Ferrous-Metal Matrix Composites: Status, Scope and Challenges
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Graphical Abstract

Abstract
The present paper is an effort to culminate the status, scopes and challenges in the development of ferrous metal matrix composites (FMMCs). The FMMCs are old but less in use than the non-ferrous metal matrix composites (NFMMCs), as far as literature and actual applications are concerned. Therefore, this stimulates the exploration of the reasons behind the scarcity of literature and field applications of the FMMCs, which must be investigated scientifically. The powder metallurgy route is the most used process for fabricating iron and steel based FMMCs by reinforcing particulates. At the same time, the in-situ method has been used for the fabrication and cast iron-based FMMCs. The main characteristics being considered during the designing and fabrication of FMMCs are wear resistance and improved specific mechanical properties. To fabricate cheaper and eco-friendly
FMMCs, traditionally used costly reinforcements such as SiC, WC, TiC, SiO$_2$, TiO$_2$, TiB$_2$ are required to be replaced by inexpensive industrial wastes like red-mud, fly-ashes and grinding swarf. The data extracted from the web of science exhibited that the FMMCs have been researched less than the NFMMCs. The increasing number of research papers on FMMCs indicates a bright future. FMMCs are going to be a favourite topic among researchers and manufacturers. Higher strengths, wear resistance, dimensional stability at elevated temperatures, and, most importantly, the lower cost will put forward the FMMCs as a stiff competitor of NFMMCs. In developing and mass production of FMMCs for field applications, challenges like oxidation and higher weight still require special research efforts.

**Keywords:** MMCs, Ferrous MMCs, Stir-casting, Powder metallurgy, Mechanical properties, Tribological.
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# List of Abbreviations

| Sr. No. | Symbol/Abbreviation | Meaning                                      |
|---------|---------------------|----------------------------------------------|
| 1       | CFA                 | Coal-Fly Ash                                |
| 2       | MMC                 | Metal Matrix Composite                      |
| 3       | FMMC                | Ferrous Metal Matrix Composite              |
| 4       | NFMMC               | Non-Ferrous Metal Matrix Composite          |
| 5       | IMMC                | Iron Metal Matrix Composite                 |
| 6       | RSM                 | Response Surface Methodology                |
| 8       | P/M                 | Powder Metallurgy                           |
| 10      | ROM                 | Rule of Mixtures                            |
| 11      | RO                  | Ramberg Osgood                              |
| 12      | Wt. %               | Weight Percentage                           |
| 13      | Vol. %              | Volume Percentage                           |
| 14      | Hv                  | Vickers’s Microhardness                     |
| 17      | $\rho_c$           | Density of Composite                        |
| 24      | $\sigma$           | Stress                                      |
| 25      | $E$                 | Young’s Modulus                             |
| 28      | $\sigma_y$         | Yield Strength                              |
1. Introduction

The importance of materials in our life can be presumed from the fact that the early phase of civilization was designated after the names of materials such as Stone Age, Bronze Age, Copper Age, and Iron Age. Nevertheless, the natural composite materials are an integral part of human life throughout the evolution of society [1]. The common examples of natural composite materials comprise woods, bones, stones etc. even the bodies of living beings themselves represent a type of natural composite. With the passage of time and consequent upon the immense growth in requirements of new and advanced facilities, various new materials have come up. The prominent fields like aerospace, automobile, health, sports, manufacturing etc. are in the focus of material scientists and engineers. These fields require the materials, which exhibit the having higher specific strength, hardness, wear resistance and dimensional stability at elevated temperatures. The metal matrix composites (MMCs) are proven to be capable of fulfilling the above requirements [2].

The MMCs are synthesized by combining two or more materials with distinct chemical, physical, and mechanical properties which are held together mechanically owing to the difference between their thermal expansions (CTE) coefficient. The soft metal or alloy serves as continuous part and called as matrix, whereas the hard and discrete material uniformly dispersed throughout the matrix is known as reinforcement. The large difference between the melting temperatures of matrix and reinforcement are among the primary requirements in syntheses of the MMCs [3]. MMCs inculcate metallic properties of matrix-like ductility and toughness with high strength and high modulus and hardness of the reinforcement, which strengthen the MMCs against shear and compressive loads along with high-temperature service capabilities. Higher strength to weight ratio is an exciting and specific industrial requirement and is challenging to obtain using a single material, even alloys. In a nutshell, the MMCs are bridging the requisite properties of the soft and tough matrix with hard and strong ceramics in a single material having high shear and compressive strength and the ability to withstand high temperatures [4]. Hence, the physical, chemical and mechanical properties obtained from MMCs are entirely distinct from their constituent materials i.e. matrix and reinforcement. The MMCs are generally known for their best properties such as modulus, hardness, strength, thermal stability, corrosion, wear resistance etc. Thus, the above properties make the basis for the difference between traditional alloys and advanced materials, i.e. MMCs [5]. Among the various MMCs, the non-ferrous matrix composites (NFMMCs) encompass the major fields of application. Further among the NFMMCs, the aluminum metal matrix composites (AMMCs) is the dominating class [6]. Whereas the ferrous metal matrix composites (FMMCs) catering few real applications as compared to the NFMMCs hence, the FMMCs lacked in research and development. However, the consistency of research in the field of FMMCs has established in few applications such as heavy road transport vehicles and railways. The synthesis of FMMCs requires intensive care to save them from oxidation and reaction with the reinforcements. Therefore, the solid-state process such as powder metallurgy (P/M) is the often-adopted route for the synthesis of particulate metal matrix
composites (PMMCs)[7]. In P/M the requirements of lower temperatures not only protect the ferrous materials from reaction with the environment and reinforcements but also contributes to protect the environment by saving the materials, energy, and post-machining.

Hence the P/M can be termed as green, environment-friendly, tecno-economic and sustainable manufacturing process. In attaining the prerequisite properties in the MMCs synthesized by P/M technique[8]. The fundamental and derived properties of feed stocks such as powders and particulates required to be studied for evaluating their suitability. The apparent density, tap density, particle size, particle size distribution, flow rates, Hausner’s ratio, Carr’s index and angle of repose are the significant indicators of suitability of feed stock for P/M processing. While cold compaction of the feed stock and subsequent sintering during P/M processing, their compressibility and densification become the culminating point in attaining the satisfactory properties in the MMCs [9]. The compacting load, lubrication regime and sintering strategies such as temperature, time and rate play an important role to regulate the microstructure of the MMCs. The higher difference between the thermal and physio-mechanical properties of the metal matrix and ceramic reinforcement materials enable to the beneficial microstructural and physio-mechanical evolution in the MMCs [10]. Among the many established ceramic reinforcements such as SiC, TiC, Al₂O₃ and WC which are inexpensive materials like red mud and coal-fly ash (CFA) have come up as a promising reinforcement to the metal matrices. Utilization of theses reinforcements not only reduces the cost of MMCs but also benefits the society by solving the environmental problem of solid waste management [11]. During the last two decades, MMCs have evolved as a new class of materials to cater to the challenging requirements of aerospace, aviation, automobiles, marine engineering, sports, bio-implants etc. The scope of the MMCs is beyond our imaginations and records as far as their area of applications is concerned. Sometimes, MMCs are also called advanced materials as far as their fabrication; characterizations, properties and area of utilizations are concerned [12]. The major aspects of MMCs are graphically shown in figure 1.
2 Types of Matrices and Reinforcements

In addition to the established metal matrices and reinforcements, many new and inexpencible materials are also being tried to synthesise MMCs. The metal matrices often undertaken in the research of MMCs include aluminum, magnesium, copper, iron, titanium, steel, cast iron etc. [13]. So far, most of the MMCs developed belong to the popular aluminum matrix with different reinforcements such as oxides, carbides, borides, nitrides, and fly ash. Due to its low density and corrosion resistance, aluminum has been the focal material used in the aerospace and automobile industry. Among the NFMMCs, aluminum-based MMCs dominate almost all sectors, starting from road transport vehicles to satellite launch vehicles [14]. Like road and air transportation, the designers and the engineers are bound to reduce the amount of emission, which contributes to a considerable amount of pollution as CO$_2$ and other harmful residues. The weight of the vehicle is the primary concern. Its reduction directly contributes both to the reduction of emission and enhanced efficiency of the vehicle[15]. In addition to the non-ferrous metal matrix composites, the ferrous metal matrix composites are the future candidates for aviation and road transportation. The hypothesis of the dominance of aluminum matrix composites has been verified by the graphical representation of data obtained from the web of science [16]. However, it is beyond the reality that each research paper could be found in a period. But a significant amount of research papers has been considered to intend the direction of research in the field of ferrous matrix-based composites[17].
The research data found to be significant during the last two decades, i.e., 2000 to 2020. From the graphical representation in figure 2, it can be observed that the number of research papers for both NFMMCs and FMMCs has increased considerably. The number of aluminum matrix-based research papers is higher up to the year 2019 by 6 to 8 times compared to the ferrous matrix-based composites. But in the year 2020, a small decrease has been observed for aluminum-based composites. This data is a good indication for the ferrous matrix-based composite that the number of research papers is increasing every year. However, as compared to aluminum matrix composites, a healthy challenge is seen ahead of researchers who are keen to work in the field of ferrous matrix-based composites[18]. Hence, thorough, scientific, and efficient efforts must be initiated to find out the various heralds in developing ferrous metal matrix composites for a new field of applications. The problem starts from the beginning of the manufacturing processes irrespective of the type of process, i.e. solid state or liquid state. Usually, all metals prone to be highly reactive at elevated temperatures. Ferrous metals like iron and alloys like steel are prone to oxidation at temperatures considerably lower than their melting temperatures [19]. Various matrix and reinforcements materials often used for the fabrication of MMCs are exhibited in figure 3.
The reinforcements are the main game-changer in the MMCs system. The type, amount, size, and shape being reinforced play an important role in tailoring the properties of matrix material. Commercially, particulates are attractive reinforcement due to the lower production costs based on simple manufacturing processes [20]. The more specifically morphological and topographical-based categorization of reinforcements is deliberated in figure 4[21,22]. Coal-fly ash (CFA) reinforcements are being used abundantly in fabricating various engineering materials like bricks, cement and metal-matrix composites (MMCs). Specifically, low weight MMCs are being fabricated by reinforcing inexpensive CFA successfully to enhance their mechanical and tribological properties [23]. The use of CFA as reinforcement contains huge scope of fabrication of cheaper MMCs and solving the problem of solid waste management.

Figure 3 Reinforcement types: (a) categorization and (b) morphology.
Such materials are being used extensively in aerospace, automobile, aviation, marine, sports and power industries. CFA mostly contains spherical particles of SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$ and TiO$_2$ with varying particle size range from 1 μm to 100 μm. The CFA is a mixture of dense and hollow particles which are generally termed as precipitator and cenosphere respectively [24]. Precipitator particle reinforcement is commonly used for inducing favorable mechanical properties such as hardness, stiffness, wear resistance etc. in relatively softer metal matrices. As per ASTM C618, Indian CFA falls in the F-category which contains at least 70 % SiO$_2$ and Al$_2$O$_3$. Contribution of SiO$_2$ particles in F CFA is more than 50%, hence used to strengthen the MMCs through excellent load-bearing mechanisms [25]. There is an abundant amount of coal fly ashes available, particularly in the year of 2018-19 about 195 thermal power plant produced 217.04 Mt of CFA. Hence, there is immense scope of utilization of CFA as reinforcement to the metal matrices to fabricate cheaper MMCs [26].

