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Original Article

Effect of mixing method and particle size on hardness and compressive strength of aluminium based metal matrix composite prepared through powder metallurgy route

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ABSTRACT

Properties of metal matrix composites (MMCs) are affected by various process variables such as particle size of powders, the proportion of reinforcement material, mixing methods, sintering temperature, and duration. The significant drawback of stir casting is reinforcement segregation, which is too difficult to avoid. Hence, the powder metallurgy route is utilized to prepare Al-MMC. In the current work, aluminium-based MMC is fabricated with varying proportions of silicon carbide (SiC) as a reinforcement material. Mixing of powders is done using V-Blender and barrel mixer with three different mixing techniques and the mixing quality of prepared powders is assessed. A significant reduction of mixing time, i.e., more than 50%, is achieved through a novel barrel mixer as compared to a conventional V-blender. Two important properties, hardness and compressive strength of fabricated Al-MMC, are experimentally investigated. At the same time effect of the mixing technique is also studied, and it is evident that hardness and compressive strength improved when powders are mixed using a barrel mixer. Thus, a novel approach to powder mixing has been achieved. An increase in SiC proportion by 5% resulted in an increase in hardness by 14%. The average compressive strength of Al-MMC is highest when reinforcement content is 25%. Due to the uniform dispersion of particles achieved through barrel mixer, compressive strength of MMC is 8–20% higher than the strength of those MMC for which powders are mixed through conventional V-blender. A similar effect is

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observed in the hardness also, where the average hardness of MMC is 10–20% higher, for which powders are mixed through barrel mixer. Hence, the newly designed barrel mixer provides an effective solution for the quality mixing of powders through the powder metallurgy process for fabricating Al-MMC.
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1. Introduction

Due to several unique characteristics and the scope of tailor-made properties, metal matrix composites (MMCs) have gained attention from researchers. MMCs are superior to conventional materials in terms of specific properties such as lower densities, high specific strength, higher fatigue, and creep resistance are a few examples. Commercially produced MMCs could demonstrate high wear resistance and lower thermal expansions, making them suitable for use in nuclear components, special integrated circuit chips packages for spacecraft, etc. Many companies and reputed automobile manufacturers also adopted MMC for some critical components like turbine blades, drive-shafts, pistons for engine cylinders, to name a few. In the particulate MMCs of Al and Mg, particles like SiC, TiC, and Al_2O_3 are reinforced into the Al and Mg metal or alloy matrix. The addition of Mg [1] in SiC or Al_2O_3 based MMC can play a significant role in achieving tailored properties like ultimate tensile strength and creep resistance. The desired properties of MMCs can be attained by varying the size, type, and concentration of reinforced particles [2].

Among many processes available for fabrication, powder metallurgy (PM) offers flexibility and ease of fabrication of MMCs. Compared to processes like stir casting [3], powder metallurgy is free from undue chemical reactions, wettability issues, and segregation of particles due to density, surface tension, and temperature gradient. If the powders are mixed well, the problems mentioned above can be easily overcome. One of the main advantages of this process is that mixing of matrix material and reinforcement takes place in solid-state, there is reasonable control over the processing variables, and it is comparatively easier to retain the reinforcement material without any phase change or chemical reaction, unlike stir casting process [4]. One of the significant drawbacks of the stir casting process is reinforcement segregation, which is too difficult to avoid. This issue is not present in the powder metallurgy process. Torralba et al. [5] suggested powder metallurgy as one of the more straightforward and effective processing routes for the fabrication of metal matrix composites. It is prudent to know that particle seizes of reinforcement and shape will affect the properties of target material, i.e., MMCs, to a large extent. The compaction pressure may be affected by particle size and strength of reinforcement particle. Porosity and large-angle grain boundary formation are the major issues that can be addressed with modification in the sintering process. Necessary tooling is also more uncomplicated than other processes like pressure infiltration spray deposition, and the process is economical compared to PVD, CVD, and other special techniques like rapid prototyping. This powder metallurgy can offer a good combination of metal and non-metals to fabricate various MMCs. It is also possible to avoid reaction products and their formation in powder metallurgy which usually happens in liquid state processing of MMC. The quality of components and their properties are very much dependent on the mixing of powders and uniformity of dispersion of reinforcement when MMCs are fabricated through powder metallurgy. Many researchers have given great importance to the mixing or blending of powders. Powder metallurgy involves three main steps: mixing powders, consolidation or compacting, and post-processing. Hence, to take the fullest advantage of the powder metallurgy process, due importance should be given to the mixing or blending of powers [6].

