the $\alpha+\beta$ phase field, whereas β phase deformation promotes dynamic recovery (DRV) [6]. Titanium alloy is very difficult to process at a very low strain rate due to instability, such as flow localization, adiabatic shear, and cracks. Initial microstructure significantly affects the hot deformation parameters and activation energy to deform. The Ti-900 alloy, characterized by an $\alpha+\beta$ titanium structure, has been recently developed for use in aerospace applications. Mo is employed as β stabilizing ingredient in this alloy, whereas Zr serves as a neutral element and Al serves as α stabilizer as normal. It shows higher tensile and yield strength (both in room and high temperature) compared to one of the most used titanium alloys, i.e., Ti-6Al-4V, while ductility remains almost the same [7-8]. While Ti-900 and TC11 alloy exhibit notable similarities, their chemical compositions differ, and there is a scarcity of research on the high-temperature processing of TC11 alloy. Moreover, the initial microstructure of the material plays a vital role in influencing its deformation parameters and flow stress. Surprisingly, there is a lack of substantial studies addressing the impact of the initial microstructure on the high-temperature deformation behaviour of the TC11 alloy. The existence of a coarse lamellar microstructure in the TC11 alloy poses challenges during the processing phase. Optimal conditions for processing TC11 alloy have been determined at a temperature of 950°C and a strain rate of 0.001s⁻¹ [9-13]. The aim of this present article is to investigate the high-temperature deformation behaviour of the recently developed Ti-900 alloy, establish a processing window, and correlate it with the microstructure. Detailed analysis of flow stress-strain behaviours and kinetic rate equations during the deformation is carried out.

2. Materials and methods

The composition and mechanical characteristics of the $\alpha+\beta$ Ti-900 alloy in its initial state are detailed in Tables 1 and 2, respectively, as per the findings from material supplier and funding agency. The β transus temperature for the alloy is within the range of 1000°C. The starting microstructure of the (as-received) Ti-900 alloy mainly consists of equiaxed α grain along with sharp, small needle-type β flecks (Fig. 1 a). It is observed that the volume% of the α phase is 65% while the β phase consists of 35% volume fraction. The material is manufactured through vacuum arc melting (VAR) followed by rolling to a 15 mm diameter and heat treatment (solution treatment + aging).

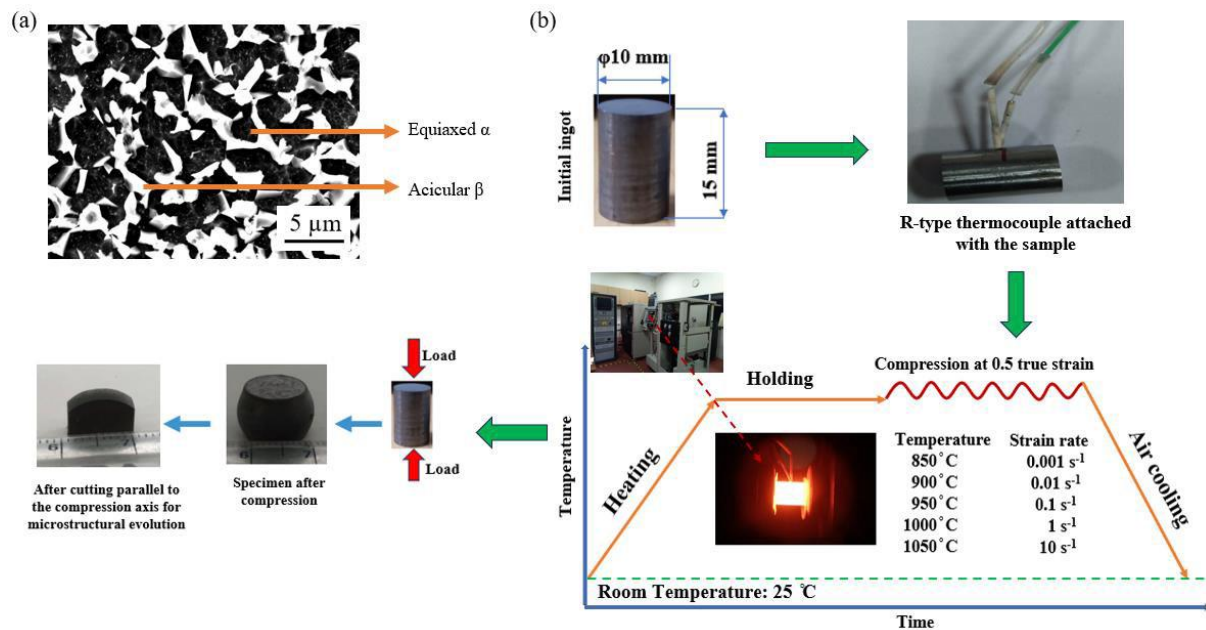
Table 1. Chemical compositions of Ti-900 alloy.

Material	Wt.%	Material	Wt.%
Al	6.5	O	0.15
Mo	3.2	C	0.1
Zr	1.8	H	0.0015
Si	0.25	N	0.05
Fe	0.2	Ti	Bal.

Specimens, featuring a 10 mm diameter, undergo isothermal compression tests using the Gleeble 3800 thermomechanical simulator. The deformation temperature and strain rate are varied from 850 °C to 1050°C and 0.001 s⁻¹ to 10 s⁻¹, respectively. An R-type thermocouple is attached (welded) to the samples before starting the experiment to measure the deformation emperature, and the extensometer measures the strain

Table 2. Tensile properties of Ti-900 alloy.

Properties	Test temperature	
	Room	500 °C
0.2% Yield Strength	950 MPa (min.)	600 MPa (min.)
Ultimate Tensile Strength	1030 - 1230 MPa	685 MPa (min.)
% Elongation [5D], min.	10%	14%
% Reduction in Area, min.	25%	55%

**Fig. 1.** a) Microstructure of the as-received Ti-900 alloy, and b) schematic view of the hot deformation test.

3. Results and discussions

3.1 True stress-strain behaviour

Flow stress vs strain plots for deformed samples at different strain rates and temperatures are presented in rate during the test. Nickle-based lubricant is applied to both ends of the sample along with a graphite sheet to get rid of friction during the test. The specimens are subjected to heating at a rate of 10°C/s, held for a duration of 2 minutes, and then compressed at a consistent strain rate, followed by air quenching. All tests are performed in an argon gas (inert gas) atmosphere so that it can't be corroded (to minimize oxidation) at high temperatures. In Fig. 1b, the schematic of the process flow is illustrated. Following the successful completion of compression, specimens are cut along the compression axis, followed by metallographic polishing and etching using Kroll's reagent for microstructural analysis with the JEOL SEM IT 300.

Fig. 2a-e, demonstrating favourable formability at high temperatures. In all instances, an escalation in strain rate corresponds to an increase in flow stress, attributable to strain hardening. Elevated strain rates, due to a decrease in the time available for dislocation mobility, result in increased resistance to deformation, leading to heightened flow stress. In the majority of cases, the flow stress undergoes a swift ascent, reaching its peak at remarkably low strain values ($\epsilon < 0.05$), followed by a phenomenon of flow softening i.e., dynamic recovery or dynamic recrystallization. Maximum flow stress (peak stress) value (nearly 300 MPa) is reached when the temperature is 850°C and strain rate 10s⁻¹ (Fig. 2 a) while the minimum is observed at 1050°C and at strain rate of 0.001s⁻¹ (Fig. 2 e). The temperature of 850°C is way below β transus temperature of the alloy, which means α phase volume% will be more compared to β phase volume% at 1050°C. That results in higher resistance to deformation as α phase is difficult to deform due to its HCP crystal structure, compared to β grain (BCC). HCP crystal has less number of slip systems compared to BCC structure, resulting in lower dislocation movement. Flow stress-strain plots suggest the deformation mechanism also.

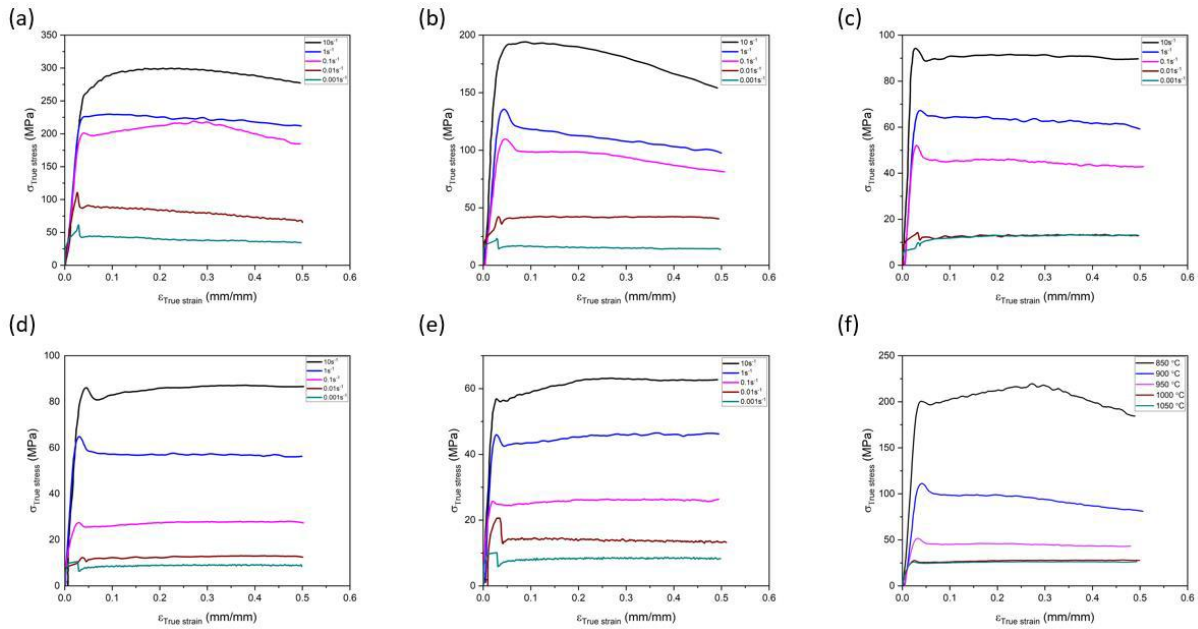


Fig. 2. True stress vs true strain plots for Ti-900 material at (a) 850°C, (b) 900°C, (c) 950°C, (d) 1000°C and (e) 1050°C temperature and at various strain rates. (f) at different temperatures and a constant 0.1s⁻¹ strain rate.

In instances where the deformation temperature is low, and the deformation rate is high (Fig. 2a-2b), flow softening prevails due to limited time for heat dispersion generated during local plastic deformation and a rapid increase in local temperature as a consequence. On the contrary, under conditions of a low strain rate, the flow stress remains relatively unchanged with increasing strain. At elevated temperatures, moderate flow softening is evident across all strain rates (Fig. 2c-2f). Almost every occasion exhibits steady-state flow due to the dynamic equilibrium between hardening and softening. The flow stress is markedly affected by temperature. Flow stress decreases with temperature primarily due to thermal softening. At high temperatures, atomic mobility inside the material increases, which triggers the dislocation densities during deformation. The resistance to deformation is notably significant within the temperature range of 850°C to 900°C when compared to the deformation temperature of the β phase. (Fig. 2 e). This is attributed to the increase in KE of the material's atomic movement with rising temperature, leading to a decrease in binding force and a reduction in the critical shear stress necessary for crystal slippage.

4. Kinetic analysis

Conducting a kinetic analysis during the high-temperature deformation of the alloy seeks to clarify the mechanisms at play during deformation at high temperatures. This analysis involves measuring various parameters that influence the deformation process, such as deformation temperature, stress, strain, and strain rate.

4.1 Strain rate sensitivity exponent

The strain rate sensitivity factor, also known as “ m ,” plays a significant role in evaluating the plastic characteristic of the material. It is a crucial parameter that determines the material's plastic properties. In general, a higher value of the exponent indicates increased plasticity of the material. When the value of “ m ” exceeds 0.5, it serves as an indication of the material's superplastic behaviour.

Conversely, a negative value of “ m ” suggests that material is susceptible to defect during deformation and it should be avoided. The dynamic constitutive equation (equation 1) indicates the correlation between the flow stress and strain rate of the alloy, considering the alloy's deformation temperature and strain within the given condition.

$$\sigma = K \dot{\epsilon}^m \quad (1)$$

Where, σ = flow stress (MPa), K = constant, $\dot{\epsilon}$ = strain rate (s⁻¹), and m = strain rate sensitivity exponent. m also can be expressed by equation 2:

$$m = [\partial(\lg \sigma) / \partial (\lg \dot{\epsilon})]_{\epsilon, T} \quad (2)$$

Fig. 3a shows the effect of temperature on the strain rate sensitivity factor. It can be seen that between 0.01s⁻¹ and 1 s⁻¹, the value of m exhibits minimal variation with temperature, but for 0.001s⁻¹, changes observed are more. The maximum value of m (> 0.6) is observed at 900 °C and 0.001s⁻¹, which indicates that in that region, the material reached its superplasticity (as the value of m > 0.5). Strain rate between 0.01s⁻¹ to 1s⁻¹ for all temperature materials has good plasticity for deformation, but at a high strain rate (10s⁻¹), the ‘ m ’ value appears as negative, which indicates that the deformation under this condition leads to instability.

4.2 Strain hardening exponent

The Ludwik function model is commonly employed to analyze the thermal deformation characteristics of alloy, particularly the hot work hardening. Within this model, the strain hardening exponent (n) plays a crucial role in indicating the equilibrium between work hardening and thermal softening processes. This exponent significantly influences the stability of deformation and the material's workability, making it a vital parameter for characterizing the uniform plastic deformation ability. The mathematical equation for the model is as follows (equation 3).

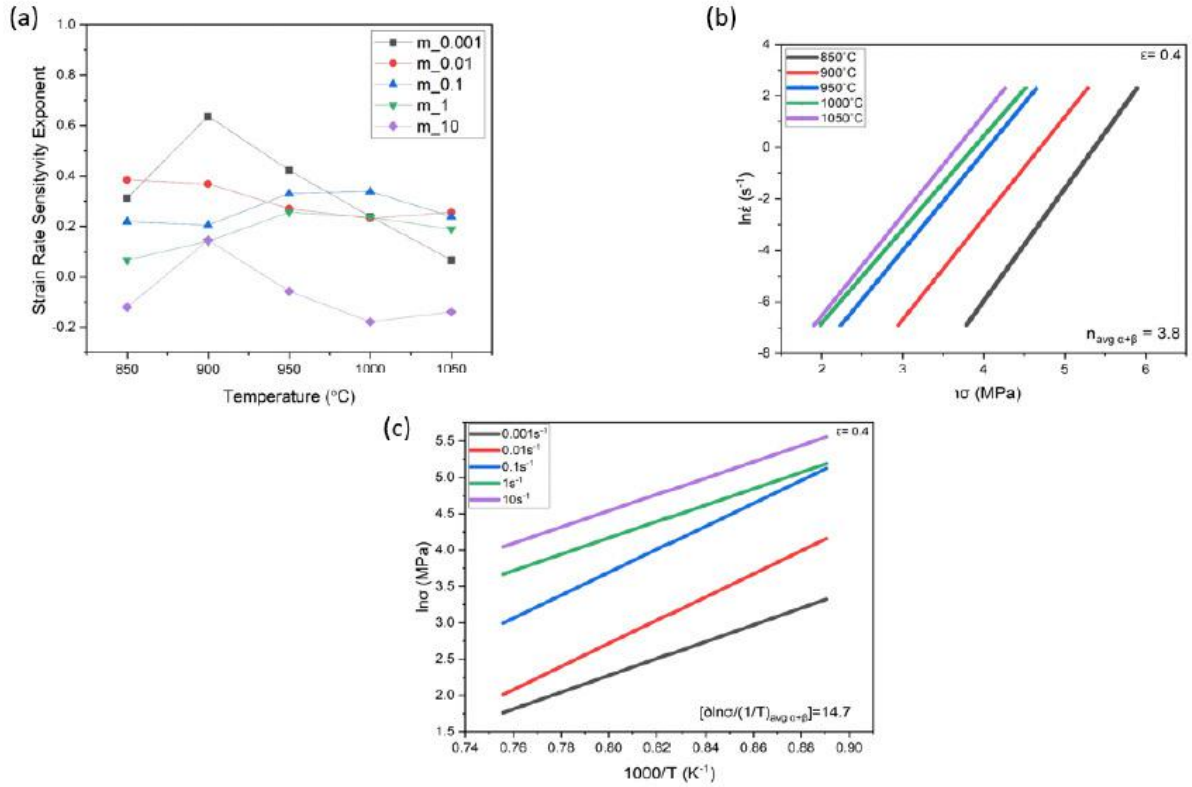


Fig 3. (a) Temperature vs strain rate sensitivity plot, (b) $\ln(\dot{\epsilon})$ vs $\ln\sigma$ to calculate 'n', (c) $\ln\sigma$ vs $1/T$ plot for determining 'Q'.

$$\sigma = \sigma_0 + K\epsilon^n \quad (3)$$

Where, σ_0 = yield stress (MPa), K = strength coefficient, ϵ = strain and n = strain hardening exponent. n can be calculated with the further deduced equation (equation 4).

$$n = \frac{1}{m} = \left[\frac{\partial \ln \dot{\epsilon}}{\partial \ln \sigma} \right]_{T, \epsilon} \quad (4)$$

The slope between $\ln(\dot{\epsilon})$ vs $\ln\sigma$ (Fig. 3 b) indicates the value of strain hardening exponent (n). The average value of 'n' in $\alpha+\beta$ is 3.8.

4.3 Activation energy

Activation energy during the hot deformation of metals refers to the energy barrier that must be overcome for dislocation motion to occur and for plastic deformation to take place at elevated temperatures. The subsequent "constitutive equation" (equation 5) delineates the relationship between deformation rate, temperature, and flow stress aiding in the calculation of activation energy.

$$\dot{\epsilon} = A\sigma^n \exp \left[-\frac{Q}{RT} \right] \quad (5)$$

Where; A =material constant; T =temperature, Q =activation energy (kJ/mol); and, R =gas constant (8.314 J mol⁻¹ K⁻¹). Q can be calculated by using the following equation (6).

$$Q = Rn \left[\frac{\partial \ln \sigma}{\partial (1/T)} \right]_{\dot{\epsilon}} \quad (6)$$

In Fig. 3c, the plot of $\ln\sigma$ against $1/T$ is utilized to determine the activation energy ('Q'). The average value of Q for deformation in the $\alpha+\beta$ field is determined to be 531 kJ/mol.

Ti-900 exhibits a nearly identical activation energy in the $\alpha+\beta$ phase when compared to other titanium alloys such as TC11, Ti64, and TC6. This similarity indicates substantial deformation occurring within that phase field. At elevated temperatures, increased thermal energy within a material enhances atomic mobility and facilitates the motion of dislocations, consequently reducing the energy barrier for plastic deformation.

4.4 Development of hot processing maps

The processing map, grounded in the principles of the Dynamic Material Model (DMM) theory, consists of two primary components: the material instability map and the power dissipation map. This map provides a direct representation of the thermal parameters range associated with both stable and unstable deformation zones. It serves to describe the regions of the material processing instability as well as safe processing areas, enabling the optimization of thermal processing techniques for materials. In accordance with the DMM theory, the workpiece undergoing thermal processing displays nonlinear energy or power dissipation. The energy consumed during processing is converted into both viscous heat and structural modifications within the material of the workpiece. In the material processing power dissipation process, the total instantaneous power (P) applied to the system by external sources is generally divided into two components: power dissipation (G) and power dissipation co-quantity (J). Power dissipation (G) is accountable for the energy transformed through the plastic deformation of the material, specifically leading to viscoplastic heating [14, 15]. On the other hand, the power dissipation co-quantity (J) is utilized for microstructural evolution, including phase changes, instability, DRV and DRX. P can be revealed by the following equation (equation 7):

$$P = \sigma * \dot{\epsilon} = G + J = \int_0^{\dot{\epsilon}} \sigma d\dot{\epsilon} + \int_0^{\sigma} \dot{\epsilon} d\sigma \quad (7)$$

Strain rate sensitivity exponent (m) can be determined by equation (8)

$$m = \frac{dJ}{dG} = \frac{\dot{\epsilon} d\sigma}{\sigma d\dot{\epsilon}} = \left[\frac{\partial \ln \sigma}{\partial \ln \dot{\epsilon}} \right]_{\epsilon, T} \quad (8)$$

$m=1$ for ideal linear dissipation system, and J becomes J_{max} ; Finally, process efficiency (η) can be determined by equation (9) given below:

$$\eta = \frac{J}{J_{max}} = \frac{2m}{m+1} \quad (9)$$

A higher η value indicates greater deformability of a material. Equation 10 is employed to identify the unstable region during deformation

$$\text{Instability parameter } [\xi(\dot{\epsilon})] = \frac{\partial \ln \left(\frac{m}{m+1} \right)}{\partial \ln \dot{\epsilon}} + m < 0 \quad (10)$$

At still higher temperatures (i.e., 1000°C and 1050°C), microstructure transforms to widmanstätten structure (Fig 5. d & e). Acicular α and β phases are formed randomly due to air cooling from on or above β transus temperature. At temperatures of 850°C and 900°C, along with a strain rate of 0.01s⁻¹, the microstructure predominantly exhibits equiaxed grain formation (Fig. 6 a & b). Elevated temperatures and strain rates induce significant lattice distortion and strain accumulation, leading to dynamic recrystallization. This process transforms a majority of the acicular β grains into equiaxed β grains. The microstructure observed at 950°C with a strain rate of 0.01 s⁻¹ predominantly exhibits a bimodal grain structure, although the density of equiaxed α grains decreases (Fig. 6 c). microstructure observed at 950°C with a strain rate of 0.01 s⁻¹ predominantly exhibits a bimodal grain structure, although the density of equiaxed α grains decreases (Fig. 6 c). Acicular lamellar microstructure is observed at β phase and 0.01 s⁻¹ deformation. Although at low temperatures (850°C and 900°C) and higher strain rate (0.1 s⁻¹ to 10 s⁻¹) microstructure mainly consists of equiaxed α/β grain only, with increased temperature and strain rate β phases are globularized (Fig. 7, 8 a) and started converting into

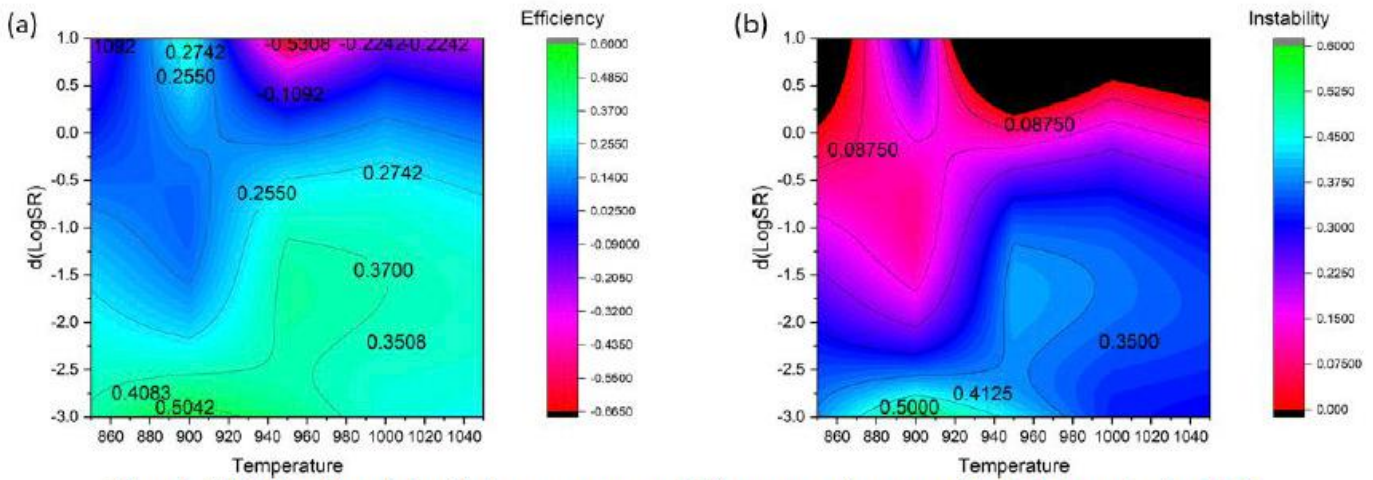


Fig. 4. Ti-900 alloy (a) efficiency map and (b) processing map for 0.4 true strain [16].