3 Fabrication Techniques for MMCs

With the advent and development of materials, there has been a requirement of compatible manufacturing processes. The established manufacturing processes for metals are used for MMCs with suitable alterations. The techniques often used to synthesise MMCs can principally be classified as the solid-state and the liquid state. There are many subclasses and hybrid processes came into use to solve the problems of MMCs fabrication. Specifically in the manufacturing of MMCs many new processes also came up. Systematic classification of the various process involved in the fabrication of MMCs is graphically exhibited in figure 5[21].

3.1 Stir-Casting

Casting had been a traditional route of shaping materials since prehistoric times. The same casting technique with little modifications is used for the fabrication of MMCs. The ease of operation and cheapness established the stir-casting as frequently used process for developmental and industrial purposes. Due to lower melting point aluminum based MMCs has been the major area of application
of stir-casting route. But, due to the low density and wettability of ceramic reinforcement particles, their uniform distribution in the metal matrix becomes uncontrollable using stir-casting method [27]. The reinforcement particles tend to sink or float depending on the density from the matrix, resulting in the heterogeneous distribution of reinforcement which results in undesirable physio-mechanical properties of the MMCs. Due to these difficulties, the stir-casting process is not suitable for materials where the difference in densities of matrix and reinforcements is very high. However, the stir casting process is ideal for aluminum matrix composites, where the density of matrix and reinforcements are almost same [28]. The ferrous metals require more energy to melt and form to oxidise and pollute environment. Generally, the stir-casting route is not much suitable for producing FMMCs. However, melting route is used to synthesise FMMCs by in-situ formation of reinforcements [29]. The schematic representation of the stir casting process is shown in figure 6[30].

![Figure 5 Stir-casting process set-up.](image)

### 3.2 Powder Metallurgy

Powder metallurgy (P/M) is another vital technique used for synthesis of more dense, accurate and robust MMC components. Mechanical alloying is preferred for the synthesisization of materials (powders) to tailor the prerequisite physical properties of starting powder materials. In this process, the powder particles undergo a series of welding, fracturing, and rewelding processes under the high energy of ball milling. Ball milling is generally used mechanical alloying technique prior to processing the powders through P/M [31]. To densify the powder mixture, either cold compaction is followed by sintering or compaction or sintering is done simultaneously. In first case the sintering is carried out in an inert environment. During sintering, the diffusion among the matrix particles occurs when heated near their melting temperatures. During this course, the powders densify rapidly,
resulting in the reduction of porosity and surface area of the particles [9]. P/M induces significant properties in the MMCs like higher dislocation density and refined grain sizes, which improves the mechanical properties of the composites. In recent years, techno-economic and environmental concerns derived a significant growth in the demand for ferrous powder metallurgy (P/M) components considering their favorable specific mechanical properties. Consequently the P/M has grown as a vital manufacturing technique in the mass production of intricate, near-net-shape bulk parts from toilsome materials with prerequisite properties [32]. The details of various steps involved in the synthesis of MMCs using the P/M technique are explained graphically in figure 7[33].

![Figure 6 Schematic of powder metallurgy process.](image)

### 3.2.1 Prerequisites for Powder Metallurgy

The physio-mechanical properties of the starting materials such as powders and particulates influence the P/M process and results in the specific properties of the final product. Good flowability of the powders/particulates is the key requirement to compact the components with minimum defects both in green and sintered states. Further, the good flow of powders/particulates contributes the timely delivery to the compaction die imparting reduced lead time [34]. The flowability, compressibility and densification characteristics of starting materials relied upon their morphology, particle size distribution, apparent density, tap density and surface properties. Hausner ratio and angle of repose are often adopted for evaluating the flowability of the powder like materials. Whereas the compressibility of the powers is exhibited by Carr’s index and linear compaction equations [35].

### 4 Literature Survey

The category of FMMCs comprises a broad area as far as matrix materials are concerned. Steel, cast iron and pure iron matrixes are found to be the frequent used for fabricating the FMMCs. The significant literature pertaining to the above types is detailed in the following sections.
4.1 Steel Matrix Composite

Traditionally alloys were successfully catered to a wide range of requirements of at that time as compared to their pure metals. This property tailoring of pure metals had been carried out by microstructural modifications imparted through alloying and heat treatment [36]. In recent times the MMCs have become the culminating point of research owing to the infinite scope of property tailoring to suit the ever-challenging field of applications. The most enchanting attribute of MMCs is their ability to the trade-off between density, strength and wear behavior which was the limiting point in case of alloys [37]. In comparison to the alloys, the MMCs possess better frictional properties like the moderate coefficient of friction, negligible lubrication etc. Wear resistance is one of the attractive attributes resulting in enhanced tribological properties of MMCs [38].

Steel is well-known and prominent material that evolved with time and used in almost every aspect of life on earth and space. The steel matrices reinforced by ceramic are significant materials owing to the ease of synthesization and combination of mechanical tribological properties [39]. The growth in the manufacturing industry has stimulated the exponential rise in environmental challenges. Therefore, similar to other efforts initiated towards saving environment degradation, the optimized use of materials or modification of existing materials needs the hour. The billions of tons of steel are being used worldwide can be reduced significantly by tailoring them as metal matrix composites. The principal use of steel in air and ground transportation can face various types of loads and wear challenges. The steel-based composites are successfully being developed to cater for its most lacking property of lower specific strength and wear resistance [40]. Kuforiji and Nganbe [41] synthesized, characterized and assessed the wear of metal matrix composite of SS 316L-Al₂O₃ having 50 wt.% of each. The wear resistance of the composite has been found 7.2 times higher than the SS 316L. It has been concluded that using mechanical alloying and improved compacting and sintering, the steel composites reinforced with higher alumina amounts can be synthesized with high wear resistance. Ziejewska et al. [42] first time investigated the influence of size (0.7μm and 5.0μm) and volume (5 vol % and 20 vol %) of WC particles in sintered low alloy steel metal matrix composite on its resistance to abrasion of a friction pair. Corrosion resistance was also investigated in a 3.5% NaCl solution. It has been reported that both volume fraction and the particle size of WC reinforcement have a significant effect on the sintering process of low alloy steel MMC. It has been concluded that with increased reinforcement volume and decreased particle size resulted significant enhancement in the density. This was happened due to large shrinkage that occurred during sintering. The reduced particle size has also exhibited an improved surface finish and coherence with the matrix. With 5% vol reinforcement of WC a significant reduction in wear was found during the ball-on disc wear test. The above amount of reinforcement has also resulted in better corrosion resistance than the sintered matrix material.

Sahoo et al. [36] studied the influence of titanium diboride reinforced stainless steel AISI 304 MMC. The composite synthesized by the powder metallurgy technique was investigated for the effect
of sintering parameters on the MMC densification. The hardness and deformation of the MMC were also evaluated using microhardness and nanoindentation techniques. It has been reported that a maximum of 92% densification was achieved at 2% titanium diboride at a sintering temperature of 1100°C. Whereas the uniform distribution of 4 vol% of diboride and sintered at 1100°C resulted in significant enhancement of hardness, elastic modulus, and strength of the MMC. Fallahdoost et al. [39] investigated tribological behavior of the Astaloy 85Mo steel composite synthesized by reinforcing alumina nanoparticulate through powder metallurgy (P/M) technique. The effects of different wt.% of reinforcement have been explored by dry sliding wear at room temperature. It has been reported that despite resulting in the reduction in mechanical properties, the porosity of the composite enhanced the tribological properties. Oxidation, adhesive, and abrasive mode of wear have been reported to be followed on the increased load. The optimum wear resistance has been found at 3 wt.% alumina nanoparticles with a porosity of 15.38% and hardness of 105.4 HV5. Velasco et al.[43] evaluated the wear behavior of austenite stainless steel 316L reinforced with TiAl MMC synthesized by the P/M technique. The wear resistance of MMCs was found to be enhanced with an increased amount of TiAl at a sintering temperature of 1250°C. At the same time, the coefficient of friction was least affected by the sintering temperature. The transformation of wear debris from austenite to martensite has been reported. Velasco et al.[44] studied the mechanical and corrosion characteristics of AISI 316 L steel reinforced Al2O3, Y2O3. The B2Cr and BN were added as sintering enhancers for reactive sintering of the composites during synthesis through P/M technique. The composites got significant densification due to the presence of B2Cr and BN which enhanced the reactive sinterability. The Y2O3 reinforcements reported to be better compared to the Al2O3 reinforcements. The strength and ductility of the composites found to be inferior to the matrix material. However, significant enhancements in the hardness have been reported as a function on increased amounts of reinforcements. Further the corrosion resistance of the composites found to be better than the matrix. Sahoo et al. [45] presented the mechanical properties and wear behaviors of MMC fabricated by the hot-pressed method using stainless steel as a matrix and TiB2 as reinforcement. The contributions of different strengthening mechanisms in improving the mechanical properties of MMCs were quantified. The Taylor strengthening has been concluded as dominating strengthening mechanism active in the microstructure of the MMC. Considerable enhancement in the wear resistance has also been reported on increased TiB2 reinforcements.

Xiao et al. [46] presented the mechanical and microstructural properties of high-speed steel (H13) composite by reinforcing W-Mo-V HSS synthesized through laser metal deposition. At 40% of W-Mo-V HSS the carbide particles were traced near the grain boundaries of H13 matrix. As a result of the further increment of reinforcement, the carbides resulted in a continuous network. Improvement in the microhardness from 541 to 799 HV was reported with increased content of W-Mo-V HSS resulting in significant improvement of wear behavior. Patankar and Tan [47] synthesized stainless steel (316L)-SiC composite using P/M technique. The main finding reported is that during the
processing of the SS316L-SiC composite, Fe-SiC phase was found at 1100°C because of reactive sintering. Further, the amount of Fe-SiC phase was increased with increasing the temperature to the melting point. **Pagounis and Lindroos** [48] synthesized stainless steels and tool steels- Al₂O₃, TiC, Cr₃C₂ and TiN composite using hot-isostatic pressing (HIP). It has been reported that the inclusion of a low volume fraction of ceramic particulate reinforcements significantly increases the wear resistance of the steel matrices without deteriorating the corrosion properties. On the other hand, reductions in the tensile strength, ductility and toughness were observed. **Akhtar et al.** [49] observed the different mechanisms of evolution of reinforcements in the stainless-steel matrix-TiB₂ and TiC composite during synthesis by powder metallurgy. TiB₂ grew in hexagonal prismatic or rectangular shape whereas TiC in a spherical shape. The reciprocating sliding wear test of the composite reported the decreased wear loss on increased reinforcement amount. The polishing wear followed by micropolishing wear mechanisms were found in the case of composites containing high volume fraction of the reinforcements. Whereas the composites containing low volume fraction of the reinforcements micropolishing and grooving were the dominant wear mechanisms. **Wang et al.** [50] reported the physio-mechanical properties of high-strength steel(35CrMo)-TiC composite synthesized through P/M and subsequent heat treatment. The heat-treated composite has shown excellent mechanical properties with a relative density of 99.7%, the hardness of 65 HRC, Transverse rupture strength of 1850 ± 20 MPa, respectively. The composite has been concluded as a suitable material for refractory molds cold work molds and some gaskets. **Kan et al.** [51] reported the mechanical and wear behavior of AISI 304 stainless steel- (Nb, Ti) composite synthesized through stir casting. It has been reported that the morphology of the reinforcing carbide phase significantly affects the bulk hardness and sliding wear performance of the composites. Hence, the prediction of sliding wear performance of ferrous metal matrix composites solely using bulk hardness is not useful.