Depending upon the matrix material and reinforcement material, its shape, and size of particles, ball mill, v-blender, planetary ball mill [5], tubular mixer [6] have been used by several researchers. It is observed that ball milling is used in many cases, owing to its simplicity of operation and good quality of powder mixing in a reasonable time [7,8]. However, less information is available on using v-blender and barrel mixer with twin rotation system, which is used in the present study. According to Obadele et al. [9] quality of powder-mix is influenced by various parameters such as particle size, particle shape, type of mixer, use of a binder, duration of mixing, etc. Clustering and aggregation are the two common issues in mixing fine powders; Malin et al. [10] used a four-blade impeller at 1800 rpm to mix the powder while introducing the effect of high shear pre-dispersion followed by another low-speed ball milling (LSBM) to get uniform dispersion of carbon nanotubes (CNT) in the matrix of Al-6061 fine powder. The results were encouraging, and good quality of powder mixing was observed. Depending upon the functional element of the mixer, i.e., impeller, agitator, drum, etc., there can be changes in the size and shape of the particles the powders are being mixed. In some cases, sharp edges are broken, and particles get combined to form a compound particle. Especially in the ball milling approach, this phenomenon can be very well observed. Mendoza et al. [11] fabricated an aluminium based MMC with copper, nickel, and graphite-reinforced in powder form. They used a high-speed milling process to mix the powders. It is evident that as the mixing time increases, the compounding of particles may happen, which in turn affects the followability of powders in the mixing chamber. Mechanical properties of MMC can be affected to some extent by the change of particle shape. Also, it can affect the degree of porosity void formation tendency in the case of sintering of MMC.

Loh et al. [12] used a particular type of mixer, in which twin vertical mounted blades were used to mix the powder. The blades were so designed to have minimum relative surface area. The design of the blade and high speed of rotation could reduce the agglomeration, but they observe microbubbles at some places in the powder mix. According to them, these microbubbles can cause in-homogeneity to a certain extent. If the constituents are not stable chemically, prolonged mixing can negatively affect the quality of the powders' mixture. If a polymer-based agent assists the mixing of powders, then temperature control is a must during the entire mixing process to avoid the scope of any undesirable chemical reactions. Homogeneity of powders is affected by the cohesiveness of powders being mixed. Cohesive powders are least affected by segregation, even though there can be a difference in particle shape and size. Hence, cohesive powders and a good mixer guarantee the uniform dispersion of reinforcement particles in the matrix material. Oka et al. [13] found that using a continuous mixer with rotating blades results in better homogeneity of blended powder compared to V-blender. A prolonged mixing is needed through V-Blender to get a reasonable degree of homogeneity of blended powder. Sometimes agglomerates are naturally found in the powder itself. These agglomerates are individual primary crystallines that are held by weak attractive forces. If these kinds of agglomerates are found in the powders, it may pose challenges for the mixer and the quality of powder mixing [14]. Conventional laboratory methods can be the assessment of mixing quality, like element testing, XRD analysis, titration methods, etc. However, few studies apply a scientific process like numerical analysis and use such techniques. Stefan et al. [15] did an experimentally validated discrete element method (DEM) numerical analysis to model and predict the mixing process. Various physical conditions, mixing parameters, and boundary values were models, and simulations were carried out successfully. A good agreement was found between simulated experiments and real-time experiments. The MLH12 paddle mixer carried out Real-time mixing of powders. The relative standard deviation (RSD) serves as one of the effective measures to assess the mixing quality of the powder, and it should reduce with the mixing time.