The power dissipation efficiency map for a 0.4 true strain is depicted in Fig. 4a. The domain with the maximum possible efficiency (40-54%) is identified at temperatures ranging from 880°C to 950°C and a strain rate of 0.001s⁻¹. The peak efficiency is specifically observed at 900°C and 0.001s⁻¹. In Fig. 4b, the processing map is presented, where the black shaded areas indicate the unstable region. At a higher strain rate (10 s⁻¹), the alloy exhibits instability in deformation due to flow localization and adiabatic shear. It is necessary to minimize the instability regimes whenever possible.

4.5 Microstructural evolution

From Fig. 5 to Fig. 8, the microstructure revealed that when the alloy is deformed much below β transus temperature, the prior α phase remains intact while the β phase undergoes partial transformation. Microstructure at 850°C and 900°C for 0.001 s⁻¹ mainly contains equiaxed primary α grain and β grain (Fig 5. a & b). But, at 900°C, most of the small acicular (needle type) β phase converts to small equiaxed phase. The microstructure observed at a temperature of 950°C and a strain rate of 0.001s⁻¹

bimodal microstructure (Fig. 7, 8 b). Temperature at 950 °C and high strain rate (0.1, 1.0 and 10 s⁻¹) shows bimodal microstructure, However, with an increase in strain rate, the β phase tends to coarsen, and the presence of equiaxed α decreases. This phenomenon is attributed to the limited time available for the equiaxed grain nucleation process. Combined with heightened strain rate sensitivity, this can result in a reduction of equiaxed grains from the bimodal microstructure (Fig. 7, 8 c). Deformation at β phase with high strain rates (0.1, 1.0, and 10 s⁻¹) reveals a lamellar structure, as depicted in Fig. 7 and 8 d & e. Both the α and β phases exhibit a coarser appearance. Numerous coarser α/β grain patches are observed at high strain rates, attributed to flow localization (Fig. 7e). α and β phase grain boundary are clearly visible at high temperature and residual β phase are seen at high strain rate.

Variation of phase volume% is shown in Fig. 9a. β phase volume% increases with temperature. At high temperature (β phase/near β phase) deformation, no DRX is seen and acicular α is observed (Fig. 9b).

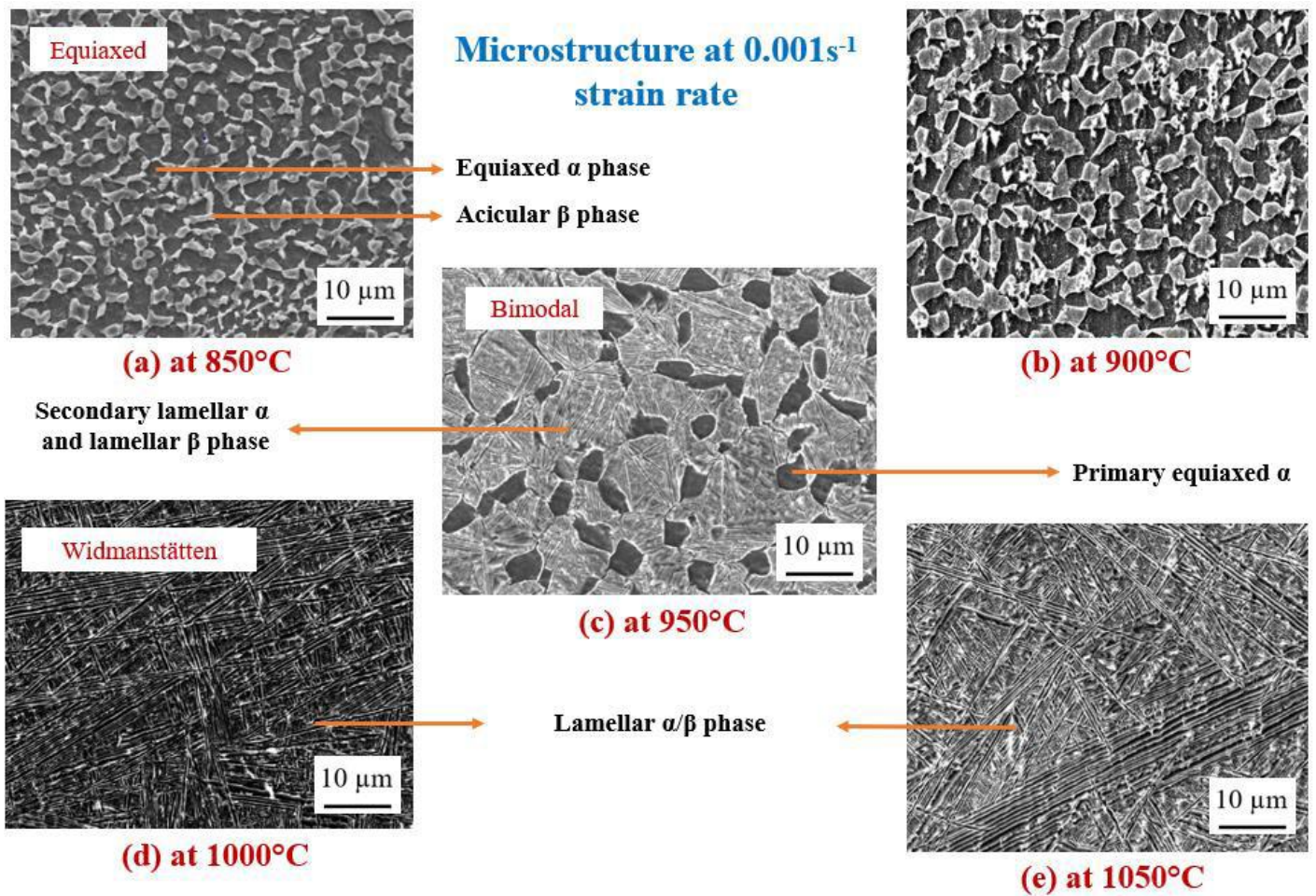


Fig. 5. Microstructures of Ti-900 alloy deformed at $0.001s^{-1}$ and different temperature.

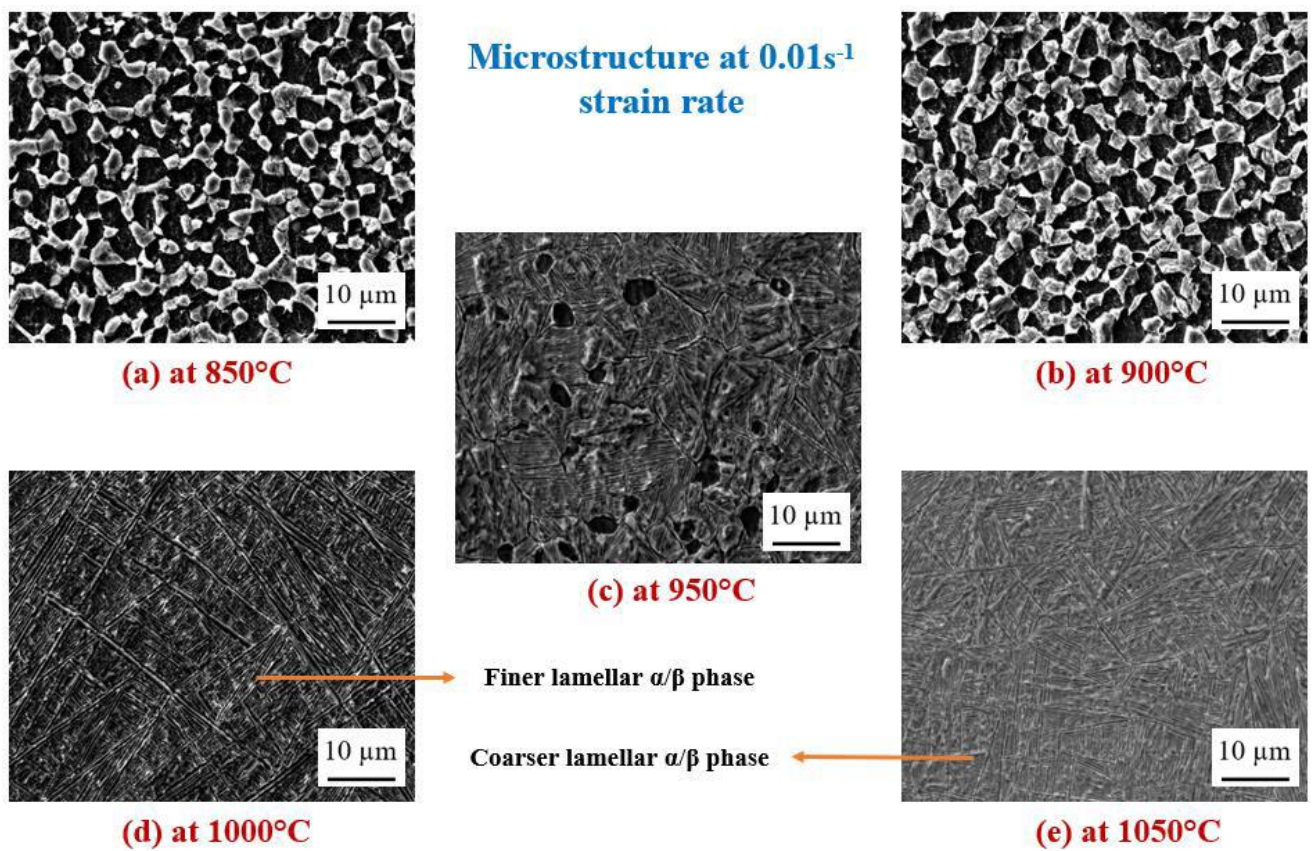


Fig. 6. Microstructures of Ti-900 alloy deformed at $0.01s^{-1}$ and different temperatures.

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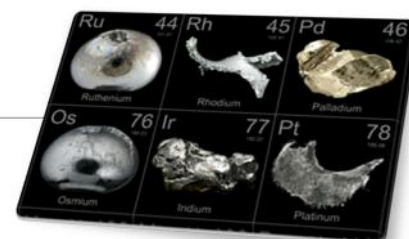
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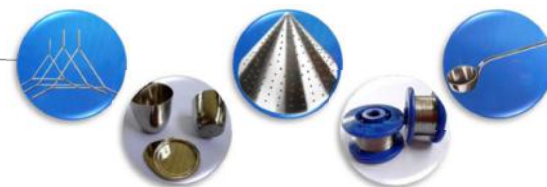
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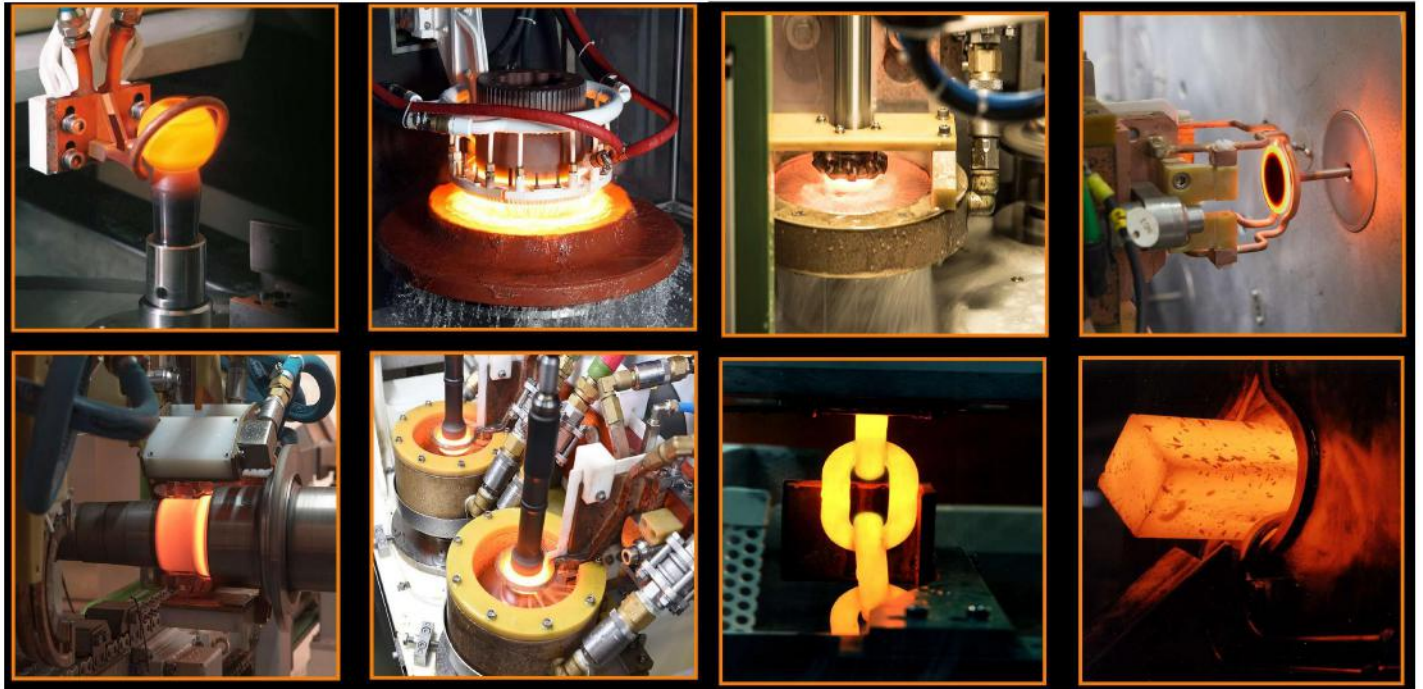
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What is friction welding?

Friction welding is a solid-state joining process that generates heat through mechanical friction between workpieces in relative motion to one another, with the addition of a lateral force called “upset” to plastically displace and fuse the materials. This process does not melt the materials, which allows for high-strength bonds with minimal defects. There are several types of friction welding, including:

- **Rotary Friction Welding:** One part is rotated relative to another under pressure.
- **Linear Friction Welding:** The parts are moved in a linear reciprocating motion.
- **Friction Stir Welding:** A non-consumable tool is rotated and traversed along the joint line.

Friction welding is commonly used in the automotive, aerospace, and manufacturing industries for joining metals and thermoplastics.



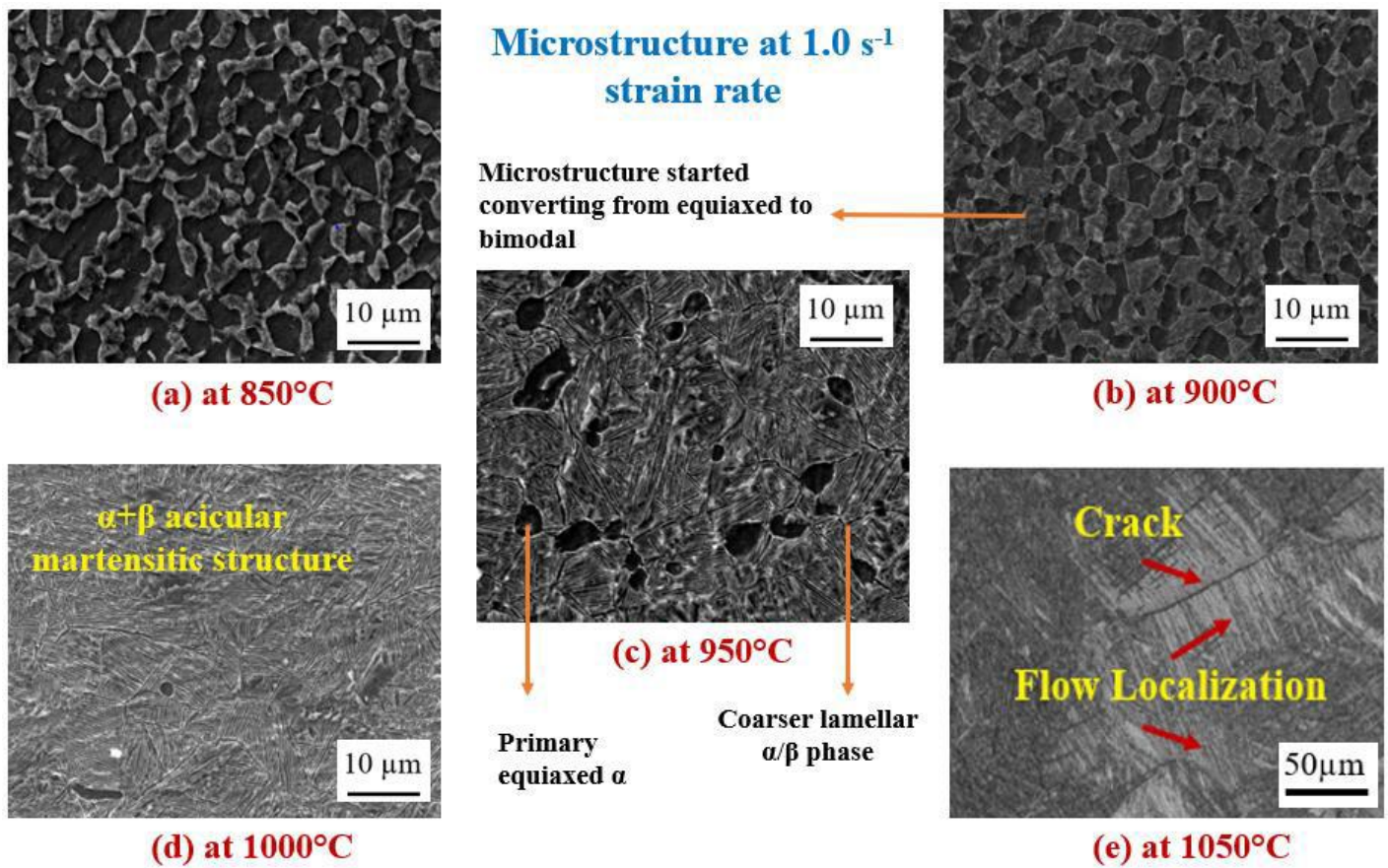


Fig. 7. Microstructures of Ti-900 alloy deformed at 1s⁻¹ and different temperatures.

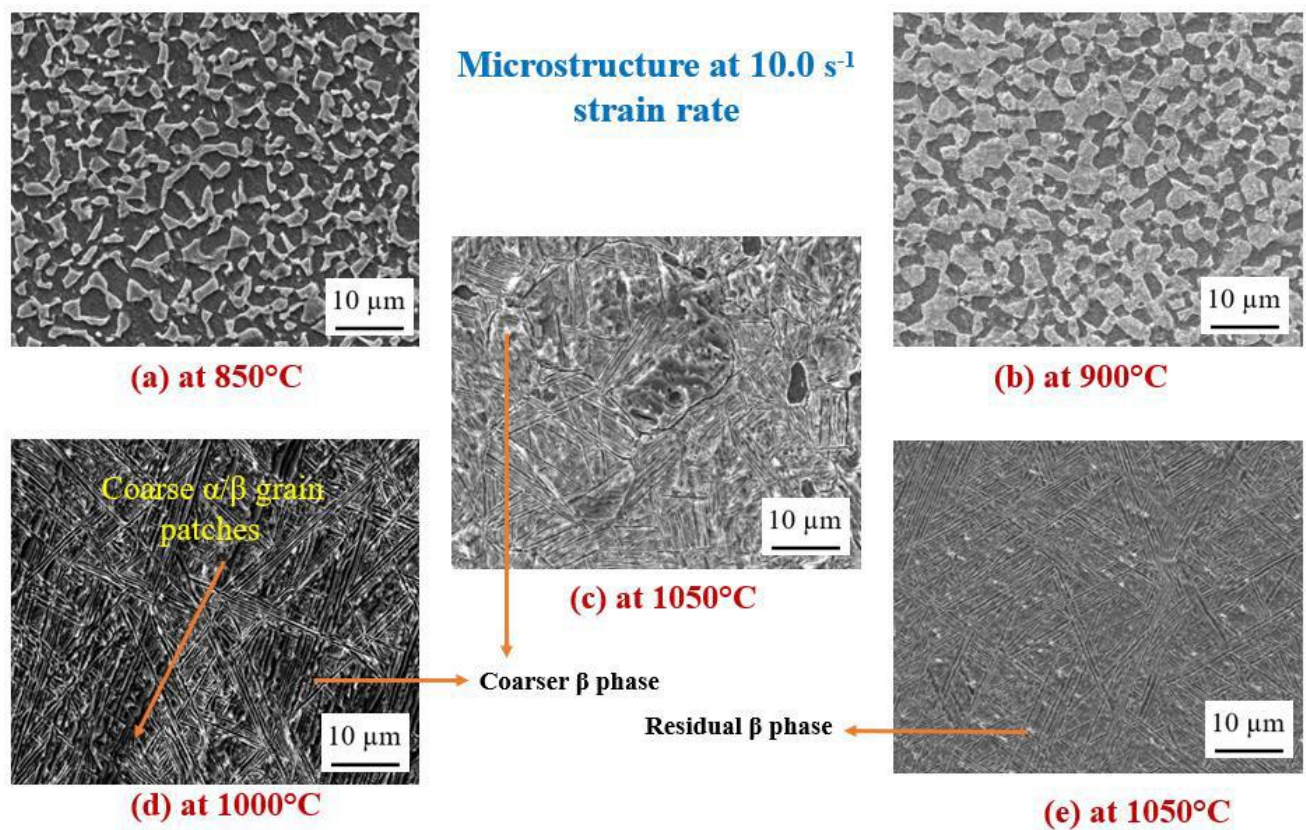


Fig. 8. Microstructures of Ti-900 alloy deformed at 10s⁻¹ and different temperatures.