**Ziejewska et al.** [52] first time investigated the influence of size (0.7 μm and 5.0 μm) and volume (5 vol % and 20 vol %) of WC particles in sintered low alloy steel metal matrix composite on its resistance to abrasion of a friction pair. Corrosion resistance was also investigated in a 3.5% NaCl solution. It has been reported that both volume fraction and the particle size of WC reinforcement have a significant effect on the sintering process of low alloy steel MMC. It has been concluded that with increased reinforcement volume and decreased particle size resulted significant enhancement in the density. This was happened due to large shrinkage that occurred during sintering. The reduced particle size has also exhibited an improved surface finish and coherence with the matrix. With 5% vol reinforcement of WC a significant reduction in wear was found during the ball-on disc wear test. The above amount of reinforcement has also resulted in better corrosion resistance than the sintered matrix material. **Parashivamurthy et al.** [38] review the research work done on steel-TiC composites. This review paper's focus was to elucidate the advantages and disadvantages of various techniques being utilized to synthesize the TiC-steel composites. The primary observation is the interphase bonding of the matrix and reinforcements of steel matrix composites, which play a
prominent role to enhance strength and wear resistance. **Louet al.** [53] studied the microstructure and mechanical properties of stellite 21, PM10V and HSS-WC hot isostatic pressed composite. It has been observed that the chemical composition of the matrix material has a significant influence on the stability of WC in the composite and interface reactions. PM10V composite was found better than the Stellite 21 composite as far as abrasive wear resistance is concerned. The main reason explained is the ductile matrix and the absence of any brittle interphases. **Srivatsan et al.** [54] explored the mechanical behaviour of tool steel-TiC composite synthesized by powder metallurgy. An improvement in yield and ultimate tensile strength due to increased TiC reinforcement was observed. The matrix-reinforcement interactions and dislocations resulted in work hardening, which further influenced the mechanical properties of the composite. The analysis of the tensile fracture of the composite sample revealed a brittle failure.

**Jbolton and Gant** [55] evaluated the toughness and hardness of AISI M3/2 high-speed steel-TiC and NbC composite synthesized using powder metallurgy. A minimal increase in fracture toughness has been seen at 5% TiC or 7.74% NbC reinforcement. Small softening has also been noticed in TiC reinforced composites due to the formation of MC carbide in the structure. The hardness of the composites has been achieved because of the formation of dislocations during heat treatment of NbC reinforced composite. Bending strength was reported to be reduced with the addition of all three reinforcements. **Das et al.** [56] compiled a review on the various synthesis routes being adopted to reinforce the TiC to the ferrous matrices. In addition to the powder metallurgy route, an alternate techno-economical process for synthesizing Fe-TiC composites is also being explored. In this regard, many kinds of research have studied various other synthesis routes such as typical casting, in-situ and carbothermic reduction to enhance the wear resistance of the Fe-TiC composites. It has been observed that the inclusion of TiC to the Fe improved the wear resistance of the composite. Further, the wear resistance has been enhanced significantly on reduced particle size and increased volume of TiC. It has been summarized that the processes like laser surface melting, plasma spray synthesis, ion beam radiation etc., are also being utilized to produce the submicron size of TiC. **Wu et al.** [57] carried out laser melting deposition of SS 316L-SiC MMC. The phases evolved in the MMCs were $\gamma$-(FeCrNi) at 4 wt.% SiC, $\gamma$-(FeCrNi) +$\alpha$-(FeCrNi) +SiC at the 8, 12 and 16 wt.%. Further, iron silicides also appeared at 16 wt.% SiC dispersed MMC. The $\alpha$-(FeCrNi) phase existed due to the tensile stress produced by the difference of coefficient of thermal expansion between SiC ceramic reinforcement and the $\gamma$-(FeCrNi) matrix. The formation of the third phases resulted in enhanced hardness of the composite from 362 HV to 974 HV. The composite exhibited dense and fine-grained matrix due to the presence of SiC inclusions. But microcracks have also been observed at 16 wt.% of SiC reinforcements. Better corrosion resistance of the composite has been reported at 4 and 8 wt.% of reinforcement compared to the 16 wt.%. **Verma et al.** [58] presented the study of steel chips-Yttria ball milling followed by powder metallurgy. It has been concluded that the steel scrap could be utilized as feedstock for powder metallurgy technique after ball milling for 5 hours. The ball to
powder ratio (BPR) found to have significant effects on the yield of powders, i.e., BPR 12:1, yielded 94.29%, whereas yield reduced to 86.945 at BPR 6:1. The microhardness of the power increased from 104.2 VHN to 140.8 VHN as a function of 1 wt.% of yttria. It has also been reported that despite the problems /limitations of ball milling to produce fair and regular powder particles, a significant future scope is contained in this field of research.

Yao et al. [59] synthesized stainless steel 304 powder and fibers composite using powder metallurgy route. The compression process of the P/M material without nitriding includes a linear-elastic stage, plastic deformation stage, and densification stage. Uniaxial compressive properties of the P/M material significantly affected by the fiber content, compaction pressure, and high temperature nitriding heat treatment. Lohet al. [60] used powder injection molding for synthesis of SS 316L-TiC composite. The precision of mixing of matrix and reinforcement found to have significant influences on the properties of composites. TiC inclusion enhanced the microhardness and density of the composites. Further, with the increased sintering temperature and heating rate, microhardness along with the density of the MMCs increased. At 1350℃ with a heating rate of 108℃/min and holding temperature of 60 min reported in maximum density in the order of 97.81 %.

4.2 Cast Iron Matrix Composite

Although the cast irons are considered a natural metal matrix composite as it contains ferrite matrix reinforced by graphite in the microstructure developed during cast iron production. The amount and morphology of reinforcement to the matrix are governed by cooling in the presence of Si and C [16,61]. Jayaprakash et al. [62] carried out wear resistance experimentation of nodular cast iron substrate on Pin-on-Disc tribometer at elevated temperatures and analyzed the data using Grey relational analysis (GRA). Sliding speed, load and temperatures were considered as input parameters wherein the load was reported as the significant parameter followed by sliding speed and temperature. The experiments have confirmed the responses of the optimized tribological behavior attained by GRA. Avcı et al. [63] presented the result of mechanical properties such as flexural strength of grey cast iron reinforced by steel plates. Further, the effect of normalization temperatures on the flexural strength of the composite has also been explored. It has been concluded that with enhanced vol. % of reinforcements and normalization temperature resulted in improved flexural strength of the grey cast iron matrix. Qiu et al. [64] reinforced high chromium cast iron matrix with zirconia-toughened alumina using rapid-flow mixing followed by high-pressure compositing (FM-PC) technique. The uniform dispersion of reinforcement in the matrix resulted in a clear and strong interface between them. The composite exhibited better wear resistance than the matrix. The wear mechanisms were reported to be changed with increasing the impact energies. Zhong et al.[65] iron-vanadium carbide (V8C7) MMCs were fabricated through in-situ followed by infiltration. The vanadium particles of 2-12 μm size were observed uniformly distributed in the grey cast iron matrix. After the decreased wear resistance on an increased amount of reinforcement, the composite exhibited 21.2 times higher wear
resistance at 20 N loads compared to the grey cast iron at 24% reinforcement. The wear mechanisms of the composite were grooves followed by broken carbide particles and re-embodiment of wear debris. Cui et al. [66] deposited coating of grey cast - TiC composite synthesized by laser cladding Grey cast iron-TiC. The TiC was synthesized in-situ from Ti and C during laser cladding. Different morphological pieces of evidence of TiC have been found in well-dispersed reinforcement in the matrix. A sufficient amount of improvements in hardness resulted in significant wear resistance of the composite coating as a function of TiC reinforcement. Kambakas and Tsakiropoulos [67] developed Cast iron-WC composite through sand casting. Uniform dispersion of WC has been found in the functional areas of the composite casting. Primary and secondary carbides of Fe, Cr, W and Co were formed in the vicinity of the WC particles. The wear characteristics of the WC reinforced composites were found better compared to their matrix material. Janicki [68]developed cast iron-TiC composite layer by surface laser alloying. The increased amounts of reinforcements, the wear rates exhibited reducing trends. This happened due to the low mean free path among TiC particles, resulting in reduced contact between the soft matrix material and counter material. Enhanced amounts of reinforcement and load resulted in a reduced coefficient of friction. The detachment of the TiC particle from the matrix during wear tests was due to the brittleness of TiC particles and their effect on the matrix in their vicinity. Niu et al. [69] fabricated Cast iron-WC composite through in-situ centrifugal casting. The WC was formed in the matrix using a W wire without the growth of graphite flanks. Various phases of iron carbide, α-Fe, WC and M6C have been detected by X-ray diffraction. A 3 mm thick iron-WC composite coating was found to have adhered to the cast iron substrate metallurgically. The WC reinforced composite samples shown lower plastic deformation and higher scratch resistance. Li et al. [70] synthesized high chromium cast iron-WC composite by liquid phase sintering. It was reported that the ferrite was the main matrix phase in the microstructure of the composite. The uniform distribution of WC particles enhanced the wear resistance of the composite. Minimal dissolution of WC particles has been observed at the corners. No degradation in the initial properties of the WC has been reported.

4.3 Iron Matrix Composite

Iron has been a vital material in physical metallurgy as its alloying with different elements gave well-established material such as steels and superalloys. Recently, iron-based metal matrix composites have come up with improved physical, mechanical and tribological properties and are successfully being used in many fields such as automobiles, aviation, sports and rail transport etc. [71]. In this era of fast growth, research is aimed to explore alternate means to replace traditional materials. Metal matrix composites contain immense potential due to their ability to inculcate various properties that cannot be obtained using conventional alloys.