Many researchers have employed high-energy ball milling of powders due to its simplicity in operation. Still, there can be certain cases where some damage occurs to the particles of some material. Peng et al. [14] reported such carbon nanotubes (CNT) issues. They came out with a different mixing approach called the wet shaking approach for mixing the CNT with aluminium powders. They combined ultra-sonication, magnetic stirring, and shake-mixing to mix well the carbon nano-tubes (CNT) with al-powder. Ethanol was used to produce a solution, and the solution was sonicated with high frequency; after that, magnetic stirring was carried out to obtain the final mixer. This approach served well to obtain good quality of mixing of CNT into aluminium powder. Hence, in light of the above facts, the mixing of powders is crucial for any part or component to be fabricated by the powder metallurgy route, mainly when a blend of powders is being used. Liao et al. [16] used a screw blender as a secondary mixer apart from the primary mixer, i.e., horizontal rolling mill, to ensure the final random dispersion of carbon nanotubes (CNT) in the matrix material. Their experimental study showed that sometimes reinforcement like CNT might require a subsequent mixing process as conventional mixing can have some issue of clustering of reinforcement material. Dispersion and presence of hard particles affect the resultant hardness of composite material, as reported by Rahimian et al. [17]; according to them, the increased content of complex particles directly contributes to the increase in hardness. Jinzhi et al. [16] reported higher hardness of composite material when powders and other starting materials were mixed or blended through high energy ball milling approach compared to those mixed with low energy ball milling approach. The hardness was 6% higher than that composite whose powders were mixed through la similar observation were presented by Eroglu et al. [18], where tungsten powder was reinforced by nickel produced the hardening effect on the resultant metal matrix composites. Lattice structures are essential for new generation material designed for high energy absorption being light in weight. This can result in high strength to weight ratio. MMCs can also have such properties. Mubasher et al. [19] reported that lattice structures like Octet, Gyroid, Kelvin, Sea Urchin, Split-P, Rhombus, SUP can exhibit excellent energy absorption and mechanical flexibility in many critical applications such as aerospace and medical and dentistry. They found that the surface roughness of these lattice structures is directly proportional to strength. They found that the diamond structure SUP structure was superior to other lattice structures in load-bearing capacity. Application of Nano reinforcement particles-based MMCs can also be explored in renewable energy devices and sources, where efficient utilization [20] is of paramount importance. By using nanofluids in specially fabricated tube solar collectors, the performance of absorption cycles can be increased to a great extent [21]. Similarly, some other special applications can also be developed [22].

Fogagnolo et al. [23] reported the significant contribution of reinforcement material for the increase of hardness, the hardness of base material was 65 HV, while the hardness of MMC was written between 192 and 209 HV, which is almost three times the hardness of base material; also they could show the significant difference between the hardness of powder as obtained and mechanically alloyed powders. In another experimental study, Bodukuriet al. [24] also reported an increase in the hardness of composite material when the proportion of B4C was increased in the composite material. A similar phenomenon was also reported by Tosun and Kurt [25], where the hardness of MMC was found enhanced along with the increased content of reinforcement and sintering temperature. Zhao et al. [26] reported an increase in strength of aluminium and tungsten-based MMC; they found that there was a significant increase in strength of composite when the reinforcement proportion was increased, they used nickel as reinforcement, tensile strength increased from 600 MPA to a whopping value of 1850 MPa with the increased proportion of nickel to 55%. They suggested that efficient and effective transfer to applied load to the well-bonded matrix and reinforcement particles increases strength. The only concern they revealed was that there should not be any traces of brittle oxides formation, which is detrimental to the strength of composite material. The homogeneity of microstructure without particle agglomeration is also a basis for increasing MMC's strength. If SiC particle acts as a solid nucleus, then higher chances are there to enhance the strength of the particle reinforced MMC [27]. Similar results while doing an experimental study on aluminium-based MMC reinforced with fly-ash were reported by Avinash et al. [28]. The increased content of fly ash also resulted in the enhancement of strength as compared to that of commercial aluminium. However, the strength of SiC or Nickel-based MMC is much higher than the fly ash reinforced aluminium composites. Another study was carried out by Mimoto et al. [29] revealed that reinforcement of carbon nano-tubes (CNT) increased strength, and they suggested that not only increased content of reinforcement but also solid solution hardening contributed to the enhancement of mechanical strength.