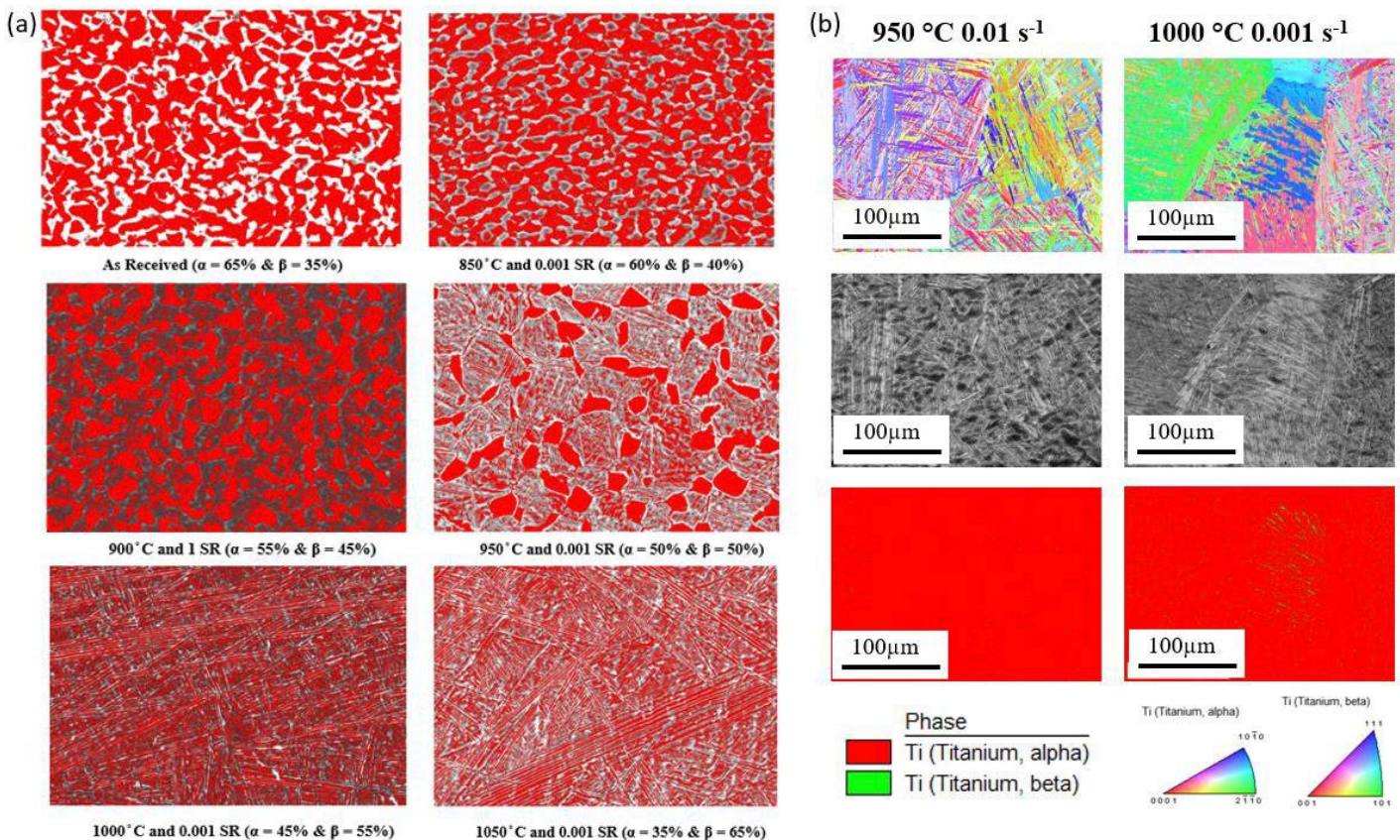


Fig. 9. (a) α and β phase volume% variation with temperature, (b) IPF, IQ and Phase map for the two deformed samples at different conditions.

Conclusion

The present study explores the hot deformation characteristics and flow behavior of the novel Ti-900 alloy. The following key conclusions have been drawn from the investigation.

- Flow stress exhibits sensitivity to both strain rate and deformation temperature. It rises with an increase in strain rate at a constant temperature and decreases with temperature at a constant strain rate. In all instances, it reaches its maximum value at very low strain. The material demonstrates good deformability at elevated temperatures.
- The material can undergo processing within the temperature range of 880°C to 950°C and at strain rates between 0.001s⁻¹ to 0.01s⁻¹, with peak efficiency noted at 900°C and 0.001s⁻¹. However, at a high strain rate (10s⁻¹), an instability region is indicated. Strain rate sensitivity factor (m) increases with temperature. Higher temperatures enhance atomic diffusion and dislocation mobility, resulting in increased m value.
- Activation energy for deformation of Ti-900 alloy with initial equiaxed microstructure in $\alpha+\beta$ field is 531 kJ/mol, indicating good deformability at high temperature.
- Equiaxed microstructure can be observed at temperature 850°C and 900°C transitioning to a bimodal structure at 950°C, while at higher temperature it exhibits widmanstätten structure. At higher temperatures, a Widmanstätten structure is observed, accompanied by an increase in β grain size. The augmented strain rate results in a reduction of equiaxed α grains within the bimodal microstructure. This phenomenon is attributed to the constrained time available for the equiaxed grain nucleation process, coupled with an increased sensitivity to

- thermal softening and residual β phase is observed. Deformation at high strain rates, flow instability and flow localization are observed.

Declaration of conflicting interests

The authors declare no potential conflict of interest with respect to the research, finance, authorship and/or publication of this article.

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Microstructure of the linear friction welded Ti6Al4V alloy

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Abstract

Linear Friction Welding (LFW) is an established technology for blisk (bladed disk) welding of aeroengines. LFW is a solid-state joining process where the joint is formed by oscillating one workpiece over the other under an applied normal load. The present work describes the LFW process carried out on a Ti6Al4V alloy. Welding was carried out on a custom-built 500 kN linear friction welding machine. Samples were welded at the frequency of 40 Hz with an oscillating amplitude of 1.5 mm. A normal pressure of 100 MPa was applied and an axial burn-off of 6 mm was achieved. Microstructural investigations show the welded region consists of two zones, viz., the Weld Center Zone (WCZ) and the Thermo-Mechanically Affected Zone (TMAZ). These two zones are collectively termed as Plastically Deformed Zone (PDZ). Heat Affected Zone (HAZ) was not specifically observed. The microstructure at the weld center zone consisted of α' martensite formed during cooling from the high-temperature β phase while, the TMAZ consisted of deformed α and β grains. The process of welding takes place in three stages. Stage 1 starts with microscopic contact at the asperity level. During stage 2, asperities deform and generate heat followed by complete seizure of the two contact surfaces. The plasticized material is expelled out as flash during stage 3.

Keywords: linear friction welding, Ti6Al4V, plastically deformed zone, martensite, solid-state joining.

1.0 Introduction

Linear Friction Welding (LFW) is a solid-state joining process. The metallurgical joint is formed by oscillating one workpiece relative to another under an applied compressive force [1, 2]. The heat generated at the oscillating surface causes the interface material to plasticize. The plasticized interface material is then removed as flash. This causes the workpiece to shorten in the direction of the applied load known as burn-off. Burn-off helps in removing interfacial contaminants and oxides to form a good metallurgical bond. Three major process parameters control the weld quality in LFW. Oscillating frequency, oscillating amplitude, and the applied compressive normal pressure/force. However, there are other factors like welding time, burn-off, and final forging pressure that can also influence the weld quality. LFW being a solid-state joining process has many advantages over the conventional welding processes. LFW is an established technology for blisk welding of aero-engines [2, 3]. Titanium alloy (Ti64) is a material of choice for the blisk due to its high strength-to-weight ratio. LFW is effective for welding titanium

due to its high yield and shear strength and low thermal conductivity [4]. The typical microstructure of linear friction welds of Ti6Al4V consists of three distinct zones: the weld center zone (WCZ), the thermo-mechanically affected zone (TMAZ), and the heat-affected zone (HAZ). The WCZ and TMAZ in essence both are plastically deformed zones but they possess vastly different microstructures. The WCZ undergoes Dynamic Recrystallization (DRX) in the single phase β region, while the TMAZ is deformed below β transus temperature [5–8]. The present investigation reports the LFW of Ti6Al4V using a newly developed linear friction welding machine. The machine developed is the first of its kind in India. The weld process is interpreted based on the machine output data. Microstructural investigations are carried out by optical and scanning electron microscopy. Mechanical characterization is carried out by micro indentation technique.

2.0 Materials and Methods

Ti6Al4V samples with dimensions 25 mm x 25 mm x 70 mm were used for the welding having a welding area of 25 mm x 25 mm. The base material with an equiaxed microstructure of α phase and intergranular β was used. The average composition of Ti6Al4V is given in Table 1.

Table 1. Chemical composition of Ti6Al4V

Material composition						
Element	Al	V	O	Fe	C	Ti
Wt %	6.1	4.2	0.16	0.14	0.003	bal

LFW was carried out using a 500 kN LFW machine. Welding was performed at an oscillating frequency of 40 Hz with an amplitude of 1.5 mm and a normal pressure of 100 MPa. A 6 mm burn-off control was given. After welding, the samples were cut across the cross-section and metallographically polished for microstructural investigations. Microstructural studies were carried out using optical and scanning electron microscopy (SEM) operated at 30 kV. Vickers hardness test was carried out in the welded region at a load of 200 gf with a dwell time of 15 s and with an interval of 40 μ m.

3.0 Results and Discussion

Figure 1 shows the microstructure of the base metal. The base metal showed equiaxed morphology with 12 % volume of β phase at room temperature. In Ti6Al4V alloy, the α phase is stabilized by Al and the β phase by vanadium. The average grain size was measured to be 20 μ m.

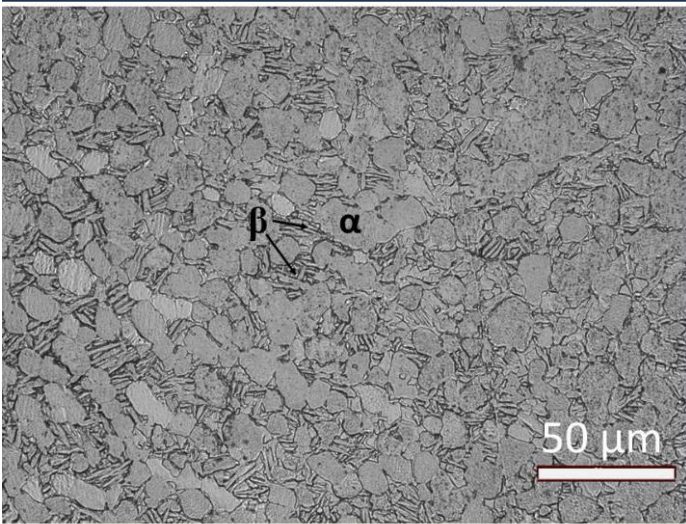


Fig.1 Microstructure of the base metal showing equiaxed morphology.

Figure 2 shows the linear friction welded Ti64 alloy. One specimen is oscillated while the other is held stationary with a normal force being applied. The material that is expelled from the interface comes out as a flash. Flash forms in both the longitudinal and lateral directions. The flash formed along the longitudinal direction shows ripple morphology.

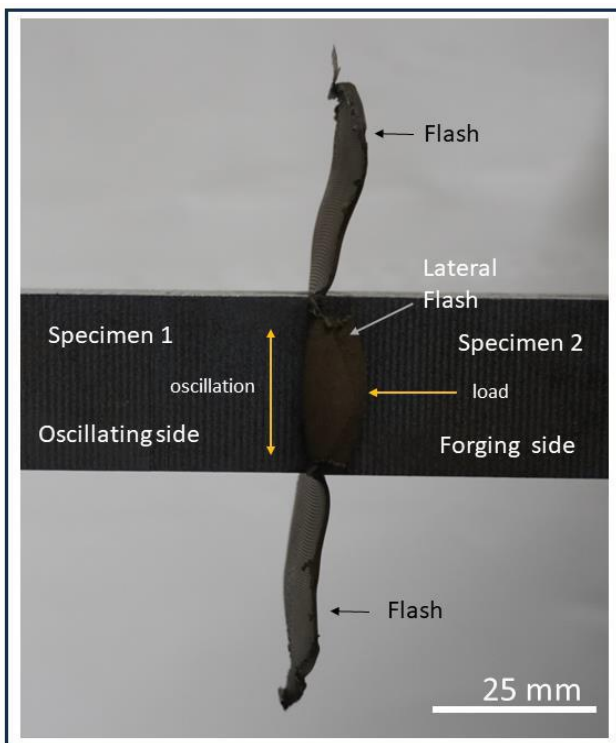


Fig. 2. Photograph of the welded Ti6Al4V alloy. longitudinal flash with ripple morphology is seen.

The typical optical micrograph of the linear friction welded sample is presented in Fig. 3. The interface zone between the two specimens is marked as PDZ (plastically deformed zone). The PDZ thickness was measured to be around 0.75 mm. This zone consists of the weld center region (WCZ) as well as the thermomechanically affected zone (TMAZ). The weld center zone makes up the interface between the two specimens. Although, both the WCZ and TMAZ are plastically deformed zones, the WCZ has a vastly distinct microstructure as it undergoes DRX above the β transition temperature.

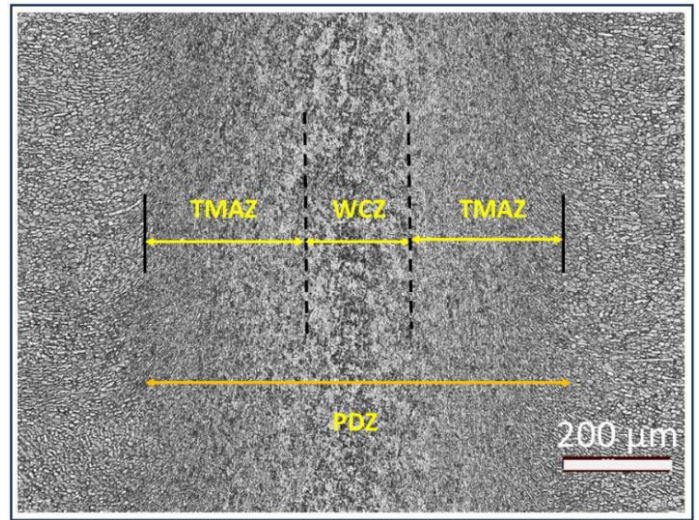


Fig. 3. shows a typical cross-section micrograph of the linear friction welded Ti64 alloy. The PDZ consists of two zones: WCZ and TMAZ. The thickness of the PDZ is around 0.75 mm.

Figure 4 shows the microstructure of TMAZ region. This region undergoes deformation below the β -transus temperature. The microstructure of the TMAZ shows elongated α and β phases. The elongation is along the oscillation direction.

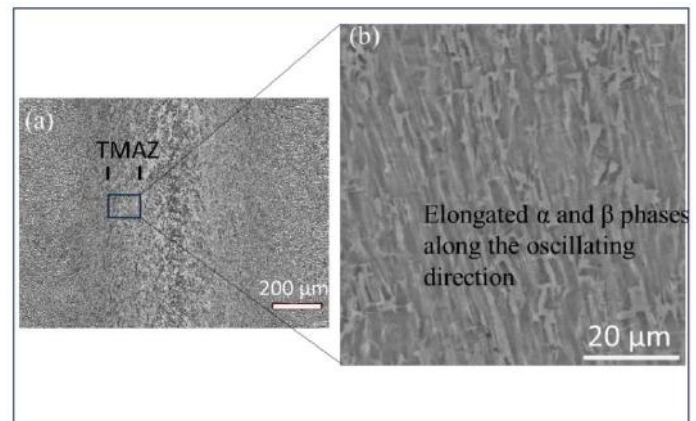


Fig. 4 (a) optical micrograph of the PDZ, and (b) higher magnification SEM micrograph of the TMAZ region showing deformed and elongated α and β phases.

The microstructure at the WCZ is formed by the transformation from the high-temperature β phase. Fig 5 (a) shows the optical micrograph of the WCZ. It indicates the lath morphology of the phase after transformation from the β phase. Fig 5 (b) shows the high magnification SEM micrograph of the WCZ showing α' martensite morphology. Literature reports that the weld center zone consists of widmanstatten [6, 9, 10] or martensite [6, 11, 12]. This difference is because of the cooling rate [5, 13]. However, there are also reports on the microstructure of the weld center other than widmanstatten or martensite [9, 14, 15]. The WCZ experiences higher cooling rates than the flash and it is expected that the α' martensite will be formed.

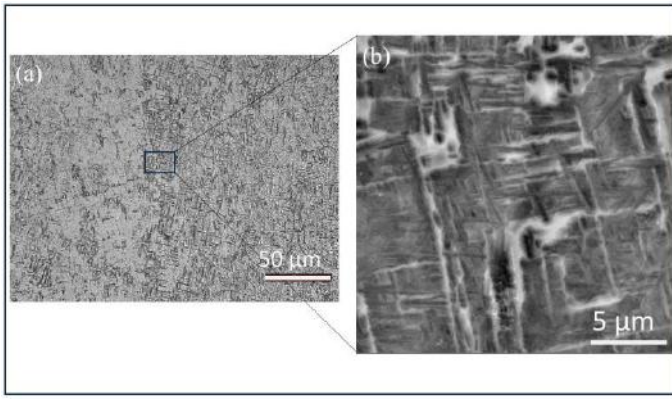


Fig. 5 (a) Optical micrograph of the WCZ, and (b) high magnification SEM micrograph showing lath α' martensite.

The process of welding takes place in three stages and is shown schematically in Fig. 6. Stage 1: This is an initial phase where asperity level contact takes place and heat is generated by asperity deformation. The plastic deformation takes place at high strain and strain rates. True area of contact increases.

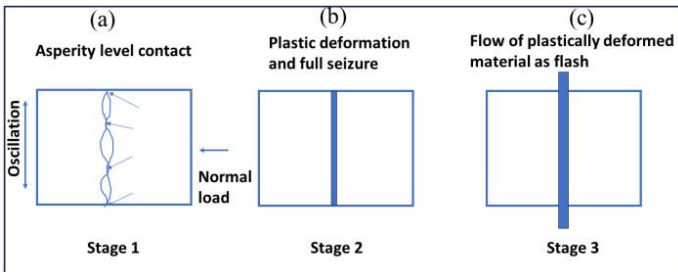


Fig. 6. (a) Stage 1 asperity level interaction (b) stage 2 plastic deformation and full seizure, and (c) stage 3 interface material

“Stage 2: This is a transition phase where asperity level seizure and subsurface deformation takes place. The heat generated due to plastic deformation causes the material to plasticize and the real area of contact increases to 100 %, i.e. the complete seizure takes place between the two pieces. The heat generated is conducted to the subsurface region causing the material to soften and the flash starts to begin. For Ti64 alloy, the burn-off begins when the interface temperature reaches the β -transus temperature. Stage 3: This is known as the equilibrium phase. Burn-off and axial shortening take place by the expulsion of the interface material forming the flash. The flash removal takes place at a constant rate.

The stages during LFW are monitored by the LFW machine. Fig. 7 shows the plot of oscillating load and burn-off vs welding time. The stage 1 and 2 are represented in the flatter portion of the burn-off curve. During this stage, the PDZ develops at the interface. The equilibrium phase is represented by the steady-state burn-off region where the material is expelled at a constant rate. The mechanical properties of the PDZ were evaluated by microhardness testing. Fig. 8 shows the microhardness profile as a function of distance from the weld center line.”

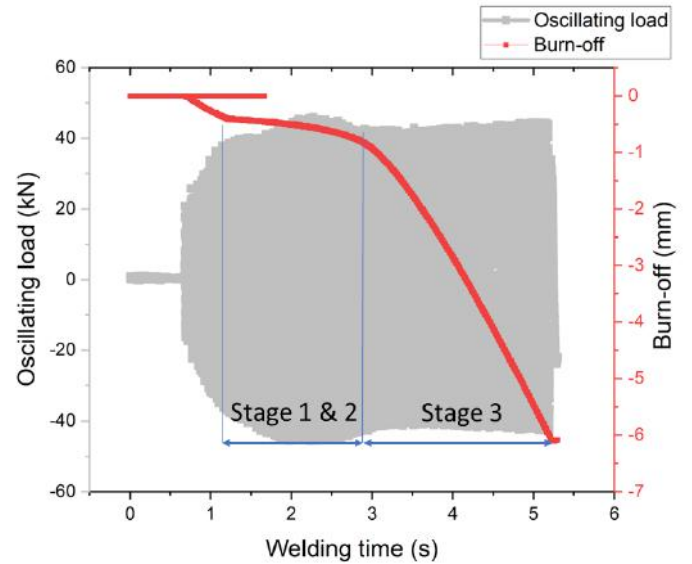


Fig. 7. Plot of Oscillating load and burn-off with welding time.