Abdollahi et al. [72] carried out the optimization of powder metallurgy parts synthesized by iron and recycled grey cast iron powder. The effect of cast iron powder percentage, compaction
pressure, sintering temperature and time were investigated on the density, transverse rupture strength and hardness of the sintered samples using Response surface methodology (RSM). Main effects and interactions were found using analysis of variance (ANOVA) and regression analysis. It was concluded that iron-jet-milled grey cast iron is very economical for producing powder metallurgy parts with various properties. The mathematical model was found in the error range of 1 to 8% during confirmation tests. Xu et al. [73] investigated the dwell time's effect during the sintering of ball-milled Fe-Mn-Si powder on its densification, microstructure, weight loss and tensile properties. The compacted powder mixture at 400 MPa pressure was sintered at 1200°C for 1, 2 and 3 hours, respectively. The sintering was effective when carried out for 1 hour, but it was not of much significance for 2 and 3 hours sintering. Bardhan et al. [74] analyzed the sintered iron powder component's density using response surface methodology (RSM). It has been confirmed that the density of P/M components is significantly affected by compacting pressure, sintering temperature and time. The experimental data has been used to obtain results using RSM second-order equation for predicting the density by central composite design. The fitting of experimental data has been found significant in the second order RSM by (ANOVA). Zhang et al. [75] presented the effect of graphite and sintering temperature on microstructural and mechanical properties of iron using the powder metallurgy route of synthesization. Three levels of graphite % and sintering temperatures were undertaken to complete the study. It has been reported that with an increase of graphite from 5%-20% and the sintering temperature from 600°C to 1100°C, the mechanical properties have enhanced significantly. The reasons behind these significant enhancements are the gradual change of microstructure from pearlite to ferrite along with the increased grain size of austenite. Whereas the hardness enhancement had taken place due to the lattice distortion with the formation Fe3C with an increasing amount of graphite and high sintering temperatures. Sharma et al.[76] characterized the iron-alumina metal matrix for structural and mechanical behaviors. Iron-alumina (5wt. %) composition synthesized by ball milling, subsequent compacting was done at 10, 12.5 and 15 KN respectively. Compacted specimens were annealed at 900, 1000 and 1100°C respectively for 1 hour. Synthesized specimens were characterized for density, hardness and microstructure wherein a dense phase microstructure was found in microscopic images containing a well-dispersed nano iron aluminate phase. A significant enhancement in density from 4.69 to 5.50 g/cm³ and hardness from 63 to 94 HRH has been reported after secondary treatment.

Gupta et al. [77] investigated the sintering and hardness behavior of Fe-Al2O3 nanocomposite. The pure iron and aluminum oxide powders were milled together and subsequent sample synthesization was done using the powder metallurgy route. Sintering of the samples was carried out in an inert atmosphere at temperatures 900-1100°C for 1 to 3 hours. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) have been used for microstructural and phase studies of the composite. SEM revealed a dense nanophase of iron-aluminate formed due to reactive sintering between the powders. Density has also been found to increase with an increase in sintering
temperature and time except at 900°C for 1 and 2 hours. The ductility of the samples was maintained up to 10 % Al₂O₃. Beyond this amount, the samples were found brittle due to an increased amount of iron-aluminate. Jian et al. [78] studied the effects of chromium on microstructure and two-body abrasive wear behavior of Fe₃B Cast alloy. The three wt.% of borides to the Fe found to be forming ferrite, pearlite and eutectic boride. However, the chromium addition enhanced the microhardness many folds with affecting the borides. Chromium of 2 wt. % was found limiting amount beyond which the toughness started reducing by touching 4.704 MPa√m. The wear resistance also got enhanced up to 3 wt. % of boride and then slightly decreased. Feldshtein and Dyachkova [79] presented the tribological, mechanical and microstructural changes resulted from oxide, boride and diamond nanocrystalline reinforcement added to the iron matrix. Compressive and tensile strength of the composites has been enhanced by 1.5 to 3 times; however, the best results were reported at 0.2-0.3 wt.% of ultrafine-grained diamonds, which were 0.5 wt.% of chromium borides and 0.2-0.5 wt.% of alumina or oxides. The coefficients of friction of MMCs reduced 2 to 3 times as compared to the base P/M material on the other hand the critical seizure pressure got improved by 2 to 5 times. The overall resistance of the MMCs toward wear has been enhanced by 2-4 times. Panakkal et al. [80] compacted iron by hot isostatic compaction. The effect of porosity on the elastic modulus and Poisson’s ratio have been studied systematically. A linear relationship has been reported between the elastic moduli and the ultrasonic velocities. The use of ultrasonic velocity as a predictor of elastic moduli is recommended for porous materials. Poquillon et al. [81] carried out uniaxial cold compaction of iron at 100-350 MPa. The density of the compacts found varied linearly with the compaction pressure and following different stages such as elastic, particle sliding and particle deformation. It has been concluded that in comparison to the spherical powder the spongy powder exhibited higher compressibility.

Tiwari et al. [82] demonstrated the densification of Al-Iron composite fabricated through P/M route. The green and the sintered density of the compacts increases with increase in compaction pressure and sintering temperature up to 550°C. A drop in the sintered density has been found at 590°C due to swelling of compacts, which has been explained based on the Kirkendall effect. Lin et al. [83] demonstrated the physio-mechanical properties of iron-Ti composites fabricated by powder metallurgy. The increase of the Ti addition of 23% resulted in Ti-Fe intermetallic formation and reduced density of composites. Further, the as-sintered composites present relatively good workability. The tensile strength and elongation achieved are 1360 MPa and 9.3%, respectively. Kov and Kibak [84] fabricated iron-boron composites using powder metallurgy technique. The inclusion of boron substantially improved the sintering up to 800°C. The selected sintering regime and micro additions of boron increased the density of sintered ingots. Zhu et al. [85] studied the densification behaviour of Fe-Cr, Fe-Mo, Ni, Co and atomized iron powder mixture during cold compaction at pressure 30 MPa to 165 MPa. Two simultaneously occurring processes at high pressures were observed in powder mixtures compared to the individual powders. One was the flow and deformation
of the atomized iron powder, and the other was the rearrangement and fracture of Cr–Fe and Mo–Fe powders. Among the alloy powders of iron, the atomized iron has been reported to have better compactability, fluidity and plasticity compared to the Cr–Fe and Mo–Fe powders.

Kumar et al. [86] deposited iron-Cr-Si-C composite coating on the mild steel substrate using atmospheric plasma spraying (APS). The coating was found to have crystalline phase dispersed in the amorphous matrix. Compared to the substrate the coating showed better microhardness and corrosion resistance. Optimum corrosion-resistant and mechanical properties were found in the coating deposited at a plasma power of 29 KW. Ramesh and Srinivas [87] studied the friction and wear behaviour of iron-SiC composite synthesized by direct metal laser sintering technique. The hardness and wear resistance of the composite have shown considerable improvements on increased content of SiC up to 7 wt. % to the iron matrix. The laser speed had shown inverse effects on the hardness and wear resistance of the composite. However, the coefficient of friction of composites exhibited linear relation with SiC content under identical test conditions. Dyachkova et al. [88] studied the tribological behavior of iron matrix composite fabricated through powder metallurgy. The iron matrix composite is significantly found to be influenced by the type and content of graphite, alumina and zirconia nanoparticles. The coefficient of friction was found unchanged over time but increased on the addition of all three reinforcements together. Anal et al. [89] fabricated Fe-TiB₂ composite through aluminothermic reduction followed by powder metallurgy. The abrasive wear resistance of the composite was found to be better than that of a high-chromium iron. The composite also exhibited good high-temperature stability. During the annealing of the composite at 900 °C the TiB₂ particles remained stable without any change in particle size. Bandyopadhyay and Das [90] evaluated mechanical and tribological properties of Fe-TiC composite synthesized through aluminothermic reduction and powder metallurgy. Titanium carbide reinforcement imparted enhanced hardness in the composites and resulted in decreased impact toughness. However, during annealing, the hardness of composites decreased. The wear resistance of the composite was also found better than the reference material. Chen et al. [31] evaluate the effects of wet and dry mixing of iron-2Cu-0.8C, graphite and zinc stearate. The stearic acid, alcohol wax and amide wax were used as binders. Wet mixing followed by spray-drying improved the bonding among powder particles. Using alcohol wax as binder resulted in the flow rate and apparent density as 30.6 s/50 g and 3.18 g/cm³, respectively. Alcohol wax and amide wax revealed better bonding between Cu and graphite particles. Binder-treated powder mixes found to reduce the friction coefficient among the powder particles during the cold compaction in the order of 0.012–0.026. Further, the binders exhibited a significant improvement on the mechanical properties of the sintered composite. Yılmaz [91] presented the effects of volume fraction, particle size, and sintered porosity on the abrasive wear resistance of Fe-FeCr composite fabricated through powder metallurgy route. During the wear test against 220 grades SiC abrasive paper, the wear of composite decreased on enhanced amounts of FeCr. In contrast, the wear rate increased on increasing FeCr content tested against 80 grades SiC abrasive paper. During this
transformation, the wear mechanism also got changed from microploughing to micro-cutting and microcracking. Although the porosity has a significant effect on the wear rate of Fe alloy, the wear rate of the composite was found more affected by the amount of FeCr as compared to the porosity. The wear rate of the composite was also decreased with an increase in the size of FeCr particles. It has also been concluded that the addition of Cu and graphite significantly transfer the mechanism of abrasion, which resulted in decreased wear rates.

**Gupta et al.** [92] synthesized Fe-Al₂O₃ composite through powder metallurgy process. XRD characterization of the composites confirmed the formation of iron aluminate (FeAl₂O₄) because of reactive sintering. Nano iron aluminate has been observed in the dense composite through SEM. The increased sintering temperature and time have been reported to have a significant effect on the densification of the composite. Further, the enhanced amount of iron aluminate increased in hardness number of the composite. **Gupta et al.** [93] presented the suitability powder metallurgy technique for the fabrication of homogeneous and near-net-shape composites. Further a study of the wear behaviour of Fe-Al₂O₃ composites has been carried out. The formation of aluminate (FeAl₂O₄) due to the reaction between iron and Al₂O₃ during sintering has been reported to improve the wear resistance of composite. Meagre wear rates have been observed due to adhesive wear at lower loads and abrasive wear mechanism at higher loads. **Jha et al.** [94] carried out the fabrication of Fe-ZnO₂ by powder metallurgy and subsequent characterization of SEM and XRD characterization. Wherein formation of nano sized Zr₆Fe₃O due to the reactive sintering has been confirmed. The density and hardness of the composites have been found dependent on the amount of Zr₆Fe₃O phase, which further was dependent on the sintering temperature and time. **Oliveira et al.** [95] developed Fe-Cu-diamond and 1 wt.% SiC composite through powder metallurgy to study the effects of % age reinforcement and composition of matrix (Fe-Cu) alloy on the mechanical and tribological properties. The enhanced amounts of SiC enhanced the hardness of the composite by 14%. Fe-20wt. %, Cu-1 wt.%, SiC has been reported as optimum in terms of yield strength, hardness and wear resistance of the composite. The SiC with a particle size of 23 μm exhibited wear resistance two times higher than for eight μm. **Rahman and Nor** [8] presented a study intended to optimize the temperature, lubricant and loading conditions during fabrication of green compacts from iron powder. During the powder compaction, an optimum temperature is found to be 130°C. The interparticle lubrication of the powder has enhanced the density of the green compact. However, the 0.5 wt.% of zinc stearate was found optimum when mixed with the powder for about 60 min. Ultimately, these optimized parameters resulted in decreased ejection force when the green compact was ejected from the die.