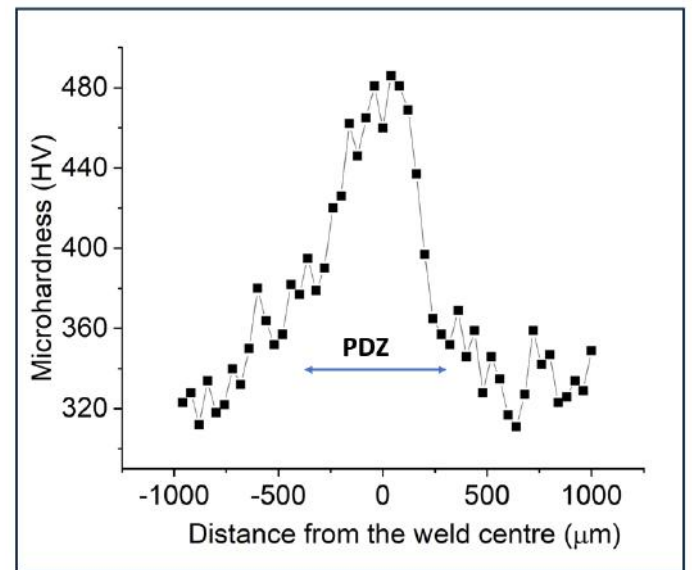


Fig. 8. Vickers hardness profile of the weld region as a function from distance from the weld center line.

The hardness at the WCZ is expected to be higher because of the refined microstructure. Several investigations have reported a lower hardness in the TMAZ than the base metal due to grain coarsening [6, 12]. Such an effect was not observed in the present case as the TMAZ exhibited a deformed microstructure and higher hardness than the base metal. Maximum hardness was observed in WCZ with a hardness value of 480 HV.

Conclusion

Linear friction welding of Ti6Al4V alloy was carried out by a custom-built LFW machine. The microstructure of the weld region was refined. The α and β phases deformed and elongated along the oscillating direction in the TMAZ. The α' martensite formed in the WCZ during cooling from the high-temperature β phase. The weld region showed higher hardness than the base metal due to refined microstructure.

Acknowledgments

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Improving Induction Furnace Steelmaking Process in India

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Abstract

Induction furnace (IF), is one of the major steelmaking routes in India. Due to the refining limitations, IF steelmaking is restricted to the production of relatively less critical, such as construction grade steels. In India, IF steel production accounts for approximately 28-30% of total steel production and yet, IF sector faces various technical (and policy) challenges that needs to be addressed. Herein, two different IF based steel plants from two different clusters in India have been explored to identify the issues pertaining to the existing steelmaking process. Based on the limited industrial data, static mass balance calculations have been done to estimate the iron yield and compare it with the actual (industrial) data. The raw materials, steel quality, process efficiency and the environmental impact, envisioning green steel possibility, in the context of IF steelmaking, are discussed. Finally, some recommendations are proposed to improve the overall IF process.

Keywords: Induction Furnace, Steelmaking, Sustainability, Static Mass Balance, Refining

1 Introduction

The steel sector in India has experienced remarkable growth, fuelled by increased demand and rapid industrialization. India's per capita consumption stands around 77.2 kg compared to the world average of 233 kg [1-2]. The National Steel Policy aims to increase the per capita consumption to 158 kg by 2030 [3]. This indicates that India's steel requirements have been growing rapidly and this will give way to opportunities in the innovation and technological developments.

There are three basic routes of primary steelmaking, namely, basic oxygen furnace (BOF), electric arc furnace (EAF) and induction furnace (IF). The contribution (% share) of these routes is shown in Fig. 1a.

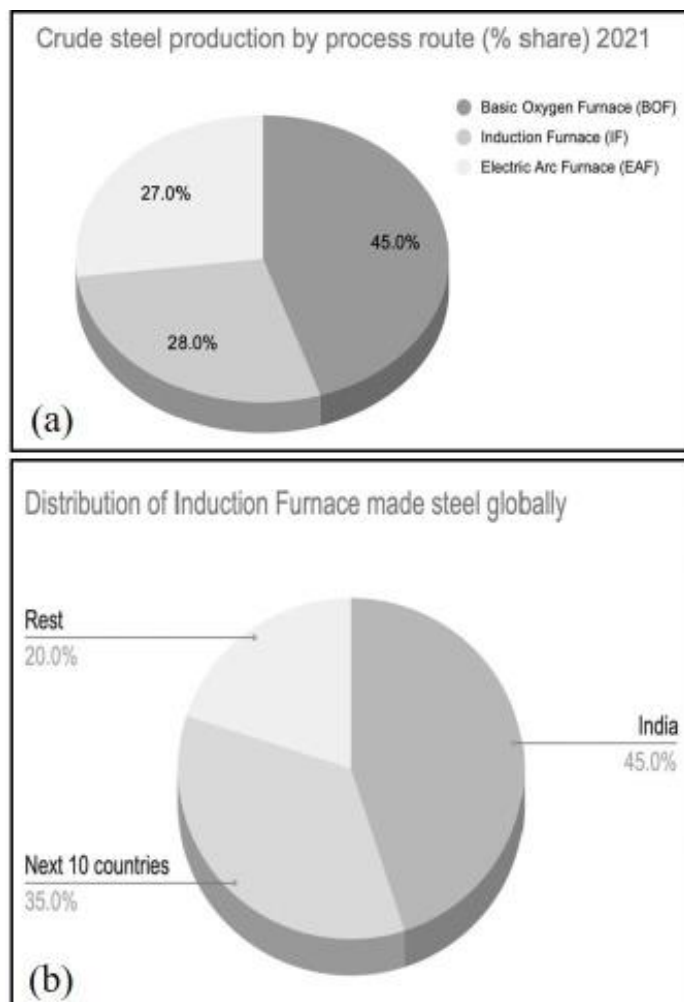


Fig. 1. (a) Percentage share of crude steel production by process route in India - FY21 [4] (b) India's share in total steel produced by Induction furnace globally (in %) - 2020 [5]

According to the World Steel Association, India holds the position of being the second-largest producer of crude steel, with a production capacity of ~118 million metric tons per annum (MTPA) in the financial year 2021 (FY21). Remarkably, around 28% of this steel production [4] in India was achieved through the utilization of the induction furnace route. On a global scale, the induction furnace steelmaking market is estimated to be valued at around \$60 billion [5]. In this context, India currently holds an impressive 45% share (see Fig. 1b) of the total steel produced worldwide by induction furnaces, amounting to ~\$27 billion in value. These figures highlight the significant role that induction furnace steelmaking plays in India's steel industry, cementing its position as a major player both domestically and globally.

The IF steelmaking process involves melting the scrap and/or directly reduced iron (DRI) with other inputs in a crucible using an electromagnetic field. IF route is flexible in terms of production capacity (up to 50 tonnes) and product mix

product mix (various construction steel grades). Induction furnaces can be easily scaled up or down based on market demand, allowing for agility in responding to changing customer requirements. The setting up of an IF factory requires relatively lower capital investment, and the commissioning process can also be completed in a shorter time frame. In India, as of FY21, more than 1150 induction furnaces are in operation [6].

In addition to the economic benefits and the flexibility in the process, the reasons for rise in IF steelmaking in India could be the availability of the feed material such as scrap and coal-based DRI. The low-grade iron ore and coal which are not suitable for blast furnace (BF) feed, are used for the production of coal-based DRI. The IF route allows for the utilization of steel scrap, in combination with DRI, reducing the complete dependency on raw materials like iron ore. This advantage is particularly crucial for small and medium-sized steel producers.

As a part of Glasgow commitments [7], India plans to achieve net zero emissions by 2070 thus the push towards sustainable and green technologies. IF steelmaking sector can be aligned with India’s sustainable development goals. This shift towards sustainable steel production is expected to drive the demand for IF technology in the coming years since it can use scrap (up to 100%) and runs on electrical energy which can be derived from renewable sources. In IF steelmaking process, the direct emissions due to fuel heating (as in EAF) or evolution of copious amount of carbon emissions during oxygen blowing/refining (as in BOF) are very limited. The energy consumption and CO2 emissions in IF process vis-à-vis traditional EAF steelmaking processes [8-9] are given in Table 1 and Table 2 respectively.

IF steelmaking sector has various technical and policy challenges that need to be addressed along with process optimization, and quality control to enhance the competitiveness of IF steel. In the present work, the current status of IF steelmaking in India has been investigated through the interaction with the industry personnel from the two steel plants located in two different clusters from central India, namely, Chhattisgarh and Jalna. The obtainable process data from these plants have been analysed. Finally, various ways by which IF steelmaking in India can be improved, are explored.

Table 1. Energy consumption (kWh per ton of steel or kWh/T) comparison between electrical steelmaking processes [8]

	EAF	IF
Energy (kWh/T)	704	530
Energy input breakdown (kWh/T)		
Electrical Energy	397 (56.4%)	515 (97.2%)
Other Sources	307 (43.4%)	15 (2.8%)
Energy consumed breakdown		
Steel	350 (49.7%)	382.6 (72.2%)
Slag	51 (7.3%)	22.3 (4.2%)
Off Gas	254 (36%)	14.3 (2.7%)
Other losses	49 (7%)	110.8 (20.9%)

Table 1. CO2 emission comparison between the steelmaking processes [9]

Charge Mix	Total CO ₂ emissions (in kgs / ton of steel)		
	EAF	IF	BF-BOF
100% Scrap	460	444	2200-2500
50% Scrap, 50% DRI	1143	1361	
20% Scrap, 80% DRI	1582	1940	

2. Induction furnace steelmaking process

Steel clusters in India are specific geographical regions where multiple steel-related industries and companies are situated in close proximity to one another. These clusters offer advantages such as shared resources in terms of transportation, logistics, energy, and raw materials. An overview of the major induction furnace steel clusters in India and their production capacity are given in Fig. 2.

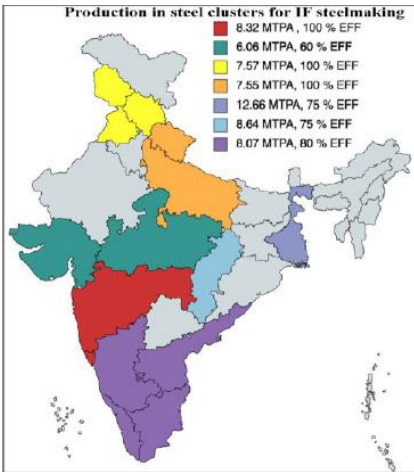


Fig 2.. Indian Map showing different steel clusters and their production and efficiency [11]

Two different IF steel plants from the central India, one each from Jalna (Fig. 3a) and Chhattisgarh (Fig. 3b) cluster have been visited to understand the process.

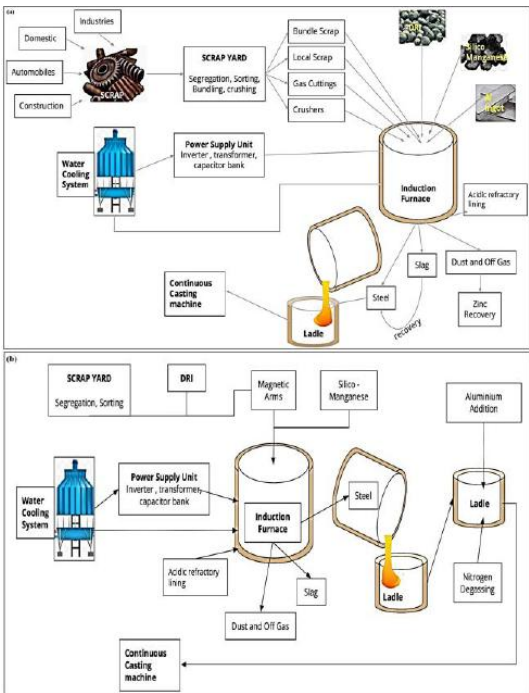


Fig 3.. IF steelmaking process (a) Jalna cluster (b) Chhattisgarh cluster

On comparing the process data from the Chhattisgarh and Jalna plants, some interesting distinctions are revealed.

1. Raw Materials: Chhattisgarh benefits from abundant sponge iron factories, resulting in readily available and affordable carbon based DRI. This cluster predominantly utilizes 70-80% DRI and the rest scrap. In contrast, the Jalna cluster relies mainly on scrap (70-80%) due to local and economic factors, with some DRI feed (Table 3).
2. Quality: Average concentration of P and combined (P and S) content meet the required standards [10] for construction-grade steel in the Jalna cluster. However, the Chhattisgarh cluster exhibits disparities, possibly due to increased DRI usage. Higher DRI quantities correlate with elevated content of phosphorus in steel (Fig. 4).

	Chhattisgarh plant	Jalna plant
Raw Material	25-30% Scrap, 70-75% DRI	70-80% Scrap, 20-30% DRI
Electricity	750 kWh/ton	620 kWh/ton
Power factor	0.95	0.96
Ramming mass	Acidic (12-15 heats)	Acidic (18-24 heats)
Efficiency	~72%	~76%
Yield	~86%	~94%
Quality of steel produced	Very Higher Phosphorus (due to use of more DRI)	Phosphorus within limits (%S+%P within Range)
Tap to Tap time	180 mins for 10 ton	90 mins for 30 tons
Melting Efficiency	Melting efficiency lower	Melting efficiency higher

Table 3: Comparison between the two steel plants from two different clusters

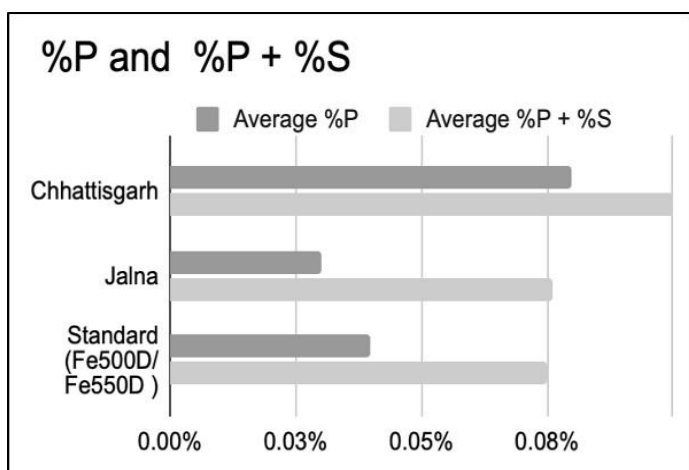


Fig. 4. Comparison of Jalna and Chhattisgarh plants on the basis of quality, %P and % (P and S) with IS 1786

3. Process and Efficiency: Chhattisgarh plant utilizes approximately 750 kWh of input energy per ton of steel, with an efficiency of around 72%. Conversely, Jalna plant requires about 620 kWh input, achieving a greater efficiency of approximately 76% (Fig. 5). The energy requirements increase with DRI usage due to the endothermic reaction of FeO with C and the melting of associated gangue. Additionally, the melting efficiency decreases with higher DRI quantities (Fig. 6).
4. Yield: The Chhattisgarh plant, relying on DRI, exhibits a lower average yield of ~86%. On the other hand, the Jalna plant, primarily utilizes scrap and exhibit a higher average yield of ~94%.
5. (5) Capacity: As of FY20, the Chhattisgarh plant demonstrates a total capacity of around 6.5 MT, with production reaching approximately 5.4 MT, indicating a utilization rate of 84%. In contrast, the Jalna plant has a capacity of about 4.3 MT and production of 3.2 MT, resulting in a utilization rate of approximately 73% (Fig. 6).

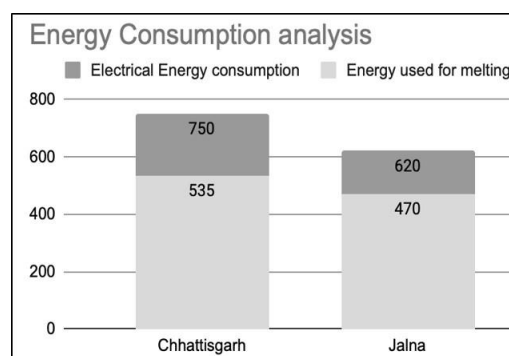


Fig 5..Comparison between Jalna and Chhattisgarh plants on basis of energy consumption

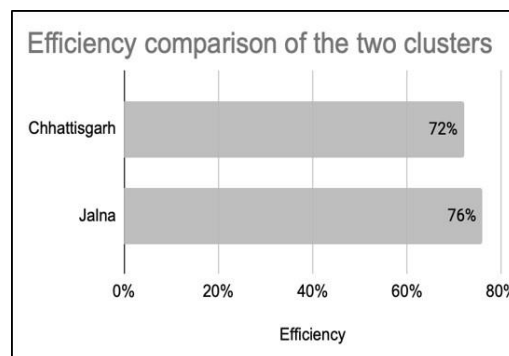


Fig 6.. Comparison between Jalna and Chhattisgarh plants on basis of energy efficiency

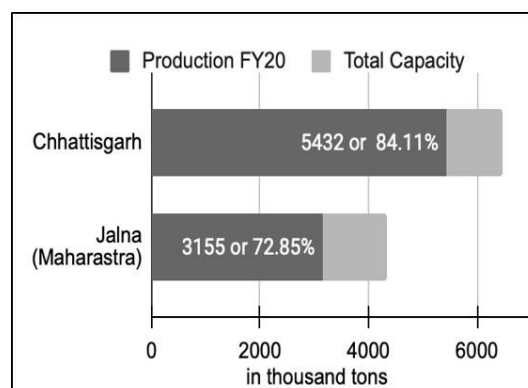


Fig 6..Comparison between Jalna and Chhattisgarh plants on basis of Capacity and % utilization

The comparative analysis of these two plants on the basis of various parameters is summarized in Table 3.

Based on the (limited) recorded data at the Jalna steel plant, the static mass balance calculations have also been carried out.

2.1 Static mass balance model (Jalna plant)

The main objective of this model was to predict the composition of final steel produced using different proportions of the charge mix according to their availability. The inputs and outputs for the mass balance model are shown in Fig. 8.

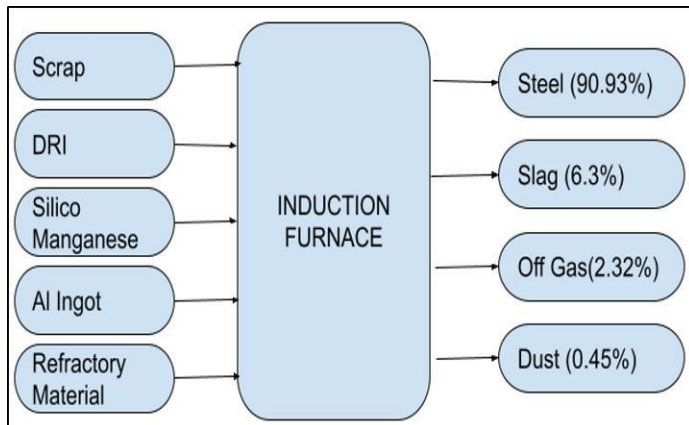


Fig 8. Schematic showing mass flow through the induction furnace

Due to insufficient process data, only seven elements (iron, carbon, manganese, silicon, aluminium, sulphur, phosphorus) were taken into consideration while performing the mass balance.

The static mass balance model has following assumptions.

- The ratio of outputs was calculated and averaged out using different heats data (from industry). This ratio was assumed to be constant for slag (6.3%) and used to calculate output steel composition. The ratio for off-gas and dust was 2.32% and 0.45% respectively.
- Composition of scrap (Table 4) was calculated using elemental mass balance of seven elements and kept constant.
- Other additives composition (Table 4) was used as provided by the plant.
- Dust composition was unknown and therefore neglected for the calculations.
- Composition of sponge iron was assumed to be constant as provided.

Table 4. Composition of various inputs and outputs used to make the mass balance model

Elements (wt%)	Fe	C	Mn	Al	Si	S	P	FeO
Local Scrap	97.06	0.95	0.55	0.62	0.75	0.03	0.04	0
Bundle Scrap	97.71	0.3	0.55	0.62	0.75	0.03	0.04	0
Gas Cutting	97.06	0.5	1	0.62	0.75	0.03	0.04	0
Sponge Iron	82.42	0.15	0.06	0.2	0.17	0.03	0.07	16.9
Silico Manganese	0	27.69	58.31	0	13.98	0.02	0	0
Al Ingot	0	0	0	100	0	0	0	0
	Fe(m)	FeO	SiO ₂	MnO	Al ₂ O ₃	Fe ₂ O ₃		
Slag	6.75	17.45	48.82	10.48	16.5	0		
Refractory Material	0	0	99.1	0	0.6	0.3		

2.2 Results of the mass balance model

The mass balance calculations have been carried out for 10 heats. The input composition (Table 5) and the output calculated for steel composition and the actual industrial results are provided in Table 6 which shows a reasonable agreement.

Table 5. Input (Industrial data, all the quantities are in kg)

Heat	Local Scrap	Bundle Scrap	Gas Cutting	Sponge Iron	Silico Manganese	Al Ingot	Refractory used	Total Input	Total Fe Input
1	11600	11720	0	0	330	0	450	24100	22710
2	26400	1000	0	3600	340	1.6	500	31842	30041
3	22910	0	0	3400	350	0.8	480	27141	25485
4	16000	15000	0	3000	360	0.8	650	35011	33052
5	18220	14400	0	3400	340	0.8	800	37161	35003
6	14340	10000	0	2800	320	0.8	520	27981	26365
7	17600	13200	0	4000	380	1.6	660	35842	33802
8	18000	10000	0	4000	340	1.6	650	32992	31064
9	14400	13470	0	3000	330	2.4	620	31822	30005
10	16680	7000	1500	5000	380	3.2	570	31133	29263

The calculated average yield through this mass balance model is around 96.28% which is close to the industrial average yield data (95.82%). The comparison of calculated and actual yield for 10 individual heats is shown in Fig. 9.

Table 4. Output (calculated composition and weight of the steel produced from the given charge mix)

(I) Calculated composition (wt%) and quantity (kg) using static mass balance									
Output	Fe	C	Mn	Al	Si	S	P	Total weight (90-92.5% of input)	Fe weight
1	98.56	0.33	0.87	0.06	0.11	0.03	0.04	22172	21852
2	98.71	0.47	0.63	0.02	0.09	0.03	0.04	29135	28760
3	98.38	0.54	0.76	0.01	0.23	0.03	0.04	24581	24184
4	99.04	0.21	0.62	0.03	0.03	0.03	0.04	32210	31901
5	98.98	0.19	0.55	0.02	0.18	0.03	0.04	33891	33546
6	98.87	0.28	0.68	0.02	0.08	0.03	0.04	25980	25686
7	99	0.23	0.63	0.02	0.05	0.03	0.04	32856	32528
8	98.91	0.26	0.6	0.01	0.13	0.03	0.04	30352	30023
9	99	0.2	0.62	0.03	0.08	0.03	0.04	29913	29613
10	98.8	0.32	0.72	0	0.08	0.03	0.05	28020	27684
(II) Industrial/Actual composition and quantity (kg) of the heats									
Heat No.	Fe	C	Mn	Al	Si	S	P	Total weight	Fe weight
1	98.85	0.2	0.67	0.01	0.21	0.04	0.03	21900	21649
2	98.85	0.19	0.65	0.01	0.22	0.03	0.05	29300	28964
3	98.76	0.18	0.73	0.01	0.25	0.03	0.05	24700	24394
4	98.8	0.2	0.67	0.01	0.25	0.03	0.04	32500	32110
5	98.84	0.2	0.67	0.01	0.2	0.03	0.05	34000	33605
6	98.78	0.21	0.69	0.01	0.24	0.03	0.05	25600	25286
7	98.81	0.19	0.7	0.01	0.21	0.03	0.05	32900	32510
8	98.86	0.17	0.68	0.01	0.21	0.03	0.05	30200	29855
9	98.82	0.2	0.68	0.01	0.23	0.03	0.04	28800	28460
10	98.82	0.2	0.67	0.01	0.22	0.03	0.05	28000	27670

To further develop the mass balance model, systematic data such as composition of scrap, off gas analysis, dust compositional analysis is needed. This static mass balance model can be used to build upon and develop a more accurate model.

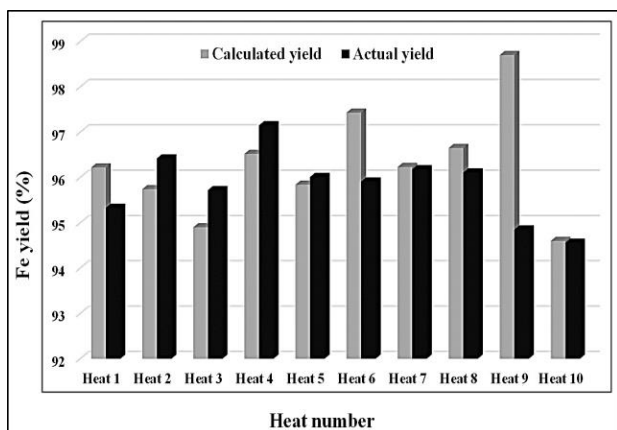


Fig 9...Comparison between the actual (industrial) and calculated yield of iron

3. Discussion

On comparing and analyzing the process data from two different IF steel plants, the issues with the present (induction based) steelmaking process have been identified. The major areas that require immediate attention are shown in Fig. 10.



Fig 9...Major areas for improvement in induction furnace steelmaking

3.1 Raw material

IF steelmaking is based on either DRI or scrap and/or a combination of these two major iron-bearing raw materials. The contribution of DRI/scrap in the input charge mix have implications on the overall process and quality. This is evident from comparative analysis (DRI-based steel plant from Chhattisgarh vs scrap-based steel plant from Jalna) and the mass balance calculations (scrap-based plant from Jalna) covered in section 2. Considering the limited/restricted refining during IF process, high-quality steel scrap which is indispensable, are scarce in India. At present, the low-grade unsegregated scrap containing (unknown) impurities are added to IF. There is also a lack of systematic supply chain setup around steel scrap collection, segregation and the availability.

Therefore, promoting and incentivizing the development of a more robust and efficient scrap collection and segregation system, would help to tackle these issues. This can involve partnering with local scrap dealers and waste management companies to improve the quality and quantity of scrap, as well as investing in technology and infrastructure to streamline the supply chain and reduce import dependence.

3.2 Quality and refining

The quality related aspects can be discussed considering the theoretical requirements and the practical status of the refining.

The primary role of induction furnace is to meet the energy requirements (melting/refining). The refining of impurities such as phosphorus and sulphur needs to be done with the addition of suitable fluxes (basic) and maintaining a basic refractory lining. High phosphorus content can negatively affect mechanical properties and increase the risk of cracking while elevated sulphur content can lead to reduced ductility and impact toughness. High S and P contents in the produced steel have often been found to be originated from the type of scrap metal used, coal based DRI, alloying additions and other fluxes. In conventional steelmaking routes, the refining is carried out under basic and oxidizing conditions (primary steelmaking) for elements such as phosphorus. In IF, the use of silica (acidic) refractory lining and difficulty in oxygen lancing during the process limit in-process dephosphorization. The silica lining leads to the formation of acidic slag. Oxygen lancing is not possible as IF has small diameter to height ratio and most of the time it operates in full capacity. Thus, oxygen lancing can cause splashing of the metal and significant refractory wear. Furthermore, silica linings erode quickly, restricting the number of heats. Yet, silica linings are predominantly used due to their lower cost compared to neutral or basic refractories [14].

The refining of impurities such as sulphur is carried out under basic and reducing conditions (secondary steelmaking). At present, the secondary steelmaking is almost non-existent in most of the IF based steel plants, indicating the inability of deep desulphurization of the liquid steel.

As per standard IS 1786: 2008 for Fe500D or Fe550D, the combined P and S content must be below 0.075% [10]. Average (observed) combined P and S content collected from a (DRI-based) steel plant from the Chhattisgarh cluster was more than 0.08% while it was meeting the requirement for a (scrap-based) steel plant from a Jalna cluster (Fig. 4). This indicates that the impurities (mainly P) introduced through the DRI to the steel could not be refined during IF steelmaking. Moreover, it also suggests the necessity of additional refining step/unit during DRI-based IF steelmaking process.

3.3 Process and efficiency

There are more than 1150 induction furnaces in operation for steelmaking in India today. Each steelmaker has defined and established their own process route without properly optimized parameters. It has also been found that there is no static mass balance model available at the steel plants since the input and output data required to make a proper

mass balance is not fully recorded or captured. The major constraints include unavailability of scrap composition data while the off-gas and dust analysis are seldom done. Without a proper mass balance model, the energy balance model or energy optimization to help improve energy efficiency is not possible. All these parameters make it difficult to bring down costs and/or reduce environmental impacts.

IF steelmakers in India are mostly small-scale enterprises that have limited or no access to the latest technology. India, being the second largest steel producer, has one of the lowest per capita labour productivities of around 90-100 tonnes [12], indicating the potential room for development. Moreover, the IF process is mostly manually handled which raises the safety concerns for workers.

3.4 Environmental concerns

Since most IF factories are small to medium scale with little to no R&D spends, they have almost no incentive to innovate and implement new technologies taking environmental factors into consideration.

3.4.1 Envisioning green steel possibility through IF process
It is important to note that achieving green steel production is a complex and long-term goal. Green steel production is possible by replacing fossil-based fuels with renewable sources. Achieving green steel production using the IF route involves adopting a combination of strategies and technologies aimed at minimizing environmental impact. Here we look at a probable path for CO₂ emission-free steel to be produced from the IF. There are direct emission sources (carbon oxidation, scrap preheating and others) and the indirect emissions (DRI production and electricity to run IF) [9].

The development and implantation of static mass balance model can reduce the carbon concentration of the steel through careful selection of the raw material combination, that is, scrap type and the DRI.

The careful preparation and sorting of scraps would help avoid introduction of impurities (non-ferrous metals, plastics, and other non-metallic foreign substances) to the IF feed and minimize the potential for pollution and facilitates cleaner steel production. DRI production results in maximum emissions. Therefore, less polluting reductants, such as, natural gas or hydrogen needs to be used for DRI production. The electricity produced by renewables such as solar, wind, hydropower or others can be used to replace the fossil fuel-based electricity which emits CO₂.

The transportation of raw materials, scrap, DRI and other consumables can be minimized through a combination of techno-economic modelling, government policies and the development of efficient steel clusters. Waste management and recycling as well as continuous research to improve furnace design, energy efficiency and quality can drive further sustainability in the IF route.

4. Conclusions

In the present work, two induction furnace-based steel plants, one each from Chhattisgarh and Jalna clusters were visited. The work can be summarized as below.

- The input charge (DRI and/or scrap) for steelmaking process vary from one steel plant to another possibly within the cluster and certainly, from one cluster to another, depending on the availability. The limited/restricted refining during IF steelmaking makes the quality inconsistent within the steel plant and/or the cluster.
- The process parameter data are either not fully recorded or unavailable, making the process difficult to understand from improvement viewpoint.
- Successful development and implementation of process models, such as static mass balance model is urgently required. Extending the know-how about the refining treatments from the conventional steelmaking routes to the IF route may lead to improvement in quality and energy efficiency.
- As the conventional steelmaking routes are shifting their focus on electrical energy (derived from renewable sources) in lieu of fossil-based fuels for melting/refining, IF steelmaking can provide a promising alternative in the future steelmaking processes.

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Conflict of interest

Authors have no conflict of interest to declare.

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Effect of inclusion on steel properties and component development

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Abstract

The performance of transmission components like crankshafts, connecting rods, and camshafts is affected by many reasons, such as design errors, manufacturing defects, inspection faults, and misalignment leading to fatigue failures. Failure due to a material defect is often associated with the presence of inclusions at the crack initiation zone. Steel making is the key process where these inclusions are generated. Control of parameters play vital role in preventing macro inclusion entrapments in final product.

Keywords: Steel Making, Non-Metallic Inclusions, Slag

1.0 Introduction

The presence of inclusions in steel composition often acts as a stress concentration zone under loading conditions, becoming a source for crack initiation, thereby affecting the tensile strength, fatigue strength, and ductility of the component. Hence, steelmaking has become more sensitive to product "cleanliness" because of the rising expectations for superior product quality in automotive transmission and industrial applications that are produced using rolled wrought steel. Large-sized and high-melting-point inclusions that are not breakable in post-forming operations like rolling and forging are most undesirable. In parts that are produced from rolled steel with a lower reduction ratio, the non-metallic inclusions (NMI) cause excessive rejections or salvage work and demand stringent process control.

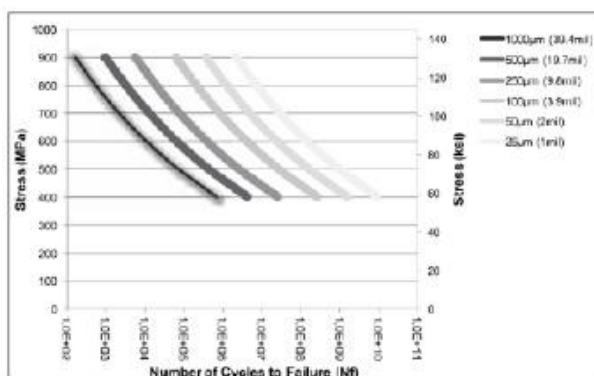


Fig 1. Relation between inclusion size, stress and number of cycles to failure in rotating bending fatigue test [2].

Steel cleanliness is best explained by its size and frequency of non-metallic inclusions such as oxides (Al_2O_3 , MgO , CaO) and sulphides (CaS , MnS). This inclusion depending on their size and distribution is known to affect the fatigue life of the component in field usage. In Fig. 1, reference is

is presented to show the effect of fatigue life to inclusion size (2). It can be seen that larger inclusion size failed at lesser number of cycles. Fig. 2 shows a subsurface non-metallic inclusion that acted as a nucleation site for fatigue failure and the EDS analysis showing oxides of calcium, silicon and aluminium.

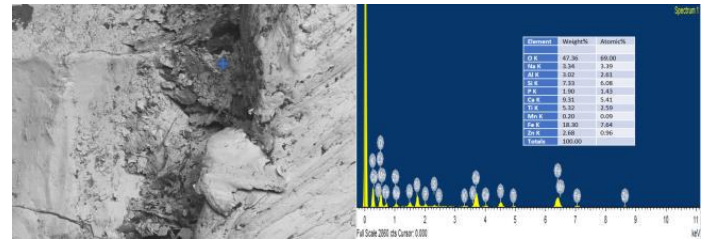


Fig 2. EDS results showing non-metallic inclusion in fracture.

2.0 Inclusion & forming mechanism.

The secondary refining process in steel making is a very critical step where the hot metal is refined, and alloys are added. Deoxidation and desulfurization are important steps as they severely affect the mechanical properties of steel. Aluminium and silicon used for deoxidation react and form micro inclusions, which agglomerate together to form macro inclusions called endogenous inclusions. These clusters or lumps are removed to their maximum by stirring and gas bubbling. However, the micro inclusions from different sources join to form larger macro inclusions. Hard and brittle oxides, particularly big alumina particles larger than $30\mu m$, are the primary cause of most fatigue failures in transmission and powertrain steel parts. Reducing the oxygen level to less than 10 ppm is known to increase the component fatigue life multiple times. To eliminate inclusion-related issues, it is necessary to control the size and morphology of inclusions during steel making. Reactions with the refractories or any other external system form exogenous inclusions where the casting process plays a major role. Reoxidation takes place during casting at different stages, like getting transferred from ladle to tundish or tundish to mould. Casting powder and covering compound are used to lubricate and cover the surface of the liquid steel to avoid such contacts with the atmosphere. However, turbulence and the higher solidification rate of the hot steel cause the casting powder or covering compound to get entrapped in the liquid steel, causing complex macro-inclusion formation. Erosion of refractories from the well block, impact pads, loose dirt from spray linings, and broken refractory brick are a few other sources for exogenous inclusion at casting that are large and irregularly shaped.

2.1 Slag entrapment

There are different ways in which the slag gets entrapped into the liquid steel. During the taping of the steel from the

ladle to the tundish, there will be a vortex created, which will suck the slag into the liquid steel. Also, vigorous stirring is required during the desulfurization if the steel needs the sulphur to get out of the metal phase and enter the slag phase. If the ladle is not cleaned properly, the slag lining of the previous heat would get entrapped in the liquid metal and combine with micro inclusion in further processes, forming macro inclusion. The high velocity of the steel causes turbulence, which leads to the erosion of the refractory lining, which will be carried away by the melt.

3.0 Control of non-metallic inclusions during steel production

It is practically not possible to produce steel without any inclusion in the heat. The steel cleanliness control depends initially on secondary steel making, which includes the time and location of additions, slag-metal reactions, slag composition, temperature optimization, coalescence of inclusions, elimination of inclusions by flotation and absorption in slag, absorption capacity of fluxes, and vacuum degassing. Control of slag composition is vital for preventing reoxidation. amounts of FeO and MnO carried over from the converter will favor the formation of Alumina inclusions. Thick ladle slag after tapping indicates slag carryover and the addition of basic slag. Slag conditioner is known to reduce the FeO + MnO content. Excessive stirring in vacuum degassing exposes the steel for oxidation and promotes refractory erosion. The source of inclusion gets multiplied if better process control is not adopted in casting. Various metallurgical and process factors like argon gas protection in shroud and stopper rod, extent of Submerged entry nozzle (SEN) dipping in mould, nozzle geometry, shape of mould, presence of electromagnetic stirring, electromagnetic brake facilities in caster are known to influence the clean steel making. The probability of inclusion increases as the super heat drops, which generally means more casting speed, precipitation of inclusion.

Hot metal is exposed to atmospheric reoxidation during the transition from ladle to tundish (or) from tundish to mould. Lancing due to self-opening failure of ladle will result in O₂ pick-up, causing more inclusion or nozzle clogging. MgO based tundish refractory mass linings is advantageous over silica based, as the dissolved aluminium in the steel might react with refractory lining and decompose to SiO₂. Addition of basic tundish flux is advantageous in preventing N₂ pickup and absorbing inclusions. The flux with lower SiO₂ is recommended than the rick husk which is commonly used.

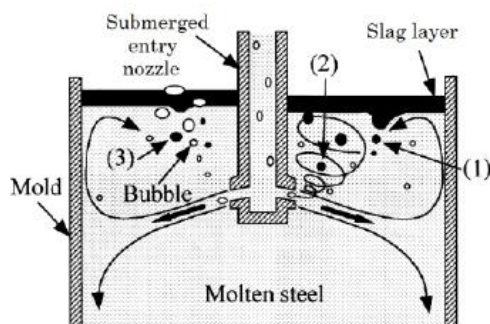


Fig 1. Sketch of various flow conditions in the continuous casting mold causing slag entrapment [6]

It is important to maintain half a tundish of steel during casting transitions and at the end of the sequence, since the of slag accumulated in tundish might enter mould due to vortex formation. Clogged nozzles, tundish and ladle transitions, casting speed, superheat, mould fluctuations are frequently related to defect generation in the casting process. Casting mould is the last stage for inclusion removal before solidification. High or large variations in casting speeds result in poor inclusion flotation. Fig. 3, shows the different condition of slag entrapments that is possible in mold. The angle of SEN port largely influences the carryover of mold slag depending on the casting speed, superheat and appropriate SEN modelling necessary. The stopper with argon needs to be optimized for steady and the mould fluctuation stability need to be restricted to ± 3 mm.

4.0 Techniques of Evaluation

Micro-inclusion rating on the steel is commonly performed analysis for qualifying steel, which gives very limited information on the rolled steel due to small area of inspection. SEM analysis shall be performed in addition to get clear evaluation of steel due to its large area volume of steel inspection.

Immersed ultrasonic testing: Immersion ultrasonic testing is an efficient method to detect large inclusions, voids, and segregation. A sample milled in parallel plan is placed in a water medium and scanned with a signal transmitted through a probe. The frequency of the probe shall be 10MHZ or 25MHZ depending on the criticality of the component. Based on the nature of the received echoes, the defect can be identified and analysed using SEM-EDS to evaluate the inclusion composition.

The sum of active oxygen and combined oxygen as non-metallic inclusions is termed as total oxygen content. Total oxygen measured with sample from mould is an indication of cleanliness. Total oxygen levels of less than 10ppm can be aimed for critical component grades. Reoxidation due to atmospheric exposure can also be ascertained though the difference in nitrogen content between ladle and mould. The deoxidation process makes the steel rapidly absorb O₂ from the atmosphere. It is necessary to restrict the nitrogen pickup to less than 1-2ppm.

Sulphur Print, this easy-to-use macrographic technique tells the difference between a macro inclusion and a crack by etching out areas with sulphur. Blue fracture and step-down testing are other popular techniques used to reveal macro inclusions larger than 0.5 mm.

5.0 Conclusion

The main sources of inclusion at various stages of steel making that affect a component fatigue life, process controls required to control the inclusion and some of evaluation method is discussed. To improve the fatigue life of component, it can be safe to assume that a good ladle refining and casting process is must to reduce the total inclusion of any heat casted.

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Optimizing Turbocharger Performance with Producer Gas: A Parametric Study on Energy Conversion Efficiency

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Abstract

The ecological and economic balance through technological advancement is central to engineering analysis, aiming to design sustainable and efficient systems. This study investigates the utilization of turbocharging to optimize exhaust gas enthalpy with producer gas, a sustainable alternative fuel, addressing the challenge of power derating. Parametric analysis was conducted on a turbocharger turbine interfaced with producer gas, examining variations in mass flow rate (0.03 kg/s to 0.15 kg/s) and rotor speed (6000 rpm to 45000 rpm) to assess overall performance and energy conversion efficiency. Computational fluid dynamics (CFD) simulations were employed, integrating advanced software tools (BLADEGEN, TURBOGRID, ANSYS) to model and analyze turbocharger components. The study included detailed analyses of stator and rotor meshing, turbulence modeling using the Shear Stress Transport model, and rigorous pre-processing and post-processing utilizing ANSYS CFX-Pre and CFX-Solver Manager. Results revealed insights into pressure energy conversion to kinetic energy within the turbine, demonstrating how pressure ratio variations impacted velocity and energy efficiency across varying speeds and mass flow rates. Contour plots illustrated reductions in static pressure, temperature, and total temperature with increased speed, supporting near-adiabatic assumptions. Eddy viscosity analyses highlighted turbulence at higher speeds, while streamline and vector plots characterized velocity variations and kinetic energy distribution along the flow path. Performance parameter assessments confirmed the benefits of higher mass flow rates and speeds in optimizing turbine operation. The study provides a comprehensive understanding of turbocharger turbine dynamics, emphasizing the critical relationship between operating parameters and performance metrics, offering practical insights for optimizing turbine efficiency and operational conditions in sustainable energy applications.

Keywords: Turbocharger, Turbine, interfacing, CFD, Producer Gas

1 Introduction

The primary goal of any analytical endeavor within research and development is to identify strategies that enhance the efficiency and performance of energy conversion systems, which in turn contributes to ecological and economic balance. An important aspect of research is trying to infect new cells, and cleans up the battlefield

this pursuit involves exploring alternative fuels to maximize energy extraction. The adoption of producer gas represents a significant step towards this objective, reducing reliance on fossil fuels and mitigating emissions and environmental risks. However, engines utilizing these fuels often experience a 30% to 40% reduction in power due to their lower heating value compared to conventional fuels. To address this challenge, turbocharging is employed to optimize exhaust gas enthalpy utilization before emission, effectively compensating for power loss. Turbocharging, a form of supercharging, leverages exhaust gas energy to enhance air intake, optimizing energy conversion efficiency.

Studies by Shaolin Chen et al. [1] focus on fully harnessing turbocharger potential to improve engine performance and exhaust enthalpy utilization. Notably, they achieved 0.4% torque enhancement and a 1.2% reduction in engine-specific fuel consumption without engine modifications. Meanwhile, Zhanming Ding et al. [2] investigate pulsatile flow effects on turbocharger turbines, employing one-dimensional viscous flow conditions to simulate circumferential outlet flow. Their findings align well with experimental data, highlighting key flow dynamics crucial for turbocharger efficiency.

Numerical analyses by A. Azmi et al. [3] delve into volute geometry's impact on turbocharger performance, studying secondary flow structures and pressure contours. These analyses reveal flow separation tendencies and primary flow deflections under varying pressure ratios. S.K. Nayak et al. [4] examine emission characteristics under different gas flow rates, suggesting dual-fuel engines as viable diesel alternatives under maximum load. Gourav Vivek Kulkarni et al. [5] compare turbulence models, favoring the shear stress transport model for its theoretical alignment.

Xi Wang et al. [6] conduct an energy and exergy analysis of turbocharged hydrogen engines, pinpointing major energy losses and confirming turbocharging's potential for significant brake thermal efficiency improvements. Mosca R et al. [7] delve into pulsating flow conditions and associated secondary flows, employing high-resolution simulations to reveal vortex behaviors under varying mass flow rates. Thangaraja Jeyaseelan et al. [10] underscore sustainable energy, emphasizing emissions challenges and alternative fuel solutions. The research by Anand Shivapuji et al. [13] investigates the impact of producer gas on engine performance, highlighting thermo-physical discrepancies compared to conventional fuels. Experimental studies by M. Govardhan et al. [15] at IIT Madras explore turbine rotor flow dynamics, observing reduced adverse pressure gradients with increased tip clearance. Based on this extensive literature review, our

clearance. Based on this extensive literature review, our study aims to analyze turbocharger turbine flow dynamics, focusing on parameters like total pressure, temperature, velocity, and Mach number. We intend to optimize turbine rotor-stator interfacing to enhance operational efficiency and performance metrics, ultimately facilitating a comprehensive understanding of flow field variations under diverse boundary conditions.