**Zarebski and Putyra** [96] carried out sintering of iron compacts through different methods. Among the various methods used, spark plasma sintering (SPS) has been found better as far as the density and shrinkage are concerned. But large pores have been reported in the samples sintered by SPS as compared to the conventional sintering techniques. **Fernandez et al.** [97] fabricated iron matrix composites reinforced by TiB₂ particles formed in-situ from Fe-Ti-B based melts. Enhanced
particle size of TiB$_2$ has been reported on addition of various alloying elements. Minimal effect of sintering has been observed on chemical compositions, crystal structure and mechanical properties. 

Jahani et al. [98] carried out the study of physical, microstructural and mechanical properties of Fe-TiB$_2$ composites synthesized through powder metallurgy process. The composites were developed at optimized parameters i.e. cold and hot pressing at 45 MPa and subsequent at 1100°C for 60 min. It has been reported that the reinforcement up to 20 vol. % imparted significant improvements in the mechanical and ultra-high temperature properties of the composite. Further, microstructure-based finite element analysis has successfully been utilized to verify the experimental results. Kattamis and Suganuma [99] fabricated and studied the tribological behaviour Fe-Ti-C particulate metal matrix. The composite was synthesized through in-situ (precipitation) of TiC from Fe-Ti-C melt and powder metallurgy route. The microstructure of composites was controlled by the melt composition, uniformity, and cooling rate. Further, the size and amount of TiC melt composition, mixing time and cooling rates found to be influencing the dispersion of reinforcement to the steel and cast-iron matrices. The specific wear rate and friction coefficient were reported to be decreased by increased amounts of reinforcement. The reduced size, interparticle space and heat treatment of matrix were concluded the main reasons for improved tribological behaviour.

Zhou et al. [100] deposited surface composite of iron-WC on cast iron substrate through vacuum infiltration process. The effect of reinforcement amounts on the erosion wear of the composite have been studied. The wear rate exhibited decreasing trend on increased reinforcements and stated increasing after achieving the minimum levels. Wang et al. [101] developed iron-Al$_2$O$_3$/ZrO$_2$/TiC surface composite through cast sinter technique. The uniform dispersion of reinforcements in the pore-free matrix has been reported. In contrast, the concentration gradient of reinforcements has been found decreasing towards the surface of the substrate. Jing and Wang [102] synthesized in-situ Fe–TiC composite through with powder metallurgy technique. Various reactions taking place between the matrix and reinforcement have been deliberated as a function of sintering temperature as; first at 765.6 °C α-Fe→ γ-Fe; then, a compound of Fe$_2$Ti was formed at 1078.4 °C. Further, molten Fe$_2$Ti causing the formation of TiC at 1138.2 °C. Ultimately, at 1146.4 °C, the Fe$_3$C compound was evolved due to the eutectic reaction between Fe and C.

In the prevailing circumstances, the metal matrix composites are the prime materials being researched to cope with the techno-economic and environmental challenges. A Ferrous-metal matrix composite (FMMC) is one of the traditional materials but could not recognize as a non-ferrous metal matrix (NFMMCs) has achieved. The rationale of this deficient required to be investigated scientifically. Among the ferrous matrix composite, the steel based MMCs dominate candidates as far as several research papers are concerned. The reason might be the preoccupied steel position in the manufacturing industry compared to the iron and cast iron. The steel-based composites are mainly synthesized using ex-situ techniques wherein powder metallurgy and laser melting are adopted [103]. Most of the research articles are aimed to enhance the tribological and corrosion resistance
characteristics of steel matrix composites along with tensile strength and hardness. The TiC, SiC, TiB$_2$ are often reinforced to the steel matrices, whereas the oxides are rarely used [104]. The above discussion intends to summarize that compared to the bulk iron matrix composite; the cast iron matrix composites are significantly less. Since the basic microstructure structure of cast irons somewhat follows the criteria of defining the metal matrix composites. Among the different cast irons, the grey cast iron is reinforced more to synthesize composites. Hence, instead of reinforcing the other cast iron matrixes such as white and nodular cast irons, their coating is more preferred to enhance their tribological properties. More specifically, particulate reinforced cast iron composites have been synthesized by an in-situ approach using the powder metallurgy route. Wherein ex-situ strategies have been adopted in reinforcing fibrous reinforcements [105].

4.4 Comparison of Specific Mechanical Properties of MMCs

While through literature survey, it has been observed that the researchers working on MMCs always talk about one of the most attractive attributes of MMCs i.e., higher strength to weight ratio. But not a single article was found devoted to thorough investigation of strength to weight of MMCs. Hence, specific properties of established AMMCs and upcoming IMMCs are required to be compared scientifically. The efforts had always been done to explore materials with higher mechanical properties and lower density. The MMCs are capable to inculcate this characteristic in a single material. AMMCs are the dominating group of the materials of the century as far as the high-tech industry such as aviation, aerospace and road transport is concerned. It is not easy to compare two materials when only single aspect is compared at a time and gives notional impression of the material under consideration. In holistic approach not only the mechanical properties but physical properties such as density and porosity play an important role when considered simultaneously. The mechanical properties of a material divided by its density is known as specific property. This is also known by strength to weigh ratio or strength to mass ratio which denotes force per unit area at the time of failure of material. The SI units of specific strength are same as of specific energy i.e., N.m/kg. This has been considered in various design and real application of materials. Similarly, the specific microhardness of the materials is also an important parameter in case of PMMCs. Owing to the presence of unavoidable defects such as porosity, agglomeration and poor interfaces. The improvements in microhardness of ceramic reinforced MMCs is not always that significant. But the reduction in density of these MMCs are considerably significant and exhibits reducing trends that of the microhardness. This in correlation to each other shows a more significant improvements compared to individual properties like strength and microhardness. Specifically, the MMCs are known for their higher specific properties. The inclusion of traditional reinforcements such as oxides, carbides, nitrides and borides to the aluminium matrices enhances the mechanical properties significantly. But this also enhances the density of the AMMCs, this way the specific properties do show any significant improvements. On the other hand the addition of CFA to the aluminium and iron matrices reduces the density of MMCs manyfold along with microhardness and strengths. About 50 % enhancement in
mechanical properties and 50% reduction of density is witnessed in case of iron-CFA MMCs. This can be a better material to be used in manufacturing of lighter and stronger road transport. This will not only increase the speed of the vehicle and weight carrying capacity but also reduce the fuel consumption and carbon emission significantly. In the present work too the specific microhardness, specific modulus, specific yield strength and specific ultimate tensile strength have been calculated and compared with the existing literature. While going through literature of MMCs, it is observed that the researchers working on MMCs always talk about one of the most attractive attributes of MMCs i.e., higher strength to weight ratio. But not a single article is found which is being devoted to thorough investigation of strength to weight of MMCs. Hence, this underrated aspect needs scientific comparison between of established MMCs (NFMMCs/AMMCs) and upcoming MMCs (FMMCs/IMMCs). The forthcoming section is devoted to evaluated and compare various specific mechanical properties of MMCs. In addition to the technical aspects such as specific mechanical properties, economic and environmental aspects are also not been compared. At first instance the cost of established matrices (aluminium) is much higher that of iron, steel and cast iron. Similarly, the cost of established ceramic reinforcements of various oxides, carbides, nitrides and borides are costlier than the fly ash and red mud. Not only this, the solid waste management of industrial waste fly ash and other agriculture waste is the biggest problem before both the developed and developing countries worldwide. Hence this entails the immediate requirement to explore alternate matrix and reinforcement materials in the interest of life on earth. So far, we have discussed many unique properties of MMCs materials, among them the reduced density on inclusion of ceramic particles is very important. Since the reduced density of MMCs helps to improve the material overall performance through improved specific properties[106].

4.4.1 Steel Matrix Composite

Sahoo et al. [45] studied the mechanical and tribological behaviour of SS304-TiB$_2$ composite fabricated by hot pressing. The significant improved mechanical properties corresponding to reduced density are presented in the form of FOM in the following Table 1.

Table 1. FOM of SS304 MMCs as a function of TiB$_2$ content and sintering temperature.

| TiB$_2$ vol. % | $\sigma_y$ (MPa) | $H_v$ | $\rho$ | FOM |
|---------------|-----------------|-------|-------|-----|
|               | 1000$^\circ$C   | 1100$^\circ$C | 1000$^\circ$C | 1100$^\circ$C | 1000$^\circ$C | 1100$^\circ$C | 1000$^\circ$C | 1100$^\circ$C |
| 0             | 945             | 1227  | 380   | 423 | 6.63 | 7.11 | 54,162 | 72,998 |
| 2             | 1124            | 1382  | 570   | 617 | 7.13 | 7.29 | 89,856 | 1,16,967 |
| 4             | 1279            | 1435  | 660   | 675 | 6.83 | 6.99 | 1,23,59 | 1,38,572 |
4.4.2 Iron Matrix Composite

Recently, Singh et al. [107] presented the microstructural and physio-mechanical characteristics of iron-CFA composites synthesized by P/M technique. The improvements in microhardness of IMMCs is also need a deliberated expiation and comparisons with the existing literature. Therefore, by dividing the microhardness by sintered density given an increased trend in the specific microhardness as shown in Figure 8.

![Figure 8. Density, microhardness and specific microhardness.](image)

Figure 8 indicates significant improvements in the specific microhardness by a factor of two. This implies that the inclusion of CFA to the iron matrix is imparting significant improvements in specific microhardness, which enabled the IMMCs to be more practical applicable. This has been possible due to the reduced density from 7.71 at 0 wt.% of CFA to 5.12 at 15 wt.% of CFA. However, the microhardness increased from 120 at 0 wt.% of CFA to 163 at 15 wt.% of CFA. The density reduction is 33.59 % whereas the microhardness improved by 35.83 %. This follows one of the basic features of MMCs i.e., higher mechanical properties to weight ratio.