2. Methodology

The turbocharger rotor (TATA 1620 model) was initially designed using BLADEGEN (ANSYS) to incorporate variations in blade angles and thickness along the blade length. The turbine wheel was then modeled based on these specified dimensions. Subsequently, an actual stator (TATA1612 model) was disassembled and accurately measured using a coordinate measuring machine (CMM). By cutting a cross-section to facilitate comprehensive flow passage measurements, dimensions were recorded and a CATIA model was generated. This 3D model was then imported into TURBOGRID for meshing purposes. Following this, the stator meshing process was executed using ANSYS ICEM CFD, and subsequent pre-processing was carried out in ANSYS CFX-Pre 15.0. Here, essential boundary condition values such as rotational speed (in rpm) and mass flow rate (in kg/s) were specified based on prior research. For turbulence modeling, the “Shear Stress Transport” model, as identified in previous studies [5], was employed. The ANSYS CFX-Solver Manager 15.0 was utilized for solving the configured model. Upon completion, the resulting solution file was accessed using ANSYS CFD-Post 15.0 to extract all pertinent analysis outcomes. Following this initial analysis, the same simulation file was subjected to varying boundary conditions, and the post-processing procedure was repeated to generate comprehensive analytical insights.

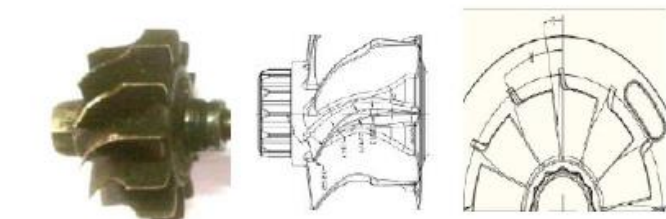


Fig 1. Rotor of TATA 1620 with Side View and Top View



Fig 2. Rotor Modeling in BLADEGEN (ANSYS)

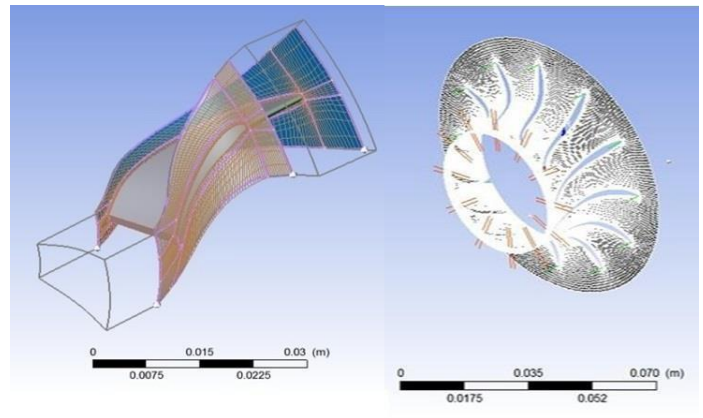


Fig 3. Rotor Meshing in TURBOGRID



Fig 4. Measurement of interior profile of casing on CMM

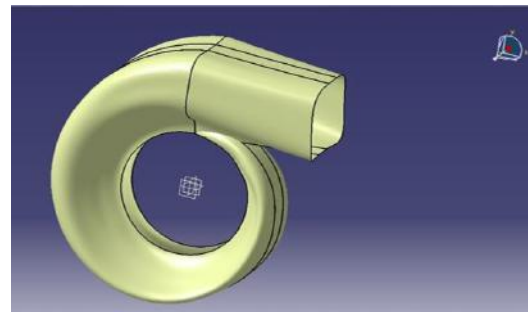


Fig 5. Stator Modeling

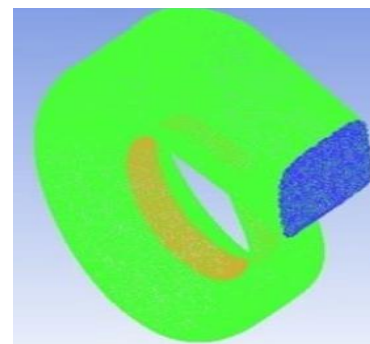


Fig 6. Stator Meshing

3. Results and discussions

3.1 Parametric study with variable speed at constant mass flow rate

The turbine underwent varying rotational speeds while maintaining a constant exhaust gas flow rate. The focus of interest lies in the conversion of pressure energy into

kinetic energy, as it directly influences power output. Contour plots are presented in this section for a mass flow rate of 0.15 kg/s across different speeds. The relationship between total pressure and outlet velocity is complementary. In this scenario, the turbocharger turbine receives high enthalpy gases at elevated pressures. As these gases expand across the turbine blades, pressure decreases while fluid velocity increases, resulting in the rapid rotation of the turbine shaft. This conversion from pressure energy to kinetic energy occurs within the specified flow path of the turbocharger turbine [18].

The Pressure Ratio (R_p), calculated as the ratio of outlet pressure (P_o) to inlet pressure (P_{in}), is analyzed alongside velocity variation contours obtained during post-processing to elucidate this energy conversion process. Fig. 7 demonstrates consistent total pressure variation throughout the stator, whereas variability is observed in the rotor region due to gas expansion on the turbine blades. This variation widens with increasing speed. Fig. 9 also illustrates velocity variation, showing a slight increase in gas velocity within the stator due to a converging cross-sectional area, and a subsequent increase from stator to rotor outlet due to pressure energy transforming into kinetic energy [6].

Examining the Pressure Ratio graph against speeds reveals that as mass flow rate increases, the curve shifts towards the x-axis, indicating more energy conversion at higher mass flow rates under constant speeds. Similarly, the consolidated graph of Outlet Velocity against speed corroborates this observation, with the curve shifting upwards as mass flow rate increases at constant speed. These graphical analyses affirm the first law of thermodynamics, specifically the steady flow energy equation, which dictates that pressure head must be converted into kinetic head, along with accounting for associated minor losses [18].

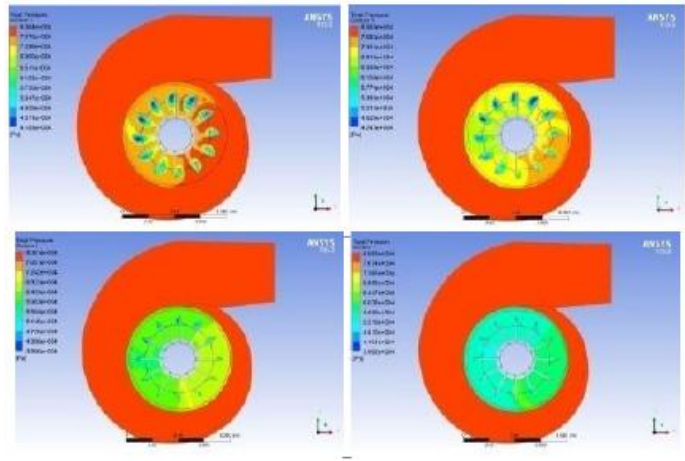


Fig 7. Total Pressure contours at 0.15 kg/s mass flow rate at 6000, 15000, 30000, 45000 rpm

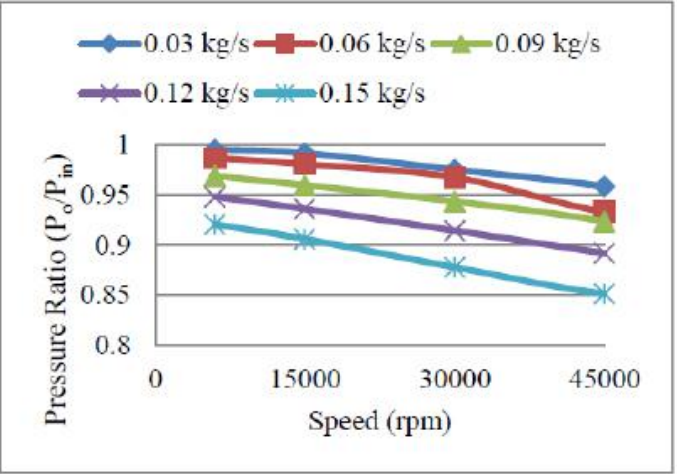


Fig 9. Velocity contours at 0.15 kg/s mass flow rate at 6000, 15000, 30000, 45000 rpm

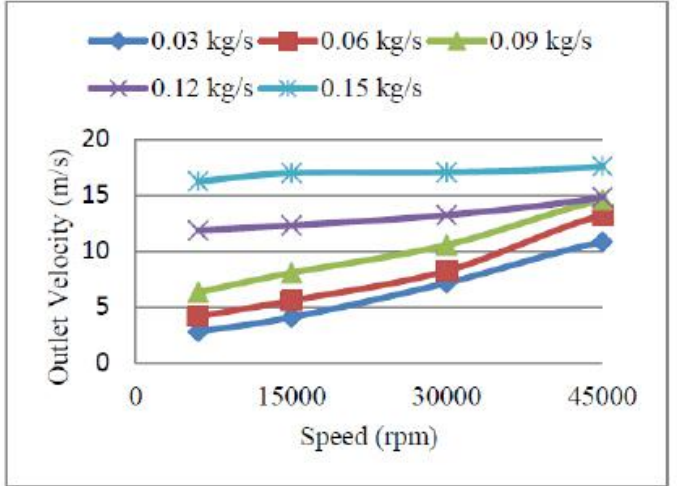


Fig 10. Variation of velocity against Speed varying from 6000 rpm to 45000 rpm at constant mass flow rates

From the Static Pressure contours, it is evident that with increasing speed, there is an amplified distribution of pressure that becomes non-uniform within the stator. This phenomenon arises due to the heightened number of fluid particles flowing through the system, causing a decrease in system pressure as speed increases. This decrease in pressure corresponds to an increase in flow velocity [6]. The graph illustrates a reduction in Static Pressure as speed escalates, correlating this reduction with an increase in velocity. Additionally, as speed increases, the curve shifts

curve shifts towards the abscissa, indicating that higher speeds and mass flow rates result in a more efficient conversion of pressure energy to kinetic energy. Although the variation in values aligns with those in Fig. 8, there are numerical discrepancies in the static pressure values. Static temperature denotes the localized temperature values at different points along the flow path, aiming for a constant temperature under adiabatic flow conditions [11]. However, external factors such as heat leakages introduce variations in temperature at different points. Contour plots illustrate the static temperature variation at a mass flow rate of 0.15 kg/s with increasing speeds. Notably, as speed escalates from 6000 rpm to 45000 rpm, temperatures near the stator inlet decrease due to higher-speed gases carrying away heat, thereby reducing local temperatures. Overall, temperature distribution widens at higher speeds, albeit with a relatively small range of variation, allowing the process to be reasonably assumed adiabatic without sacrificing accuracy. In Fig. 14, static temperature increases with speed while maintaining a nearly constant mass flow rate. However, the range of temperature variation (from 593 K to 604 K) remains minimal, supporting the assumption of nearly adiabatic conditions at approximately 600 K. These slight fluctuations in temperature (attributed to heat losses from factors like minor leakages) do not significantly impact the overall process.

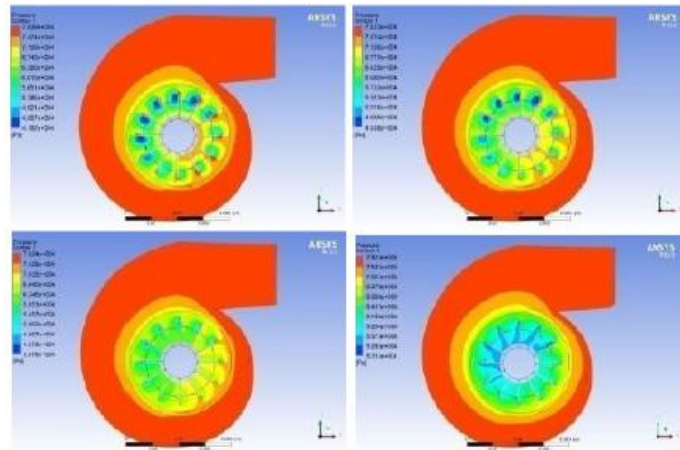


Fig 11. Static Pressure contours at 0.15 kg/s mass flow rate at 6000, 15000, 30000, 45000 rpm

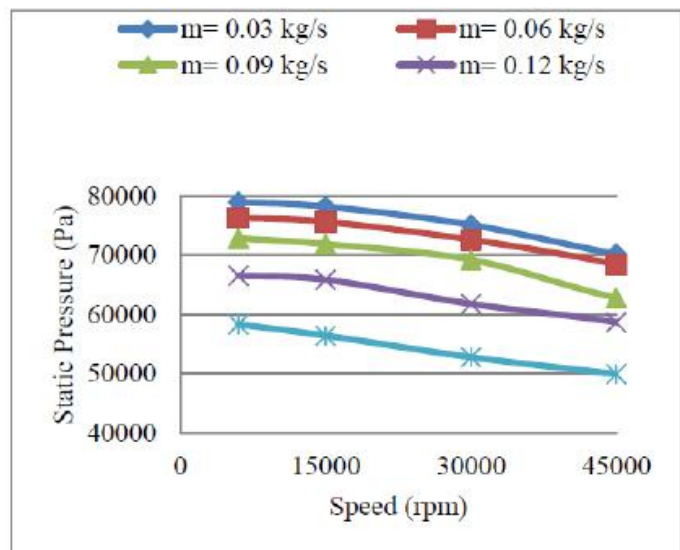


Fig 12. Variation of static pressure against Speed varying from 6000 rpm to 45000 rpm at constant mass flow rates

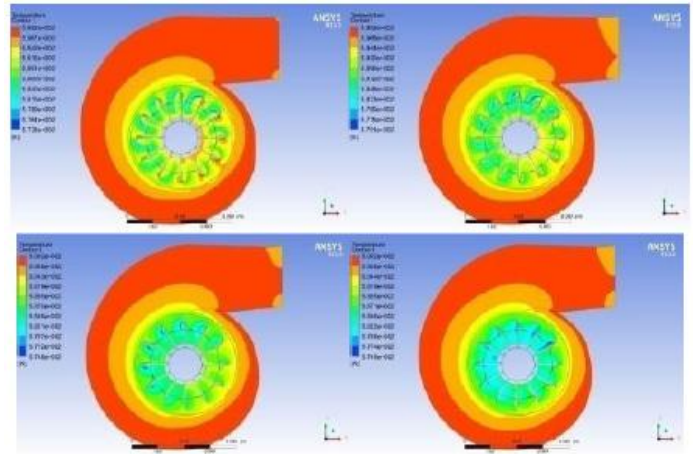


Fig 13. Static Temperature contours at 0.15 kg/s mass flow rate at 6000, 15000, 30000, 45000 rpm

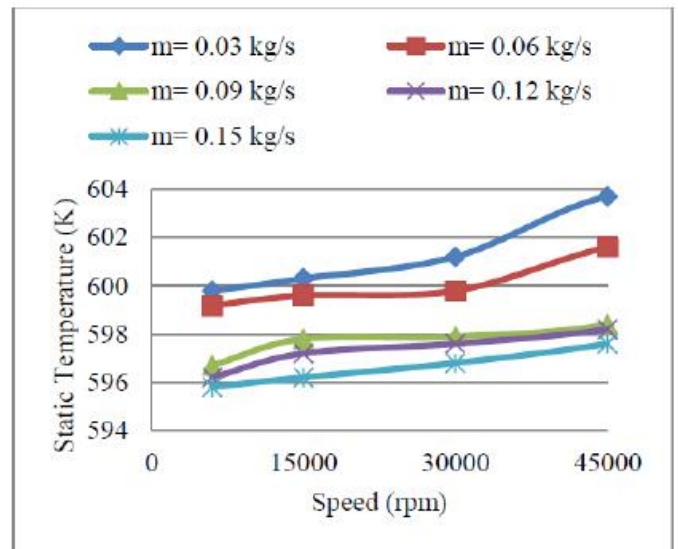


Fig 14. Variation of static temperature against Speed varying from 6000 rpm to 45000 rpm at constant mass flow rates

Total Temperature represents the temperature profile across different points within the flow field. During the pre-processing stage, the model is configured to operate under adiabatic conditions at a consistent temperature of 600K [18]. Contour plots illustrate the variation of total temperature with increasing speed at a constant mass flow rate. Along the stator, total temperature remains relatively constant due to fewer flow obstructions, whereas variations are observed along the rotor blades owing to geometric differences. As speed increases, these variations expand due to flow turbulence. Despite higher speeds exhibiting wider ranges of variation, the total temperature fluctuation remains minimal, maintaining near-constant values in compliance with adiabatic conditions.

Analyzing the consolidated data on total temperature variation across all cases, a graph depicting total temperature against increasing speed at a constant mass flow rate reveals relatively minor fluctuations. The established adiabatic process implies minimal heat transfer, thus preserving a consistent temperature [18]. Notably, the overall trend showcases a decrease in total temperature with increasing speed. Moreover, as mass flow rate increases, the curve shifts downward, indicating a slight decrease in operating temperature. For speeds exceeding 60000 rpm, fluctuations are observed at lower speeds due to unstable flow conditions; however, these

speeds due to unstable flow conditions; however, these variations occur within an extremely narrow range of 594 K to 600 K.

Eddy viscosity refers to the formation of eddies along the flow path during fluid motion. Eddies can arise from increased mass flow rate, where additional fluid flows through the same passage, and from increased velocity, as fluid encounters obstacles and must pass through certain cross-sections more rapidly, potentially leading to turbulence and eddy formation [7]. This phenomenon increases fluid resistance and reduces power output, emphasizing the need to minimize eddy viscosity for improved performance. Contour plots illustrate the variation in eddy viscosity at a mass flow rate of 0.15 kg/s, with speeds ranging from 6000 rpm to 45000 rpm. The contours reveal that eddy viscosity distribution becomes more uniform with increasing speed, corresponding to the accelerated fluid flow along the path. These contours offer valuable insights into flow behavior at different speeds. As speed increases, eddy viscosity also tends to increase, indicating greater flow resistance at higher speeds. However, a decrease in eddy viscosity is observed at 30000 rpm. Higher viscosity values are evident along the rotor flow path due to its complex geometry, whereas the stator exhibits lower eddy viscosity due to its simpler converging geometry [7]. Plotting a graph of eddy viscosity against speed at constant mass flow rates demonstrates that as mass flow rate increases, the curve shifts upward, reflecting increased eddy viscosity driven by higher speed and flow turbulence across turbine blades. Initial fluctuations at lower mass flow rates indicate flow instability, while higher speeds consistently show an increase in eddy viscosity with rising mass flow rates.

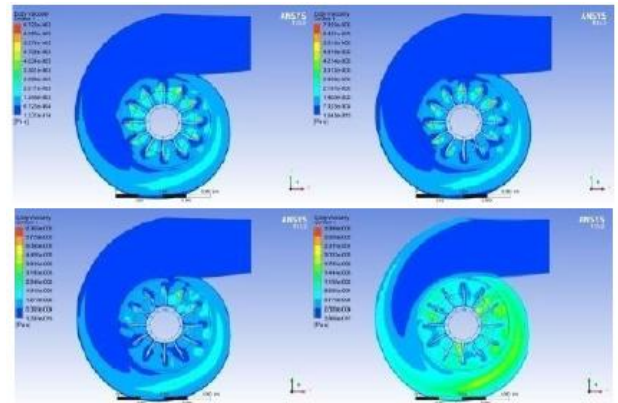


Fig 17. Eddy viscosity contours at 0.15 kg/s mass flow rate at 6000, 15000, 30000, 45000 rpm

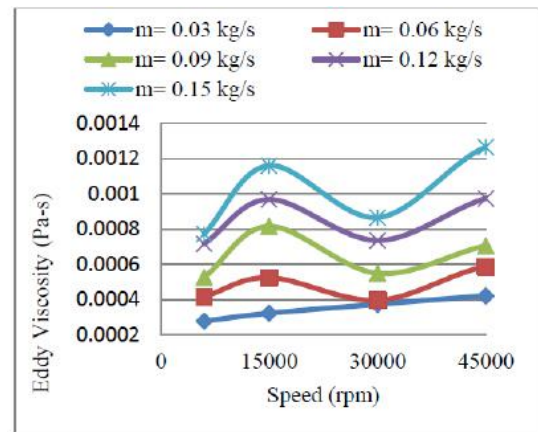


Fig 18. Variation of eddy viscosity against Speed varying from 6000 rpm to 45000 rpm at constant mass flow rates

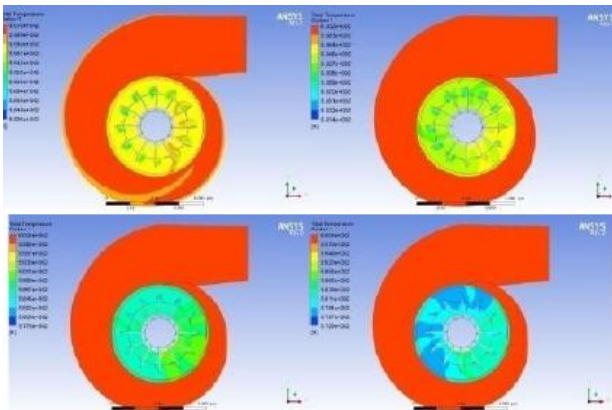


Fig 15. Total Temperature contours at 0.15 kg/s mass flow rate at 6000, 15000, 30000, 45000 rpm

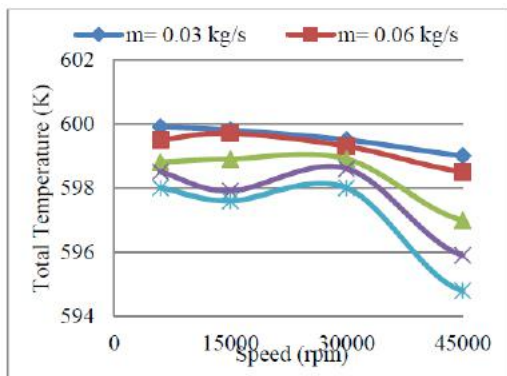


Fig 16. Variation of total temperature against Speed varying from 6000 rpm to 45000 rpm at constant mass flow rates

3.2 Analysis of Streamline and Vector Plots

The streamline plots clearly illustrate that, at a constant mass flow rate of 0.15 kg/s, as speed increases, the velocity of flow within the stator also rises [3]. This observation aligns with the Continuity Equation, where an increase in fluid inlet for a constant cross-sectional area leads to higher discharge and, consequently, increased velocity along each streamline. As the fluid progresses from the stator inlet to the rotor inlet, it traverses through a converging cross-sectional area, further boosting velocity along the path. The variation in velocity along the flow path is more pronounced at higher speeds compared to lower speeds, reflecting the greater energy of the fluid at higher velocities, which can be converted into kinetic energy. Moreover, the velocity of the fluid intensifies as it passes over the blades due to gas expansion resulting from pressure reduction and the associated conversion of pressure energy into kinetic energy. The plots demonstrate that as speed escalates, the average outlet velocity also rises, indicating a net increase in kinetic energy at higher speeds [3]. This trend underscores the dynamic relationship between fluid speed, pressure, and energy conversion within the turbocharger system.

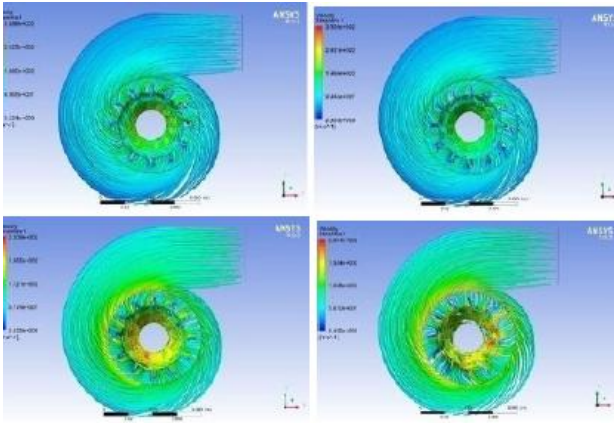


Fig 19. Streamline Plots at 0.15 kg/s mass flow rate at various speeds

Another method for analyzing velocity variations is through vector plots, which provide insights into locations along the flow path where velocity changes occur, possibly due to eddies or other factors [3][18]. Similar to streamline plots, vector plots were analyzed at a constant mass flow rate of 0.15 kg/s, with speeds ranging from 6000 rpm to 45000 rpm, revealing comparable variations.

As speed increases, the vector distribution within the stator becomes more pronounced, reflecting the increased energy of the fluid at higher speeds. Additionally, velocity intensifies as the fluid enters the hub, where the cross-sectional area reduces, further accelerating the flow. Local variations in velocity are noticeable at specific locations along the flow path, particularly at the interface between the turbine stator and rotor, where sudden changes in flow geometry induce minor losses.

The blades and rotor outlet regions exhibit higher velocities compared to the volute region, highlighting increased flow velocity over the blades due to gas expansion from reduced pressure ratio. This expansion translates into enhanced kinetic energy as mass flow rate increases. Consequently, at higher rotational speeds, the turbocharger turbine operates with greater efficiency by effectively converting more pressure energy into kinetic energy, optimizing overall performance [3][18].

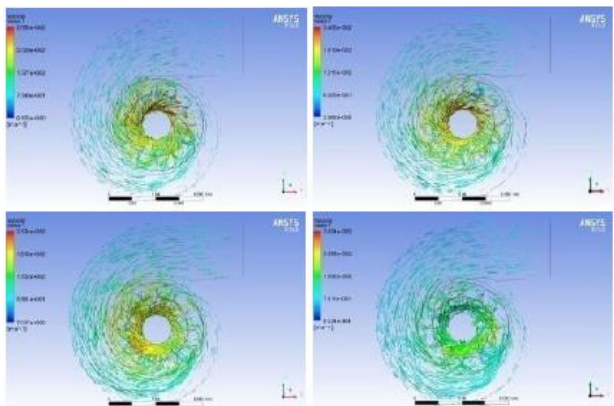


Fig 20. Vector Plots at 0.15 kg/s mass flow rate at various speeds

3.3 Overall performance evaluation

Following the analysis of parametric variations across different mass flow rates and speeds, alongside critical examination of streamline and vector plots, it becomes imperative to assess the overall performance of the turbocharger turbine [3]. Several key parameters are essential for evaluating performance, including Output Power, Isentropic Efficiency, and Polytrophic Efficiency, which are pivotal in designing systems incorporating a turbocharger component [3].

Accurate values for Isentropic Efficiency, Polytrophic Efficiency, and Output Power are derived from gas turbine performance reports generated by post-processing software [3]. When discussing the results, we define Pressure Ratio as the ratio of Inlet Pressure to Outlet Pressure, allowing for comparisons with standard variations documented in literature [3]. The Pressure Ratio is calculated using the formula:

$$R_p = \frac{P_{in}}{P_{out}} \quad (1)$$

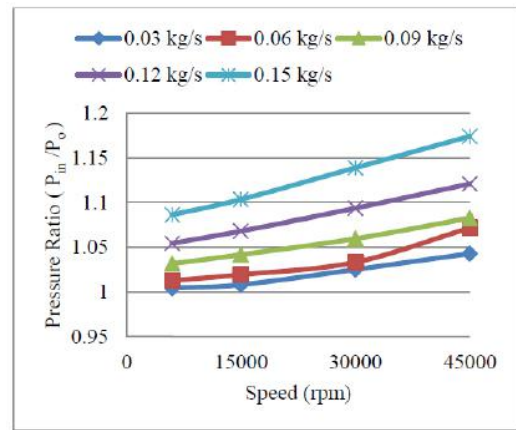


Fig 21. Pressure Ratio against speed varying from 6000 rpm to 45000 rpm at various mass flow rates

The turbocharger turbine's net output refers to the shaft power generated at the turbine shaft, which must be sufficiently robust to operate the compressor and compensate for losses incurred during transmission and operation [8]. Analysis involves plotting the variation of output power against speed at a constant mass flow rate across various mass flow rates. The Output Power versus speed curves reveal that, at a constant mass flow rate, increasing speed correlates with increased output power. Notably, at lower mass flow rates (up to 0.06 kg/s), power output is notably low due to insufficient fluid energy and a significant portion of energy being expended to overcome equipment inertia [13]. However, as fluid mass flow rate increases, higher speeds result in increased power output due to greater energy conversion. Overall, the turbine consistently generates sufficient power to drive the compressor at higher speeds and larger mass flow rates, as evidenced throughout the study, including analyses of contours, streamline plots, vector plots, and blade loading charts [8][13]. This underscores the importance of optimizing operating conditions to maximize performance relative to input parameters.

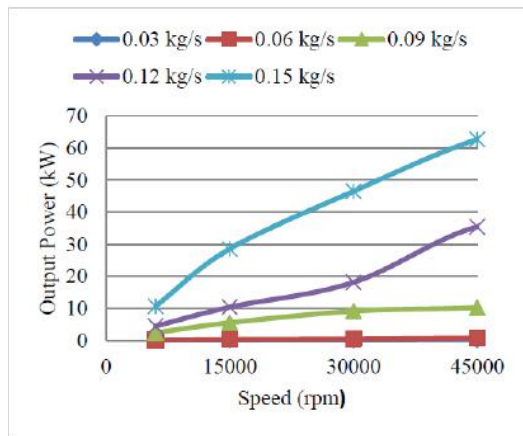


Fig 22. Output Power against speed varying from 6000 rpm to 45000 rpm at various mass flow rates

Conclusion

In conclusion, the computational fluid dynamics analysis of turbocharger turbine interfacing provides valuable insights into the impact of various parameters on power output and efficiency.

The contour plots offer a detailed understanding of parameter variations along the flow path, highlighting the distribution of numerical values and their influence on turbine performance. Notably, the reduction in pressure ratio correlates with increased velocity, indicating effective energy conversion from exhaust gas pressure to turbine rotor kinetic energy. Moreover, key parameters such as Static Pressure, Static Temperature, and Total Temperature decrease with increasing speed, reflecting gas pressure reduction over turbine blades. Conversely, Eddy Viscosity increases at higher speeds, indicating heightened turbulence. Streamline and vector plots further validate these observations by illustrating variations in total pressure and velocity at the outlet, demonstrating increased kinetic energy at higher speeds.

Analysis of performance parameters, including Isentropic Efficiency, Polytropic Efficiency, and Output Power, reinforces the impact of these variables. Higher mass flow rates and speeds correlate with increased power output and efficiencies. Based on this study, optimal conditions are identified with a mass flow rate of 0.15 kg/s and operational speeds exceeding 15000 rpm, where energy conversion variations are minimized.

This comprehensive analysis underscores the critical relationship between parameter variations and turbocharger performance, providing valuable guidance for optimizing turbine operation in practical applications.

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Activities of ASM

Bangalore Chapter



Dr. R. Raghavendra Bhat,
Chairman

Email: rr_bhat@yahoo.co.uk



Mr. K. L. Srirama,
Secretary

Email: cml.blr1997@gmail.com



Dr R. Raghavendra Bhat was conferred 2023 Class of Fellows from ASM International at Detroit, USA, in recognition of his distinguished contributions to the field of Materials Science and Materials Engineering on 17th October 2023.



ASM Bengaluru Chapter organised its 10th Annual General Body Meeting" on 17th November 2023 at Rotary Club of Bangalore, Lavelle Road, Bangalore. The main highlight of the event was that the following Office Bearers were elected for the Tenure – 2023-2025

- i) Chairman = Dr. R. Raghavendra Bhat
- ii) Vice Chairman = Mr. K. S. Subraya
- iii) Secretary = Mr. K. L. Srirama
- iv) Treasurer = Mr. L. N. Prasad



ASM Bengaluru Chapter organised an Online Technical Talk on the topic - "Thermal Interfaces in Materials Processing" by Prof. K. Narayan Prabhu Professor, Department of Metallurgical and Materials Engineering NITK, Surathkal, Mangalore, on 27th January 2024 through Zoom Meeting Platform.



ASM Bengaluru Chapter representatives Mr. K. L. Srirama, Secretary and Mr. V. Babu Sathian, Past Chairman, Bengaluru Chapter and Chairman, INC, Participated in the programme organised by MSME Development & Facilitation Office, Govt. of India Bangalore, and Kammagondanahalli Small Industries Association, Bangalore, held at Hotel Samskruthi Grand, K G Halli, Opp. MNTI Polytechnic, Bangalore 560015. Topic of the Event was:- Awareness Program on *LEAN Manufacturing Techniques under MSME schemes.



ASM Bengaluru Chapter & INC Office Bearers (Dr. R. Raghavendra Bhat, Chairman, Mr. K. S. Subraya, Vice Chairman, Mr. V. Babu Sathian, Chairman INC ; Mr. K. L. Srirama, Secretary, Mr. L. N. Prasad, Treasurer and Dr. J. R. Nataraj, Secretary, INC) participated in the Inaugural Function of the Installation of Salem Chapter of ASM International on 11th February 2024.



Dr. R. Raghavendra Bhat and Mr. K. L. Srirama were the Distinguished Speakers at the Awareness Program on Entrepreneurship, scheduled on 2nd March 2024 at Seminar Hall, Ashoka Polytechnic and ITI. They used this opportunity and shared about ASM Bangalore Chapter & its activities.

Chennai Chapter



**N. Sampathkumar,
Chairman**

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**Prof. Sushanta Kumar Panigrahi,
Secretary**

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Seminar Talk  Speaker: Prof. Kenong Xia Department of Mechanical Engineering University of Melbourne Victoria 3010, Australia Title: Novel Microstructures from Metal Powder	26.10.2023 Seminar on Novel Microstructures from Metal Powder by Prof. Kenong Xia - Mechanical Engineering Department, Editor for Materials Science & Engineering, University of Melbourne, Australia Venue: NACI 223, Seminar Room IIT Madras Organised jointly by: IIMCC, Dept of M&M Engg, IITM., ASMICC.
	30.11.2023 ASM International President Mr. Pradeep Goel's visit to Chennai Chapter and Interaction with the Members. Venue: Hotel Ramada Plaza, Guindy, Chennai 6.30 PM
	On 16.12.2023, Technical Presentation on A Novel and Simple NDT Method (DHAMES) to evaluate Metallurgical properties of steel components (Talk & Demo) By Dr. V. Moorthy, Professor School of Engineering, New Castle University, New Castle Upon Tyne. United Kingdom. Venue: Radha Regent Chennai



29.02.2024 Thursday
Inauguration of Materials Advantage Students chapter
at Rajalakshmi Engineering College Thandalam
Sriperumbadur, Chennai Inauguration Address by;

- 1) Prof & HOD (M.Engg)-REC
- 2) Principal, REC
- 3) Chairman-ASMICC
- 4) Secretary-ASMICC
- 5) Vice Chairman-ASMICC
- 6) Joint Secretary-ASMICC
- 7) Vice Chairman-ASMICC
- 8) Asst.Prof,(M.Engg)- REC

Followed by technical talk by
Mr.S.Shankar Vice Chairman on Industry 4.0. and
Importance of Knowledge on Materials to Mechanical
Engineering by Prof: Sushantha Panigrahi, Special
address by Prof:S.R.Bakshi on Materials
Advantage activities



On 09.03.2024, Saturday
Technical talk on Challenges in using High Strength Steel
in Construction and Mining Equipment by Mr. Matt Kiser -
Global Senior Engineering fellow Caterpillar Inc.Mossvile,
Illinois.

Venue: Radha Regent

Gujarat Chapter



**Nishant Shah,
Chairman**

Email: nishant@heattreaters.in



**Gaurav Awasthi,
Secretary**

Email: gaurav.r.awasthi@gmail.com



Course instructor during the theory session



Photograph with the participants and speakers

ASM International Gujarat Chapter organized a workshop on Metallography and Microstructure on 23rd September 2023. 50 participants across Gujarat from various manufacturing industries. Course instructors were Ms. Bijal Parmar - CEO of Unitech Metallurgical Services-Ahmedabad,



Group Photo

Members visit to Industry: Dana Corporation • Visit Date: December 22, 2023 • Time: 9:30 to 2:30 pm

	Date: January 04, 2024.Seminar Topic: Boron Carbide:Manufacturing Technology and Applications in Defense and Nuclear Industry. Place: Seminar Hall, CoE welding, L D College of Engineering Ahmedabad No of Participants : 35 persons
 Practical demonstration of pultrusion process.	Date: February 12, 2024 Time: 10:00 am to 4:30 pm Seminar topic: Composites: Advances in Pultrusion Technology. Place: Seminar Hall, ATIRA opposite IIM Ahmedabad, Ahmedabad No of Participants: 80 (Industry Professional, Researchers & Students)
 Dr. Fasuto Tucci during the seminar  Group Photo with the expert	Date: February 14, 2024 Time: 02:30 pm to 4:00 pm Seminar topic: Fiber Reinforced Composite: Recent Trends, Challenges and Potentialities. Place: Seminar Hall, ATIRA opposite IIM Ahmedabad, Ahmedabad No of Participants: 30 (UG students)
	Date: March 07, 2024 Time: 6:00 to 7:30 pm followed by dinner Seminar Topic: Catalysis of Change Materials for Hydrogen generation. Place: Seminar Hall, CoE welding, L D College of Engineering Ahmedabad No of Participants : 30 persons

Mumbai Chapter



**Jayesh Mukadam,
Chairman**

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**Dr. K. Rajkumar,
Secretary**

Email: drrajkumar0415@gmail.com



Technical Talk held on 25th October 2023 "8 Ps of Holistic Business" by Dr. Jagdish R. Jadhav

This talk showed the members on how to transform their business to its desired state by implementing the 8Ps of Holistic Business. Majority of businesses start in an unorganized way and then move towards an organized way. 8Ps implementation is the transformation journey from your current business state to desired business state, that too rapidly, smoothly, and efficiently. It helps to achieve balance and growth in your business in a holistic way.



Technical Talk held on 29th December 2023 "Creating a Sustainable Business" by Mr. Mohan Sane

This talk focused on how to make your business sustainable. Majority of businesses start in an unorganized way and then move towards an organized way. 8Ps implementation is the transformation journey from your current business state to desired business state, that too rapidly, smoothly, and efficiently. It helps to achieve balance and growth in your business in a holistic way.



Technical Talk held on 19th January 2024 "Magnetic Materials" by Mr. Girish, K. Mahajan & Mr. Hareesh J Sheth

This Technical talk was to provide members with information regarding Magnetic Materials. Materials that can be easily magnetized and are used to make magnets are called as magnetic materials. The talk covered:

- Type of magnetic materials
- Theory of magnetization
- Examples of materials and their properties &
- Application of magnetic materials



Industry visit on 9th February 2024
Industry visit to HAL in Ojhar near Nashik & to Avdhoot Heat Treatment Pvt. Ltd in Nashik

31 members of the ASM International India Chapter visited HAL, an aerospace and defence company, owned by the government of India located in Nashik. Next the group also visited Avdhoot Heat Treatment plant. In Nashik. The trip was very informative and useful for all the members.



Technical Talk held on 23rd February 2024
"Responsible Steel Standard" by Mr. Anantha Prabhu

The talk was to provide information to the members with regards to the ResponsibleSteel™ standard. The ResponsibleSteel™ standard is the first international standard to set forth certifiable requirements for responsible processing and production of steel. The non-profit organization ResponsibleSteel™ is behind the standard and certification initiative.



Technical Talk held on 29th March 2024
"Steels for Defence & Transport Applications" by Dr. Bhushan Rakshe

This talk focused on the different kind of steels used in the defence and transport sectors. India being second largest steel producer in the world is seeing significant development in application of steel for safe and sustainable transport solutions over last 20 years. There are numerous success stories for indigenous development of specialty steels for Indian Navy Ships, Railways, Oil & Gas Industry and many more.

Salem Chapter



**Dr. Manjini Sambandam,
Chairman**

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**Vasanth Murugan,
Secretary**

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ASM International Salem Chapter – Pre-inaugural event
05-02-2023



Opportunities for Salem MSMES in Defence Corridor-
20-02-2023



NABL Awareness Program for Salem Micro, Small and
Medium Enterprises (MSMES)
30-01-2024



ASM International Salem Chapter –Inaugural function -
07-02-2024
also Make in Salem Make it Easy Initiative



First Monthly Members Meeting of ASM International Salem
Chapter in JSW – SALEM
09-03-2024
And ASM - Directory launch to members

MA Chapter Reports

Anna University Materials Advantage Student Chapter (AUMASC)



Dr J. Sudha (Faculty Advisor)
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Ms. Ramya Dhaarani S
Student Chair
B.E., Materials Science and
Engineering



Ms. Akila Y
Student Secretary
B.E., Materials Science and
Engineering



A membership drive was held on September 21, 2023 and a brief introduction of ASM international, partner societies, its chapters across world, material advantage student chapter and AUMASC (Anna University Material Advantage student chapter) was given. Advantages and benefits of joining the chapter was propagated. 38 new applications were processed for this academic year. Participated in the Material Advantage Student Chapter Fall Membership Challenge.



Students from AUMASC attended the 4th International Heat Treatment and Surface Engineering Conference and Expo held from the 28th to 30th of September 2023 and organised by the ASM international Chennai chapter at World Trade Centre.



AUMASC along with Society of Material Science Engineers (SMSE), Anna University organized a guest lecture on the topic "Materials Engineering: How to ask questions and search for answers" on October 27, 2023. The event was presided by Dr. Hemaprabha, Assistant Professor, IIT-M.

Cummins College Of Engineering for Women, Nagpur, MA Chapter



Mr. Yogesh Dandekar
Faculty Advisor



Ms. Swara Tupe
Chair, BE, Mech Engg



Ms. Riya Khaparde, Secretary- BE
Mech Engg



Edge-pro-Knife making competition: On 14.09.2023, Competition was organized commemorate Engineers Day.



MA chapter organized 2-day Ansys Workshop organized 16-17, Oct 2023



The FeFe3 Insight Fest held on 20.09.2023 organized by the MA Chapter. The event aimed to educate students about the FeFe3 Diagram, emphasizing its significance and applications in materials science

Other Programs organized by the chapter include

1. Dobot Magician Magic
2. 3D Printing Workshop
3. Discussion of New Members with Vice - President
4. Social Awareness Drive Green Haven
5. Seminar on Technical Report Writing
6. Logo Making Competition
7. Aptitude Skills Training

Indian Institute of Technology Kanpur, Material Advantage Student Chapter



Dr. Kantesh Balani
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Shiven Ponnappureddy
PhD (MSE)



Harsha Prasad
PhD (MSE)



Membership drive 2023-2024 (20 September 2023)



A Get-Together Bonding Eve –
Freshers Event 22.09.2023



Machine learning in materials Science by Dr Anurag Bajpai (28.09.23 dealt with the fundamentals of classification, clustering, and convolution in neural networks to develop predictive models.



A Sports Event was organised Participation witnessed enthusiasm from students as well as professors.



Workshop on "Understanding Crystallographic Textures using MTEX" (10th October 2023)

Dr. Mrityunjay conducted a workshop on crystallographic textures using MTEX software. Students were introduced to the computational tools which they can use to boost their research quality. The depth of this subject matter was relayed to participants very well.

Indian Institute of Technology Tirupati, Materials Advantage Student Chapter



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Mr. Hiren Singh
Chairman
MTech



Mr. Vikrama Adithyan S
Secretary
MTech



Technical Symposium & Industry Visit On

Innovation & Developments in Foundry Industries (6th-7th November 2023)

The two-day offline Technical Symposium on "Innovation & Development in Foundry Industries" was organized by the Material Advantage Chapter Indian Institute of Technology, Tirupati, with Industry visit at "Ashok Leyland- Foundry Division, Sriperumbudur, Tamil Nadu."

Guest Include:

1. Shri V. Babu Sathian, Chairman of India National Council, ASM International
2. Shri C. Sathyamurthy, VP-Aquasub, Fdy. Div and Shri V. Narasimhan, Chairman IIF-CET
3. T S Rao, COOMEIL-Fdy.Div,
4. Shri A Balaji, GM Brakes India Foundry Division,
5. Shri Yogesh Kumar, CEO& Director DiFACTO Robotics and Automation Bangalore.
6. Dr. M Ravi Shankar, HoD of Mechanical engineering department
7. Shri Sumit K Biswas, The Registrar of the IIT Tirupati.

KLS Gogte Institute of Technology, Belagavi-Karnataka, Materials Advantage Student Chapter



Prof. Mahesh A Kori
Asst. Prof.
maheshkori git.edu



Mr. Shrinidhi Joshi
Student Chairman



Miss Aradhana Sadarjoshi
Student Secretary



Description of the activity 22 December, 2024

Awareness of Industrial materials Industrial materials play a crucial role in the development and functioning of various industries, contributing to advancements in technology, infrastructure, and manufacturing.