Jahani et al. [108] presented the influence of TiB$_2$ vol.% on mechanical properties of iron metal matrix. The data for various properties are presented in Table 2.

| Vol. of TiB$_2$ | Hv   | E  (GPa) | UTS (MPa) | Density (g/cm$^3$) | Spec Hv | Spec E | Spec UTS | FOM      |
|---------------|------|----------|-----------|--------------------|---------|--------|----------|---------|
| 0             | 115  | 64.5     | 112.64    | 7.30               | 15.75   | 08.83  | 15.43    | 11.44×10$^4$ |
| 10            | 290  | 100.1    | 229.47    | 7.20               | 40.27   | 13.90  | 31.87    | 92.51×10$^4$ |
| 20            | 300  | 126.2    | 249.89    | 6.50               | 46.15   | 19.41  | 44.59    | 145.55×10$^4$ |
| 30            | 295  | 71.7     | 109.07    | 6.15               | 47.96   | 11.65  | 17.73    | 37.51×10$^4$ |
4.4.3 Cast Iron Matrix Composite

4.4.4 Aluminium Matrix Composite

Kennedy and Wyatt [109] studied the effect of various processing parameters on mechanical and interfacial properties of aluminium-TiC MMCs. The FOM calculated based on the data of this research paper is presented in the following Table 3.

Table 3. FOM of aluminium-TiC MMC as a function of TiC wt.% and fabrication method.

| TiC vol.%/ Wt. % | E (GPa) | UTS (MPa) | Density (g/cm³) | FOM  |
|------------------|---------|-----------|-----------------|------|
| 0                | 69      | 66        | 2.707           | 1682 |
| 10/49            | 87      | 109       | 2.915           | 3253 |
| P/M              |         |           |                 |      |
| 0                | 70      | 75        | 2.701           | 1943 |
| 10/49            | 88      | 120       | 2.920           | 3616 |

Bacciarini and Mathier [110] developed aluminum alloy 6061 composite reinforced by spherical and angular alumina particulate through gas pressure infiltration. The composites were characterized for elastic modulus, shear modulus microhardness and machinability. The results and FOM are presented in the following Table 4.

Table 4. Effect of reinforcement amount type and heat treatment on FOM

| Reinforcement (60 vol %) | E (GPa) | G (GPa) | Density (g/cm³) | Hv, of Heat-treated at 530℃ | Hv of Heat-treated at 160℃ | FOM |
|-------------------------|---------|---------|-----------------|-----------------------------|-----------------------------|-----|
| Al₂O₃ Spherical (2.25 wt.%) | 150     | 58      | 3.25            | 167                         | 216                         | 57.82×10⁴ |
| Al₂O₃ Angular (2.37 wt.%)  | 150     | 58      | 3.34            | 165                         | 159                         | 41.41×10⁴ |

Parkash et al. [111] presented a unique study wherein a comparison of micro and macro hardness was carried out of high entropy alloy (HEA) particulates were reinforced to the aluminium matrix composite. It was reported that with the addition of HEA particulates both the micro and macro hardness were enhanced significantly. Further, the corresponding specific hardness of the AMMCs was also found to increased.

Table 5. FOM of aluminum reinforced by HEA

| HEA | Hv | HRB | Density | Specific | Specific | FOM  |
|-----|----|-----|---------|----------|----------|------|
Allien et al. [112] presents the significant improvements in microhardness, ultimate tensile strength and impact energy of two AMMCs on increased SiC reinforcements (5, 10 and 15 wt.%). Correspondingly an increase in the density is also been reported. The specific microhardness and specific UTS being calculated using the data available in the article are presented in the Table 6.

Table 6. Influence of aluminium alloy and SiC reinforcement on FOM.

| Matrix | SiC wt.% | Hv  | UTS (MPa) | Density (g/cm²) | Specific Hv | Specific UTS | FOM  |
|--------|---------|-----|-----------|-----------------|-------------|--------------|------|
| Al 6082 | 0      | 57.30 | 144       | 2.4562          | 23.32       | 58.62        | 3359 |
|        | 5      | 66.76 | 220       | 2.4373          | 27          | 90.26        | 6026 |
|        | 10     | 72.97 | 221       | 2.4585          | 29          | 89.89        | 6559 |
|        | 15     | 74.69 | 205       | 2.4801          | 30          | 82.62        | 6173 |
| Al 7075 | 0      | 78.55 | 152       | 2.4893          | 31.55       | 61.06        | 4796 |
|        | 5      | 88.53 | 196       | 2.4725          | 35          | 79.27        | 7017 |
|        | 10     | 92.24 | 251       | 2.4905          | 37          | 100.78       | 9296 |
|        | 15     | 95.97 | 275       | 2.5089          | 38          | 109.60       | 10517|

In another research work, Ajagol et al. [113] studied the effect of SiC reinforcements on microhardness and ultimate tensile strength aluminium matrix composites. The increased inclusion of SiC to the aluminum resulted in significant enhancement in the UTS and microhardness of the AMMCs. The specific microhardness and UTS extracted from the data of the article revelled a significant enhancement too.

Table 7. Influence of SiC content of FOM of aluminium matrix composite

| SiC wt.% | Microhardness | UTS | Density | Specific Microhardness | Specific UTS |
|----------|---------------|-----|---------|------------------------|--------------|
| 0        | 25            | 76  | 2.71    | 09.22                  | 28.04        |
| 5        | 38            | 100 | 2.73    | 13.91                  | 36.63        |
| 10       | 45            | 120 | 2.75    | 16.36                  | 43.63        |
| 15       | 49            | 129 | 2.75    | 17.81                  | 46.90        |
4.4.5 Comparison of MMCs through Figure of Merit (FOM)

4.4.5.1 Figure of Merit (FOM)

It is often difficult to explain the usefulness of a particular material by considering all its characteristics at a time. Even the deliberation of each response is also not going to solve the problem because the others are ignored. Hence, some more appropriate method or means is required to be devised for specifying the overall performance characteristics of a material. This is also required not only to quantify the behaviour of the materials but also helpful in comparing and deciding the merit with the counterpart materials. The term figure of merit (FOM) had been in use for the purpose explained above for various fields such as thermal, electrical and characteristics of monolithic and composite materials [114]. The MMCs are being designed and developed for higher mechanical properties and lower weight. Hence the FOM is of outmost importance to be considered in designing and developing MMCs for the aviation and road transport industry. The FOM for MMCs is being conceived based on the literature and represented in equation (1) [110].

\[
FOM = \frac{Microhardness \times Youngs~Modulus \times Yield~Strength \times UTS}{Density \times Porosity \times Cost~of~matrix~and~reinforcement}
\]

(1) However the selection of numerator and denominator may differ as per the objectives of the research work. Rohatgi et al.[115] carried out the effect of fly ash inclusion of the density and strength of A 356-fly ash composite. The data of strength at room temperature and at elevated temperature is given in the table below.

| Fly ash vol.%/wt.% | Strength σ (MPa) | Density ρ(g/cm³) | FOM = \( \frac{σ}{ρ} \) |
|-------------------|-----------------|----------------|---------------------|
| 0/0               | 280             | 2.65           | 105.66              |
| 5/11              | 260             | 2.63           | 98.85               |
| 12.5/27.5         | 210             | 2.56           | 82.03               |
| 17.5/38.5         | 110             | 2.55           | 43.13               |

Singh et al. [116] presented the improvements in the microhardness, density and ultimate tensile strength on inclusion of SiC particulates to the Al6063 matrix through stir casting.

| Wt.% of SiC | Microhardness (Hv) | UTS (MPa) | Density (g/cm³) | FOM = \( \frac{Hv \times UTS}{ρ} \) |
|-------------|-------------------|-----------|----------------|---------------------|
| 0           | 50.98             | 205       | 2.690          | 3885                |
| 5           | 61.40             | 213.30    | 2.723          | 4809                |
| 7.5         | 67.72             | 230       | 2.748          | 5667                |
| 10          | 75.46             | 248       | 2.769          | 6758                |
| 12.5        | 85.90             | 274       | 2.798          | 8411                |
5 Summery

The literature survey tends to learn that FMMCs have been synthesized by powder metallurgy processes worldwide. Negligible research articles came to the knowledge authors where liquid state fabrications, i.e. stir casting, being adopted to synthesise FMMCs. However, whenever the reinforcements are to be formed and used in the nanometric size in-situ process has been used. The number of research articles on FMMCs is concerned the steel is being followed by iron and cast-iron matrix composites. In terms of lower specific properties of FMMCs, density has been the barrier required to be removed. In this direction, many researchers have explored reinforcements like Al₂O₃, SiC etc. having lower densities. Further, industrial wastes like coal-fly ash (CFA) have come up with the ability to reduce the density of FMMCs significantly. The current trends in the field of FMMCs are summarized in figure 8.

![Figure 7 Trends prevailing in the research of ferrous metal matrix composites.](image)

During the literature survey, enough research work has been found related to the compaction and the densification of powder materials using the P/M process. Specifically, the iron-based metal matrix composites (IMMCs) are being synthesised using mainly two processes, i.e. in-situ and ex-situ by powder metallurgy technique. Most of the research papers are intended to carry out the characterizations to explore the IMMCs mechanical and tribological behavior [117]. The IMMCs have better wear resistance than their iron matrix both in hybrid and plain composites. In additive manufacturing, selective laser melting is mostly used to produce parts from iron-based metal matrix composites. IMMCs coatings are also being deposited on steel substrates using tungsten inert gas welding processes (TIG) [118]. The reinforcements mostly used in iron matrices are carbides, borides
and oxides, but reinforcements like alumina tend to form the third phase during reactive sintering. Recently, carbon nanotubes and nanometric particulate reinforcements are in trend. [119].

Data Availability
The data used to support the findings of this study are included within the article.

References

[1] Robb J 2020 Art (Pre)History: Ritual, Narrative and Visual Culture in Neolithic and Bronze Age Europe *Journal of Archaeological Method and Theory* 27 454–80
[2] Haghshenas M 2016 Metal–Matrix Composites *Reference Module in Materials Science and Materials Engineering* 0–28
[3] Alaneme K K, Okotete E A, Fajemisin A V and Bodunrin M O 2019 Applicability of metallic reinforcements for mechanical performance enhancement in metal matrix composites: a review *Arab Journal of Basic and Applied Sciences* 26 311–30
[4] Leon C A, Rodriguez-Ortiz G and Aguilar-Reyes E A 2009 Cold compaction of metal-ceramic powders in the preparation of copper base hybrid materials *Materials Science and Engineering A* 526 106–12
[5] Chawla B N and Shen Y 2001 Mechanical Behavior of Particle Reinforced Metal Matrix Composites **Advanced Engineering Materials** 357–70
[6] Surappa M K 2003 Aluminium matrix composites: Challenges and opportunities *Sadhana - Academy Proceedings in Engineering Sciences* 28 319–34
[7] Section M 1991 Particulate reinforced metal matrix composites - a review *JOURNAL OF MATERIALS SCIENCE* 26 14–5
[8] Rahman M M and Nor S S M 2009 An experimental investigation of metal powder compaction at elevated temperature *Mechanics of Materials* 41 553–60
[9] Narayan S and Rajeshkannan A 2011 Densification behaviour in forming of sintered iron-0.35% carbon powder metallurgy preform during cold upsetting *Materials and Design* 32 1006–13
[10] Machaka R and Chikwanda H K 2015 Analysis of the Cold Compaction Behavior of Titanium Powders: A Comprehensive Inter-model Comparison Study of Compaction Equations *Metallurgical and Materials Transactions A* 46 4286–97
[11] Manimaran R, Jayakumar I, Mohammad Giyahudeen R and Narayanan L 2018 Mechanical properties of fly ash composites—A review *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 40 887–93
[12] William D. Callister J 2001 *Fundamentals of Materials Science and Engineering* ed W Anderson (New York: John Wiley & Sons, Inc)

[13] Selvam J D R, Dinaharan I and Rai R S 2020 *Matrix and Reinforcement Materials for Metal Matrix Composites*

[14] Dasgupta R 2012 Aluminium Alloy-Based Metal Matrix Composites: A Potential Material for Wear Resistant Applications *ISRN Metallurgy* 2012 1–14

[15] Singh L, Singh B and Saxena K K 2020 Manufacturing techniques for metal matrix composites (MMC): an overview *Advances in Materials and Processing Technologies* 6 224–40

[16] Hathaway R M, Rohatgi P K, Sobczak N, Sobczak J and Corporation O T 1997 Ferrous Composites: a Review *High Temperature Capillarity* 267–76

[17] Kumar S, Singh R and Hashmi M S J 2020 Metal matrix composite: a methodological review *Advances in Materials and Processing Technologies* 6 13–24

[18] Wang B, Qiu F, Barber G C, Pan Y, Cui W and Wang R 2020 Microstructure, wear behavior and surface hardening of austempered ductile iron *Journal of Materials Research and Technology* 9 9838–55

[19] Degnan C C and Shipway P H 2002 A comparison of the reciprocating sliding wear behaviour of steel based metal matrix composites processed from self-propagating high-temperature synthesised Fe-TiC and Fe-TiB2 masteralloys *Wear* 252 832–41

[20] Kainer K U 2006 *Metal Matrix Composites: Custom-made Materials for Automotive and Aerospace Engineering*

[21] Bharat N and Bose P S C 2021 An overview of production technologies and its application of metal matrix composites *Advances in Materials and Processing Technologies* 00 1–17

[22] Almuramady N 2018 Mechanical Properties of Composites using Natural Rubber with epoxy resin 293–397

[23] Matsunaga T, Kim J K, Hardcastle S and Rohatgi P K 2002 Crystallinity and selected properties of fly ash particles *Materials Science and Engineering* 325 333–43

[24] R. Manimaran, I. Jayakumar R M G and L N 2018 Mechanical properties of fly ash composites—A review *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 40 887–93

[25] Ahmaruzzaman M 2010 2010 A review on the utilization of fly ash *Progress in Energy and Combustion Science* 36 327–63

[26] Central Electricity Authority 2020 Report on fly ash generation at coal/lignite based thermal power stations and its utilization in the country for the year 2019-2020 *Ministry of Power, Government of India* 1–78

[27] Kareem A, Qudeiri J A, Abdudeen A, Ahammed T and Ziout A 2021 A review on AA 6061 metal matrix composites produced by stir casting *Materials* 14 1–22
[28] Yigezu B S, Jha P K and Mahapatra M M 2013 The key attributes of synthesizing ceramic particulate reinforced Al-based matrix composites through stir casting process: A review Materials and Manufacturing Processes 28 969–79

[29] Bajakke P A, Malik V R and Deshpande A S 2019 Particulate metal matrix composites and their fabrication via friction stir processing—a review Materials and Manufacturing Processes 34 833–81

[30] Ramanathan A, Krishnan P K and Muraliraja R 2019 A review on the production of metal matrix composites through stir casting – Furnace design, properties, challenges, and research opportunities Journal of Manufacturing Processes 42 213–45

[31] Chen W, Cheng J, Cheng L, Chen P and Xu J 2019 Improving the homogeneity and properties of ferrous powder mixes by a novel powder mixing process Powder Metallurgy 62 74–83

[32] Hooker J A, Doorbar P J, Hooker J A and Doorbar P J 2013 Metal matrix composites for aeroengines Materials Science and Technology 0836

[33] Kumar A and Pandey P M 2020 Development of Mg based biomaterial with improved mechanical and degradation properties using powder metallurgy Journal of Magnesium and Alloys 8 883–98

[34] Zegzulka J, Gelnar D, Jezerska L, Prokes R and Rozbroj J 2020 Characterization and flowability methods for metal powders Scientific Reports 10 1–19

[35] Saker A, Cares-Pacheco M G, Marchal P and Falk V 2019 Powders flowability assessment in granular compaction: What about the consistency of Hausner ratio? Powder Technology 354 52–63

[36] Sahoo S, Jha B B, Sahoo T K and Mandal A 2018 Influence of reinforcement and processing on steel-based composites: Microstructure and mechanical response Materials and Manufacturing Processes 33 564–71

[37] Akhtar F 2014 Ceramic reinforced high modulus steel composites: Processing, microstructure and properties Canadian Metallurgical Quarterly 53 253–63

[38] Parashivamurthy K I, Kumar R K, Seetharamu S and Chandrasekharaiah M N 2001 Review on TiC reinforced steel composites Journal of Materials Science 6 4519–30

[39] Fallahdoost H, Khorsand H, Eslami-Farsani R and Ganjeh E 2014 On the tribological behavior of nanoalumina reinforced low alloy sintered steel Materials and Design 57 60–6

[40] Tomoko Sano, TS Srivatsan and Michael W P 2014 Advanced Composites for aerospace,marine and land applications (California: Springer International Publishers, Switzerland)

[41] Kuforiji C and Nganbe M 2019 Powder metallurgy fabrication, characterisation and wear assessment of SS316L-Al2O3 composites Tribology International 130 339–51

[42] Ziejewska C, Marczyk J, Szewczyk-nykiel A, Nykiel M and Hebda M 2019 Influence of size and volume share of WC particles on the properties of sintered metal matrix composites
Advanced Powder Technology 30 835–42

[43] Velasco F, Lima W M, Antón N, Abenójar J and Torralba J M 2003 Effect of intermetallic particles on wear behaviour of stainless steel matrix composites Tribology International 36 547–51

[44] Velasco F, Antón N, Torralba J M and Ruiz-Prieto J M 1997 Mechanical and corrosion behaviour of powder metallurgy stainless steel based metal matrix composites Materials Science and Technology 13 847–51

[45] Sahoo S, Jha B B, Mahata T and Sharma J 2019 2019 Mechanical and Wear Behaviour of Hot-Pressed 304 stainless Steel Matrix Composites Containing TiB 2Particles Transactions of the Indian Institute of Metals 72 1153–65

[46] Xiao H, Chen C and Zhang M 2020 Microstructure and Mechanical Properties of H13 Steel/High-Speed Steel Composites Prepared by Laser Metal Deposition Journal of Materials Engineering and Performance 29 66–77

[47] Patankar S N and Tan M J 2000 Role of reinforcement in sintering of SiC/316L stainless steel composite Powder Metallurgy 43 350–2

[48] Pagounis E and Lindroos V K 1998 Processing and properties of particulate reinforced steel matrix composites Materials Science and Engineering A 246 221–34

[49] Farid A, Guo S, Cui F e., Feng P and Lin T 2007 TiB2 and TiC stainless steel matrix composites Materials Letters 61 189–91

[50] Wang Z, Lin T, He X, Shao H, Tang B and Qu X 2016 Fabrication and properties of the TiC reinforced high-strength steel matrix composite International Journal of Refractory Metals and Hard Materials 58 14–21

[51] Kan W H, Bhatia V, Dolman K, Lucey T, Tang X, Chang L, Proust G and Cairney J 2018 A study on novel AISI 304 stainless steel matrix composites reinforced with (Nb0.75,Ti0.25)C Wear 398–399 220–6

[52] Ziejewska C, Marczyk J, Szewczyk-Nykiel A, Nykiel M and Hebda M 2019 Influence of size and volume share of WC particles on the properties of sintered metal matrix composites Advanced Powder Technology 30 835–42

[53] Lou D, Hellman J, Luhulima D, Liimatainen J and Lindroos V K 2003 Interactions between tungsten carbide (WC) particulates and metal matrix in WC-reinforced composites Materials Science and Engineering A 340 155–62

[54] Srivatsan T S, Annigeri R and Prakash A 1997 Tensile deformation and fracture behaviour of a tool-steel-based metal-matrix composite Composites Part A: Applied Science and Manufacturing 28 377–85

[55] On J D B O L T and Gan A J T 1998 Fracture in ceramic-reinforced metal matrix composites based on high-speed steel journal of materials science 3 939–53

[56] Das K, Bandyopadhyay T K and Das S 2002 A review on the various synthesis routes of TiC
reinforced ferrous based composites Journal of Materials Science 37 3881–92

[57] Wu C L, Zhang S, Zhang C H, Zhang J B, Liu Y and Chen J 2019 Effects of SiC content on phase evolution and corrosion behavior of SiC-reinforced 316L stainless steel matrix composites by laser melting deposition Optics and Laser Technology 115 134–9

[58] Verma P, Saha R and Chaira D 2018 Waste steel scrap to nanostructured powder and superior compact through powder metallurgy: Powder generation, processing and characterization Powder Technology 326 159–67

[59] Yao B, Zhou Z, Duan L and Xiao Z 2016 Compressibility of 304 stainless steel powder metallurgy materials reinforced with 304 short stainless steel fibers Materials 9

[60] Loh N H, Tor S B and Khor K A 2001 Production of metal matrix composite part by powder injection molding Journal of Materials Processing Technology 108 398–407

[61] Di Cocco V, Iacoviello F and Cavallini M 2010 Damaging micromechanisms characterization of a ferritic ductile cast iron Engineering Fracture Mechanics 77 2016–23

[62] Jeyaprakash N, Yang C H, Duraiselvam M, Prabu G, Tseng S P and Raj Kumar D 2019 Investigation of high temperature wear performance on laser processed nodular iron using optimization technique Results in Physics 15 1–10

[63] Avci A, Ilkaya N, Şimşir M and Akdemir A 2009 Mechanical and microstructural properties of low-carbon steel-plate-reinforced gray cast iron Journal of Materials Processing Technology 209 1410–6

[64] Qiu B, Xing S and Dong Q 2019 Fabrication and wear behavior of ZTA particles reinforced iron matrix composite produced by flow mixing and pressure compositing Wear 428–429 167–77

[65] Zhong L, Ye F, Xu Y and Li J 2014 Microstructure and abrasive wear characteristics of in situ vanadium carbide particulate-reinforced iron matrix composites Materials and Design 54 564–9

[66] Cui C, Guo Z, Wang H and Hu J 2007 In situ TiC particles reinforced grey cast iron composite fabricated by laser cladding of Ni-Ti-C system Journal of Materials Processing Technology 183 380–5

[67] Kambakas K and Tsakirooulos P 2005 Solidification of high-Cr white cast iron-WC particle reinforced composites Materials Science and Engineering A 413–414 538–44

[68] Janicki D 2021 The friction and wear behaviour of in-situ titanium carbide reinforced composite layers manufactured on ductile cast iron by laser surface alloying Surface and Coatings Technology 406 1–20