Description of the activity 29 December, 2023

Failure of Materials

The selection of appropriate materials is essential to ensure efficiency, durability, and costeffectiveness in different applications.

- Automotive Industry
- Plastics and Polymers:
- Composite Materials:
- Heat-Resistant Alloys:



Description of the activity 30 December, 2023

Industrial visit to heat treatment plant The visit to the heat treatment plant provided valuable insights into the intricate processes involved in enhancing the mechanical properties of metals.



Description of the activity 17-19 January, 2024

3 Days Skill Development Training On "Fundamentals of Composites Manufacturing Materials, Methods, and Applications"

The workshop successfully achieved its objectives by providing a platform for participants to enhance their knowledge of composite materials, manufacturing processes, and practical applications.



STUDENT
ACTIVITY
CENTER



2. Growing Innovator:



Date of Event : October 15, 2023
Mode of Event : Offline
No. of Participants : 98
Prize Worth : ₹ 5000

- Aimed at K-12 students, this offline event focused on sparking curiosity and innovation in materials science.
- Featured technical presentations, a metallurgical quiz, and hands-on activities to bridge theory with practical applications.

3. MetalloMania:



Date of Event : November 3, 2023
Mode of Event : Offline
No. of Participants : 240
Prize Worth : ₹ 3000

- Part of Innovision, STEELLUN's Metallomania seamlessly combined metals and markets, offering a hands-on trading experience based on real-time prices.

4. Forging Knowledge:



Genesys and Steellun
in collaboration with
FindMyTest

FORGING KNOWLEDGE
The Ultimate
Metallurgy and Biotechnology Quiz

Date: 16th Nov
Platform: Online

Prizes Worth 75K+

JOIN OUR WHATSAPP GROUP


For Metallurgy


For Biotechnology

[@genesys_nitr](https://www.instagram.com/genesys_nitr) [@steellun.nitr](https://www.instagram.com/steellun.nitr)

Date of Event : November 16, 2023
Mode of Event : Online
No. of Participants : 224
Prize Worth : ₹ 75000

- An online event in collaboration with Genesys and FindMyTest, targeting GATE aspirants in metallurgy and biotech.
- It is quiz event for metallurgy and biotech student preparing for GATE.

National Institute of Technology Tiruchirappalli, Materials Advantage Student Chapter



Dr. KARTHIK.V



ANAGH DUTTA



SIDDHANT MUNDHE

Hosts guest lecture series were delivered by renowned alumni to enlighten students on the current and future scope in research and other fields. The lecture covered challenges in students' academic journeys, addressing aspects such as time and stress management, fostering corrective strategies.

Our organization orchestrated distinguished guest lectures, showcasing eminent experts specializing in material science. These lectures delve into topics such as batteries elucidating their correlation with material science, captivating an audience of 50 participants.

A perfect amalgamation of art and science, METARTISTRY allowed the participants to take on a challenging quest to exhibit an artistic outlook at metallurgical concepts.

**Sri Manakula Vinayagar Engineering College (SMVEC), Puducherry.
Materials Advantage Student Chapter**



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Mr. A. B. Sainnath
Secretary,
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The Department of Mechanical Engineering and SMVEC ASM Material Advantage Student Chapter Jointly Organized **One Day 'Workshop on Advanced Composite Materials and Opportunities in India'** on 26th August 2023 at Conference Hall. The workshop was inaugurated by the Chief Guest Mr. R. Veeramanikandan, Executive Director, Mannschaft Engineering Solution Private Limited, Puducherry. He Explained the various manufacturing processes involved in manufacturing of polymer composites and displayed various Fibers available in the market. He demonstrated the Hand Lay-Up and VARTM techniques for the preparation of laminates. Detailed design, material selection, mixing ratio, mechanical testing are discussed.



The Material Advantage student chapter of SMVEC has organized **One Day Workshop on IPR & Design Patent 14-10-2023**. Mr. P. Jayakumar, JS ARA TECH, Design Project Consultant, Chaired the Session and gave his remarks to illustrate the importance of IP, patentability assessment and the efforts being carried out by IPO for registration of IPRs.



The Department of Mechanical Engineering and SMVEC ASM Material Advantage Student Chapter Jointly Organized Guest Lecture on 'Recent Technology Developments of Powder Metallurgy and Applications' on 04th November 2023 at Conference Hall. The program was inaugurated by the Chief Guest Mr.D.Velmourougane, Director Operation Seja Sinters Private Limited, Puducherry.

He discussed about the basic steps involved in powder metallurgy process. He also Explained the various manufacturing processes involved in metal components. He demonstrated the development of gear components from SS301 powder and future demands. Around 235 students participated and benefitted through this guest lecture.



ASM Material Advantage Student members participated and attend 4th Conference & Expo, Heat treatment & Surface Engineering September 28-30, 2023 Chennai India. Our students participated in poster presentation in the tile 'Effect of nanoparticles on wear resistance of SS304 metal matrix nanocomposites' and received best poster award.

Sri Siva Subramaniya Nadar College of Engineering, Materials Advantage Student Chapter



Dr.D.Ananthapadmanaban,
Associate Professor
ananthapadmanaband@ssn.edu.in



Venkatanathan, Final year Mechanical
Engineering-1st from left
Student Chaiman



Mohammed Akmal Baig –Final year
Mechanical Engineering-1st from right
Student Secretary



Dr.D.Ananthapadmanaban, Faculty Advisor of MA chapter of Sri Siva Subramaniya Nadar College of Engineering was invited to the International Conference on Heat treatment and surface Engineering during 28th-30th September 2023 as an organizer. One of our students Mr Venkatanathan was already involved in the Conference and his report is given separately. During the inaugural ceremony, Venkatanathan was given a special mention.

SSVPSs B.S.Deore, College of Engineering, Dhule Materials Advantage Student Chapter



Prof. Dr. Sanjeev Suryawanshi.
Professor and Head



Mr. Saurav Pawar
BE (Mechanical)



Mr. Saurabh Patil
BE (Mechanical)



Arth 2k23 (22 May 2023)

The project competition, "Innovative Use of Materials in Project Development," was held under the banner of ARTH 2k23. Event focused on the innovative use of materials in project development. The competition was successfully completed with overall funding of USD 1,221 received for the event. A total of 180+ participants took part in the competition. Dr. Pradeepji Goyal, President of ASM International was the chief guest of the event. Judging was based on presentation skills, self-contribution, poster/model quality, and topic relevance (innovative use of materials in the project). Winners were awarded with cash prizes, trophies, and certificates.



2nd ARTH 2K23 (23 Nov 2023)

The consecutive event of ARTH 2K23 named 2nd ARTH 2k23 was held successfully by Material Advantage Chapter (MAC) SSVPS Dhule for the exposure of ongoing development in projects developed by colleagues around from 12th Science, Diploma and Engineering streams. The 2nd ARTH 2k23 has the theme of 'Innovative Project Ideas'. More than 20 groups with 40 plus students participated successfully in this event. The event had two categories such as poster and model presentation for different educational groups. During the valedictory ceremony the winners received cash prizes, trophies and certificates for their contributions.

VIT University, Bhopal, Materials Advantage Student Chapter



Dr. Balaguru S
Dean SMEC



Lavanya Basera
B.Tech Robotics & AI



Mahin Nandipa
B.Tech Aerospace1



Bridge-A-thon

Bridge-A-thon provided a platform for teams of 4- 5 members to design and construct functional bridges using ice cream sticks and glue.

Participants exhibited remarkable teamwork, ingenuity, and problem-solving skills throughout the event. The event was held on May 11, 2023.



2nd International Conference on Sustainable Technologies and Advances on Automation, Aerospace and Robotics (STAAAR 2023) 15-16, Dec 2023.

The School of Mechanical Engineering at VIT Bhopal organized the conference. Researchers from various organisations presented their findings in the Conference.

Prof. Dr. Manoj Gupta from National University of Singapore graced the inaugural function as the Chief Guest. Prof. Dr. Ashish Vashishtha, Aerospace Engineering, South-East Technological University, Carlow, Ireland was the Guest of Honour



The Materials Innovators Challenge showcased the exceptional creativity and problem-solving abilities of our college students. Teams present engaged in a 30- minute quiz based on modern advancements in material science and then were tasked with developing innovative solutions for the problem statement provided within the 1-hour duration. This event was held on Feb 22, 2024.



Material & Music Fusion Concert captivating audiences with its innovative blend of materials and music. The event showcased a diverse array of musical performances featuring unconventional instruments crafted from various materials, each highlighting the unique acoustic properties they possess. This event was held on Feb 23, 2024.

Technology updates

Challenges Present Battery Technologies:

Battery technologies face persistent challenges despite their increasing popularity in electric vehicles (EVs), hindering widespread acceptance. Issues like limited driving range, high maintenance costs, battery-related concerns, and inadequate charging infrastructure prevail, particularly in many Asian markets. Moreover, the initial high purchase cost and the acceptance of EV technology are significant concerns. Lithium-ion batteries, nearing physicochemical limits, present technical obstacles, with prolonged charging times discouraging consumers. A potential solution involves prioritizing LFP (Lithium Ferro Phosphate) batteries to tackle these challenges and drive EV adoption. LFP batteries offer a promising remedy to prevalent electric vehicle hurdles. With a longer lifespan, enhanced safety, and quicker charging capabilities compared to NMC (Nickel Manganese Cobalt) batteries, LFP addresses concerns regarding maintenance costs and extended charging times. Therefore, embracing LFP technology could facilitate the accessibility and widespread acceptance of electric vehicles, alleviating industry obstacles.

Despite these challenges, electric vehicles represent the future of transportation, and as long as there are ongoing technical advancements and innovations, the benefits of electric vehicles will only increase.

https://economictimes.indiatimes.com/industry/renewables/electric-vehicle-batteries-advancements-challenges-and-the-path-to-sustainability/articleshow/106022512.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst

Future of Lithium-ion Technology for E2Ws:



Electric two-wheelers (E2Ws) look promising, especially with the EMPS 2024 scheme emphasizing E2Ws and considering lithium-ion batteries as the preferred powering option. Efforts are underway to address concerns such as limited charging infrastructure through various technologies, including advanced lithium-ion battery charging strategies and Battery Management Systems (BMS). Expectations are high for advancements in lithium-ion battery technology to address range limitations. Both domestic and international investments are increasing in manufacturing, research, and development of lithium-ion battery technology, aiming to reduce costs and enhance performance. Consequently, it is safe to assume that lithium-ion technology will continue its upward trajectory over the long term.

In summary, the future outlook for electric two-wheeler lithium-ion battery technology appears positive. Manufacturers are taking this growing market seriously, evident from the rising E2W market share, which reached 13% by mid-2023. Industry forecasts suggest that out of the 20

proposed new two-wheelers in 2024, 75% or 15 models will be electric. Consumers are also recognizing the long-term benefits of electric two-wheelers, supported by advancements in energy storage capabilities and the development of nationwide fast-charging infrastructure networks. With support from central and state governments, as well as environmentalists, sustainable and efficient lithium-ion batteries are expected to thrive in the future.

<https://www.battrixx.com/riding-into-the-future-a-close-look-at-lithium-ion-battery-technology-for-two-wheelers-in-india.php#:~:text=1.-,Technological%20Advancements,riders%20as%20well%20as%20E2Ws.>

Hydrogen Fuel-cell Vehicle (HFCV):



A hydrogen fuel-cell vehicle (HFCV) utilizes the same type of electric motor as a battery-electric car to propel its wheels. However, instead of relying on a large and heavy battery, it is powered by a fuel-cell stack. In this stack, pure hydrogen (H_2) passes through a membrane where it combines with oxygen (O_2) from the air. This chemical reaction produces electricity, which in turn drives the wheels, along with water vapor as a byproduct. Functionally, a fuel-cell vehicle operates as a series hybrid, leading to its classification as a fuel-cell hybrid electric vehicle (FCHEV).

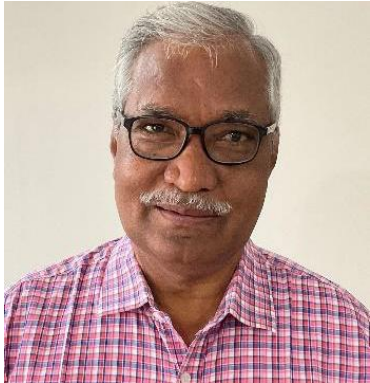
From a scientific perspective, hydrogen is not considered a fuel but rather an energy carrier. Despite this distinction, drivers of HFCVs refill their vehicles' carbon-fiber high-pressure tanks at "hydrogen fueling stations," similar in concept to traditional gas stations, with a comparable refueling time of around five minutes.

Although hydrogen is the most abundant element in the universe at the atomic level, it is never found in its pure state but is always combined with other elements. Its high reactivity makes it an effective energy carrier. The process of producing pure hydrogen for vehicles involves using substantial energy to "crack" compounds like natural gas (CH_4) into pure H_2 , with carbon dioxide (CO_2) produced as a byproduct. Currently, the majority of hydrogen production is derived from fossil fuels such as natural gas. However, when hydrogen is run through a fuel cell, it promptly releases the stored energy in the form of electricity upon combining with oxygen, with only water vapor (H_2O) emitted from the exhaust pipe.

<https://www.caranddriver.com/features/a41103863/hydrogen-cars-fcev/>

ASM Fellow Awardees - 2024

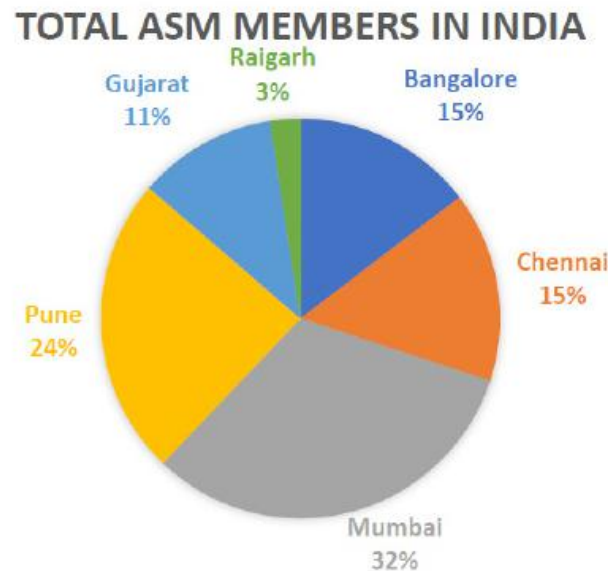
ASM India National Council on behalf of all ASM members in India and Indian Materials Fraternity congratulated the winners.

1	Prof. Srinivasa Rao Bakshi earned his B.E. and M.E. in Metallurgical Engineering from REC Rourkela and IISc Bangalore, respectively. After a stint as Scientific Officer 'C' at Bhabha Atomic Research Centre (BARC) from 2003-2005, he pursued his Ph.D. at Florida International University in 2009. Joining IIT Madras in 2010 as an Assistant Professor, he was promoted to Professor in 2021. Prof. Bakshi's research spans powder metallurgy, surface engineering, and thermal spray technologies, notably in mechanical alloying, spark plasma sintering, and materials joining. He co-established the SMART Lab at IIT Madras, focusing on thermal spray applications. With over 7450 citations and an h-index of 44, he's recognized in the Top 2% researchers list in Materials by Stanford University (2022). Awards include IIT Madras Institute Research and Development Awards in 2016 and 2022. Actively engaged in professional societies like the Indian Institute of Metals and ASM International, he served as Secretary of the ASM International Chennai Chapter and is currently its Vice-chairman. Prof. Bakshi has organized workshops, conferences, and delivered numerous invited talks.	 Prof. Srinivasa Rao Bakshi's Professor Dept. of Metallurgical and Materials Engineering, IIT Madras
2	Expertise: Corrosion Science and Engineering, PhD (1987), Department of Metallurgy, IISc. Institute Chair Professor (2010-2023), IIT Bombay Contributions: PhD: 35, MTech: 125, Publications: Papers: 250, Books: 02 Editor, Corrosion Science Journal, A Select few Recognitions:FNACE, FIIM, FECSI, FASM, MASCAT award (ECSI-2003), Meritorious Contribution Award (NIGIS-2009); Prof. S.P. Sukhatmate Excellence in Teaching Award & Prof. HH Mathur Award for Excellence in Applied Sciences (IIT Bombay & 2016 & 2023), VASVIK award for industrial research (2014)	 Prof. V S Raja Emeritus Fellow, Department of Metallurgical Engg & Materials Science, IIT Bombay
3	Dheepa has an M.Sc (Engg.) and a PhD, in Metallurgical Engineering, from the Indian Institute of Science, Bangalore. Dheepa has more than 24 years of total work experience in the area of gas turbine materials, leading the research and development of high temperature materials and manufacturing technologies for gas turbines, for General Electric and Pratt & Whitney. She is the inventor of several new technologies having over 35 patents, and has developed more than 50 technologies / process applications that are now running in several gas turbines and steam turbines. She is a pioneer in the area of Additive manufacturing and has developed several applications for metal laser additive manufacturing and thermal spray coatings as a unique technology enabler for gas turbine component life extension. She is a Distinguished alumnus of the Indian Institute of Science.	 Dr. Dheepa Srinivasan Dean, Research & Innovation, Ramaiah University of Applied Sciences, Bangalore

ASM members in India

1.0 Individual Members

Indian ASM membership is one of the 2nd largest memberships after United states of American. More than 700 members which includes: individual, sustaining and student members are part of ASM family in India. The membership is divided into several chapters such as Bangalore, Chennai, Gujarat, India (Mumbai) and Pune Chapters. The distribution of membership across chapters is shown below.



2.0 Chapter Sustaining Members:

Chapter sustaining members play an important role in ASM activities. Being a sustaining member, they have special privileges in the types of activities being conducted such as Networking with local vendors, manufacturers, and academics, listings on ASM Chapter letterhead, websites, and meeting announcements, participation at technical presentations at ASM Chapter meetings, Student Outreach Sponsorship, Advertising in Chapter Buyers Guide/Yearbook, Local awards/recognition, Participation in Chapter Sustaining Member events. ASM India is proud to have more than 94 sustaining members.

3.0 Material Advantage Student Chapters

College students in materials science and engineering can join Material Advantage, a joint program between four professional societies serving the materials community – ASM International, the Association for Iron & Steel Technology (AIST), the American Ceramic Society (ACerS), and The Minerals, Metals & Materials Society (TMS). Students receive membership in all four societies as well as special conference rates, magazine subscriptions, travel grants, publications discounts, and more. There are more than 20 student Material Advantage chapters in India
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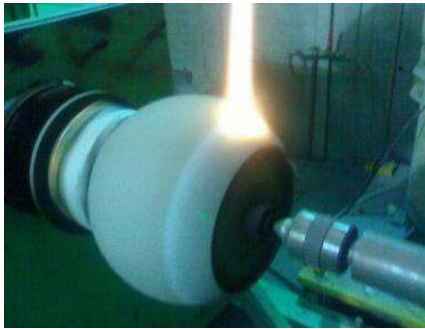
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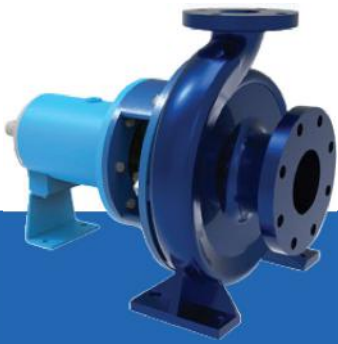
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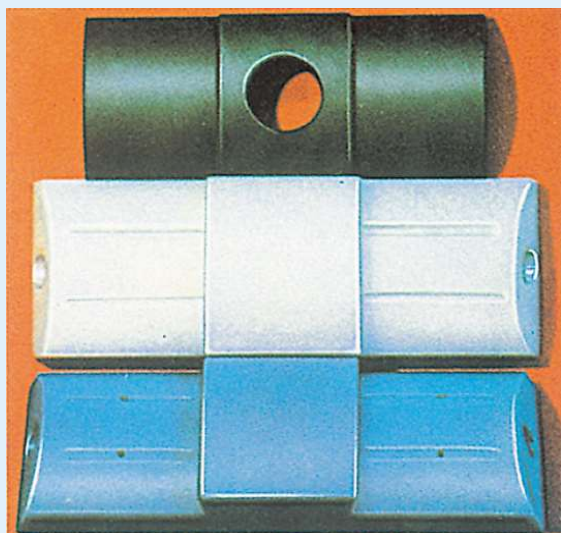
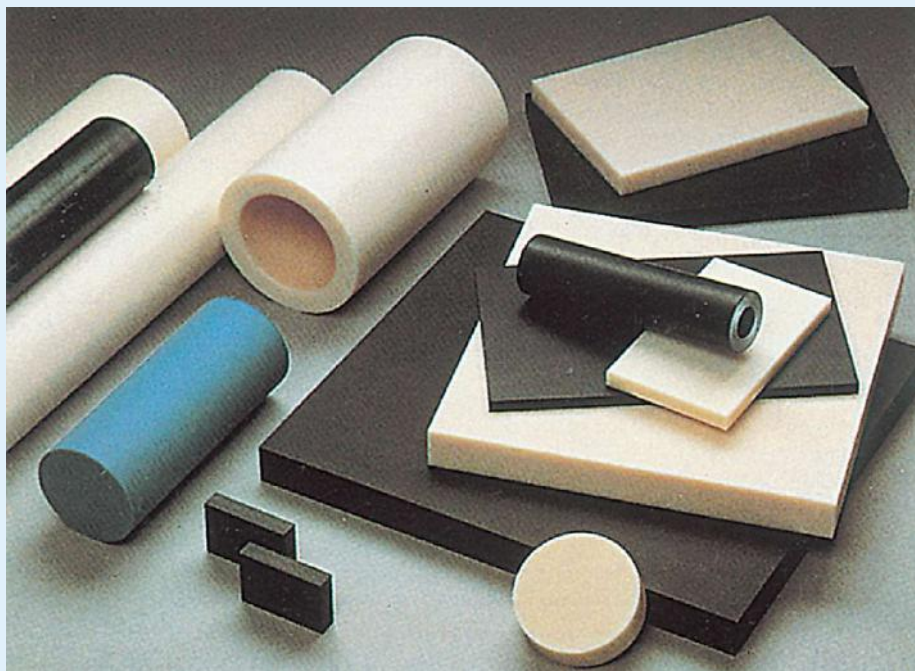
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