[69] Niu L, Hojamberdiev M and Xu Y 2010 Preparation of in situ-formed WC/Fe composite on gray cast iron substrate by a centrifugal casting process Journal of Materials Processing Technology 210 1986–90

[70] Li P, Li X, Li Y, Gong M, Tian C and Tong W 2019 Microstructure and Mechanical
Properties of Millimeter WC Particle-Reinforced High-Chromium Cast Iron Composites

Journal of Materials Engineering and Performance 28 7816–27

[71] Terry B S and Chinyamakobvu O 1991 Carbothermic reduction of ilmenite and rutile as means of production of iron based Ti(O, C) metal matrix composites Materials Science and Technology 7 842–8

[72] Abdollahi H, Mahdavinejad R and Leavoli R P 2015 Investigation and optimization of properties of sintered iron / recycled grey cast iron powder metallurgy parts journal of engineering manufacturing 229 1010–20

[73] Zhigang Xu , Michael A. Hodgson , Keke Chang , Gang Chen X Y and P C 2017 Effect of Sintering Time on the Densification, Microstructure, Weight Loss and Tensile Properties of a Powder Metallurgical Fe-Mn-Si Alloy Metals MDPI 7 81

[74] Bardhan P K, Patra S and Sutradingh G 2010 2010 Analysis of Density of Sintered Iron Powder Component Using the Response Surface Method Materials Sciences and Applications 01 152–7

[75] Zhang X, Ma F, Ma K and Li X 2012 2012 Effects of Graphite Content and Temperature on Microstructure and Mechanical Properties of Iron-Based Powder Metallurgy Parts Journal of Materials Science Research 1 48:56

[76] Sharma Shyam, Hundekar P R, Gupta P, Kumar D, Jain R, Singh N and Rawat V 2017 2017 Structural and mechanical characterization of re-pressed and annealed iron-alumina metal matrix nanocomposites Journal of Composite Materials 52 1541–56

[77] Gupta P, Kumar D, Parkash O and Jha A K 2014 2014 Sintering and Hardness Behavior of Fe-Al 2 O 3 Metal Matrix Nanocomposites Prepared by Powder Metallurgy Journal of Composites September 1–10

[78] Jian Y, Huang Z, Xing J, Zheng B, Sun L, Liu Y and Liu Y 2016 Effect of improving Fe2B toughness by chromium addition on the two-body abrasive wear behavior of Fe-3.0 wt% B cast alloy Tribology International 101 331–9

[79] Feldshtein E E and Dyachkova L N 2014 On the properties and tribological behaviors of P/M iron based composites reinforced with ultrafine particulates Composites Part B: Engineering 58 16–24

[80] Panakkal J P, Willems H and Arnold W 1990 Nondestructive evaluation of elastic parameters of sintered iron powder compacts Journal of Materials Science 25 1397–402

[81] Poquillon D, Lemaître J, Baco-Carles V, Tailhades P and Lacaze J 2002 Cold compaction of iron powders - Relations between powder morphology and mechanical properties: Part I: Powder preparation and compaction Powder Technology 126 65–74

[82] Tiwari S, Rajput P and Srivastava S 2012 2012 Densification Behaviour in the Fabrication of Al-Fe Metal Matrix Composite Using Powder Metallurgy Route ISRN Metallurgy 2012 1–8

[83] Lin F, Chen Z, Liu B, Liu Y and Zhou C 2020 Microstructure and mechanical properties of
iron-containing titanium metal-metal composites *International Journal of Refractory Metals and Hard Materials* **90** 105225

[84] V K V and B K 1997 Sintering Mechanism of Iron Powder with Boron *Powder Metallurgy and Metal Ceramics* **36** 470–3

[85] Zhu Y Z, Yin Z M, Xiang Z D and Zhe Z 2008 Cold densification behaviour of multiple alloy powder containing Fe-Cr and Fe-Mo hard particles *Powder Metallurgy* **51** 143–9

[86] Kumar A, Nayak S K, Bijalwan P, Dutta M, Banerjee A and Laha T 2019 Mechanical and corrosion properties of plasma-sprayed Fe-based amorphous/nanocrystalline composite coating *Advances in Materials and Processing Technologies* **5** 371–7

[87] Ramesh C S and Srinivas C K 2009 Friction and wear behavior of laser-sintered iron-silicon carbide composites *Journal of Materials Processing Technology* **209** 5429–36

[88] Dyachkova L N, Feldshtein E E, Vityaz P A and Mikhalski M 2020 Tribological Properties of Iron-Based Powder Composite Materials with Addition of Graphite, Alumina and Zirconia Nanoparticles *Journal of Friction and Wear* **41** 198–203

[89] Anal A, Bandyopadhyay T K and Das K 2006 Synthesis and characterization of TiB2-reinforced iron-based composites *Journal of Materials Processing Technology* **172** 70–6

[90] Bandyopadhyay T K and Das K 2004 Synthesis and characterization of TiC-reinforced iron-based composites Part II on mechanical characterization *JOURNAL OF MATERIALS SCIENCE* **39** 6503–8

[91] Yilmaz O 2001 Abrasive wear of FeCr (M7C3-M23C6) reinforced iron based metal matrix composites *Materials Science and Technology* **17** 1285–92

[92] Gupta P, Kumar D, Parkash O M and Jha A K 2013 Structural and mechanical behaviour of 5 % Al2O3-reinforced Fe metal matrix composites (MMCs) produced by powder metallurgy (P/M) route *Bulletin of Material Science* **36** 859–68

[93] Gupta P, Kumar D, Parkash O and Jha A K 2014 Effect of sintering on wear characteristics of Fe-Al2O3 metal matrix composites *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* **228** 362–8

[94] Jha P, Gupta P, Kumar D and Parkash O 2014 Synthesis and characterization of Fe-ZrO2 metal matrix composites *Journal of Composite Materials* **48** 2107–15

[95] de Oliveira L J, Bobrovitchii G S and Filgueira M 2007 Processing and characterization of impregnated diamond cutting tools using a ferrous metal matrix *International Journal of Refractory Metals and Hard Materials* **25** 328–35

[96] Zarebski K and Putyra P 2015 Iron powder-based graded products sintered by conventional method and by SPS *Advanced Powder Technology* **26** 401–8

[97] Aparicio-Fernández R, Springer H, Szczepaniak A, Zhang H and Raabe D 2016 In-situ metal matrix composite steels: Effect of alloying and annealing on morphology, structure and mechanical properties of TiB2 particle containing high modulus steels *Acta Materialia* **107**
Jahani B, Salimi Jazi M, Azarmi F and Croll A 2018 Effect of volume fraction of reinforcement phase on mechanical behavior of ultra-high-temperature composite consisting of iron matrix and TiB2 particulates *Journal of Composite Materials* **52** 609–20

Kattamis T Z and Suganuma T 1990 Solidification processing and tribological behavior of particulate TiC-Ferrous Matrix composites *Materials Science and Engineering A* **128** 241–52

Zhou R, Jiang Y and Lu D 2003 The effect of volume fraction of WC particles on erosion resistance of WC reinforced iron matrix surface composites *Wear* **255** 134–8

Wang Y, Zhang X, Zeng G and Li F 2000 Cast sinter technique for producing iron base surface composites *Materials and Design* **21** 447–52

Wang Jing and Wang Yisan 2007 In-situ production of Fe-TiC composite *Materials Letters* **61** 4393–5

Kasar A K, Gupta N, Rohatgi P K and Menezes P L 2020 A Brief Review of Fly Ash as Reinforcement for Composites with Improved Mechanical and Tribological Properties *Jom* **72** 2340–51

Gao W, Zhou Y, Han X, Li S and Huang Z 2021 Preparation and microstructure of 3D framework TiC–TiB2 ceramics and their reinforced steel matrix composites *Ceramics International* **47** 2329–37

Akdemir A, Arikan H and Kuş R 2005 Investigation of microstructure and mechanical properties of steel fibre-cast iron composites *Materials Science and Technology* **21** 1099–102

Samal P, Vundavilli P R, Meher A and Mahapatra M M 2020 Recent progress in aluminum metal matrix composites: A review on processing, mechanical and wear properties *Journal of Manufacturing Processes* **59** 131–52

Singh A, Singh J, Sinha M K, Kumar R and Verma V 2020 Investigations on microstructural and microhardness developments in sintered iron – coal fly ash composites *Sādhanā* **2020** 1–13

Jahani B, Jazi M S, Azarmi F and Croll A 2017 Effect of volume fraction of reinforcement phase on mechanical behavior of ultra-high-temperature composite consisting of iron matrix and TiB2 particulates *Journal of Composite Materials* **June** 1–12

Wyatt A R K and S M 2000 The effect of processing on the mechanical properties and interfacial strength of aluminium/TiC MMCs *Composite science and technology* **60** 307–14

Bacciarini C and Mathier V 2014 Aluminium AA6061 Matrix Composite Reinforced with Spherical Alumina Particles Produced by Infiltration: Perspective on Aerospace Applications *Journal of Metallurgy* **2014** 1–10

Prakash K S, Gopal P M, Purusothaman M and Sasikumar M 2019 FABRICATION AND CHARACTERIZATION OF METAL-HIGH ENTROPY ALLOY COMPOSITES *International Journal of Metalcasting* **2019**
[112] Allien V J, Kumar H and Desai V 2019 Dynamic analysis and optimization of SiC reinforced Al6082 and Al7075 MMCs Materials Research Express 6 1–21

[113] Perugu C S Effect of SiC Reinforcement on Microstructure and Mechanical Properties of Aluminum Metal Matrix Composite Effect of SiC Reinforcement on Microstructure and Mechanical Properties of Aluminum Metal Matrix Composite

[114] Grunlan J C, Gerberich W W, Francis L F, Hall A and Se W A 2001 Figures of Merit for Electrically Conductive Polymer Composites Jaime C. Grunlan, William W. Gerberich, and Lorraine F. Francis Department of Chemical Engineering and Materials Science, University of Minnesota 151 Amundson Hall, 421 Washington Ave SE, Min Mat. Res. Soc. Symp. 661 1–6

[115] Rohatgi P K, Weiss D and Gupta N 2006 Applications of fly ash in synthesizing low-cost MMCs for automotive and other applications Jom 58 71–6

[116] Singh J, Jawalkar C S and Belokar R M 2020 Analysis of Mechanical Properties of AMC Fabricated by Vacuum Stir Casting Process Silicon 12 2433–43

[117] Sharma A K, Bhandari R, Aherwar A and Rimäšauskiene R 2020 Matrix materials used in composites: A comprehensive study Materials Today: Proceedings 21 1559–62

[118] Kumar A and Das A K 2020 Mechanical properties of Fe+SiC metal matrix composite fabricated on stainless steel 304 by TIG coating process International Journal of Materials Engineering Innovation 11 181–97

[119] Silvestre N and Canongia N 2020 CNT-reinforced iron and titanium nanocomposites: Strength and deformation mechanisms Composites Part B 187 1–11