Nicholls et al. [30] extensively reviewed the machining behavior of MMC and found that it is challenging to predict the machining behavior and machinability of hard particle reinforced MMC; according to them, conventional Merchant's theory of single shear plane cannot be sufficient to analyze the machining of MMCs. Tool wear, surface roughness, and cutting forces become the key parameters to investigate in light of new approaches. Davim et al. [31] found that thrust force in the drilling of hybrid composites is affected by the type and presence of hard particles in the MMC; an optimization is essential to come up with the best machining parameters. Tool wear is also one of the critical issues in the machining of MMCs. Several researchers have given due importance to this critical aspect of machining of MMCs. Bain et al. [32] suggested that abrasion of hard particles like SiC or alumina immediately causes the tool wear, as each sharp edge of reinforcement particle causes severe abrasion on tool faces. Residual stresses on the machined surface affect the chip formation pull-out tendency of reinforcement particles [33]. The temperature at the shear zone significantly affects the tool wear pattern. Hence thermally assisted machining can address this issue up to some extent. Damian et al. [34] Investigated that thermally assisted machining can significantly reduce tool wear. The researchers tried to establish the scope of the laser for improved machinability. Flank wear can be greatly reduced if the matrix softening is done before machining. Khanna et al. [2] attempted the cryogenic turning of magnesium-based MMC as one of the novel techniques to address the issue of machinability of MMCs. They reported a significant reduction in cutting forces and power requirements for the machining. The lower temperature at the machining zone or cutting zone helps retain the hardness of the tool and the formation of BUE is restricted. In other experimental work Khanna et al. [35], demonstrated the scope of eco-friendly technique of minimum quantity lubrication (MQL) in the machining of titanium based MMCs. They obtained favourable results for the reduction in the cutting forces with MQL approach. The cutting forces were significantly reduced with MQL and reduction in energy was also reported.

It is inferred from the available literature that the stir casting approach can be utilized to produce metal matrix composites. However, it suffers from reinforcement segregation, which is too difficult to avoid. Hence, the powder metallurgy route is utilized to prepare aluminium-based metal matrix composite. In powder metallurgy, the reinforcement takes place in solid-state, allowing reasonable control over the processing variables. Contemplating these matters, the objective of the present work is to experimentally investigate the effect of type of mixing and type of mixer on properties of aluminium-based metal matrix composites material. Mixing time, particle size, mechanism of mixing is the few key parameters are analyzed that can affect the mixing quality of powders. Mixing of powders is done using two mixers, V-blender and barrel mixer, and three different mixing techniques are deployed. At the same time effect of the mixing technique is also studied. In the novel barrel mixer twin rotation feature, both the drum and agitator rotate in opposite directions, and powders are continuously mixed through shear and convection. Due to twin rotation stationary sites or local clustering of powders is eliminated, hence mixing quality is superior to other conventional mixers such as V-blender and the results are improved hardness and compressive strength when powders are mixed with barrel mixer. Thus a novel approach to powder mixing has been achieved. Furthermore, this work also investigated the effect of the proportion of SiC and particle size of SiC on the compressive strength of the prepared MMC. Using the experimental results, a combination of suitable mixing methods, mixing time, particle size, and concentration of SiC particles are established for the defect-free production of Al-MMC.

2. Materials and methods

2.1. *Metal matrix composite preparation*

Elemental powders of pure aluminium and silicon carbide have been used to prepare metal matrix composite material. A Schematic illustration of the powder metallurgy technique to prepare MMCs is presented in Fig. 1. Among the various reinforcement materials, silicon carbide (SiC) is most widely used in the fabrication of metal matrix composites. The availability of SiC in powder form in different sizes and purity level is another reason to prefer SiC over other reinforcement materials. SiC powder is obtained from Amity Enterprise India with 10 μm, 20 μm, and 30 μm of average particle size. Each sample of SiC powder and pure aluminium powder is tested for moisture content. Approximately 20% of SiC powder of smaller particle size, i.e., less than 30 μm, is used; this is done to take advantage of particle size, as smaller particle size contributes much to strength. The interfacial area of particle size also plays an essential role during the sintering of green compact made by powder metallurgy. Al-MMC with three different compositions is fabricated for experimental study. SiC is added to pure aluminium powder in three proportions, i.e., 15%, 20%, and 25% by weight. The pure aluminium powder and SiC powder are mixed using three approaches 1) Mixing in V-blender, 2) Mixing in V −blender with steel balls and 3) Barrel mixing with induced shear.

In the first approach, a V-Blender is utilized to mix the powders thoroughly and uniformly for 14 h, while in the second mixing method, steel balls of 12 mm diameter are also added in the V-Blender to reduce caking effect and agglomeration in the powder mix and to achieve uniform mixing of SiC in Aluminium powder. The number of balls is such that all together, they occupy around 20% of the internal volume of V-

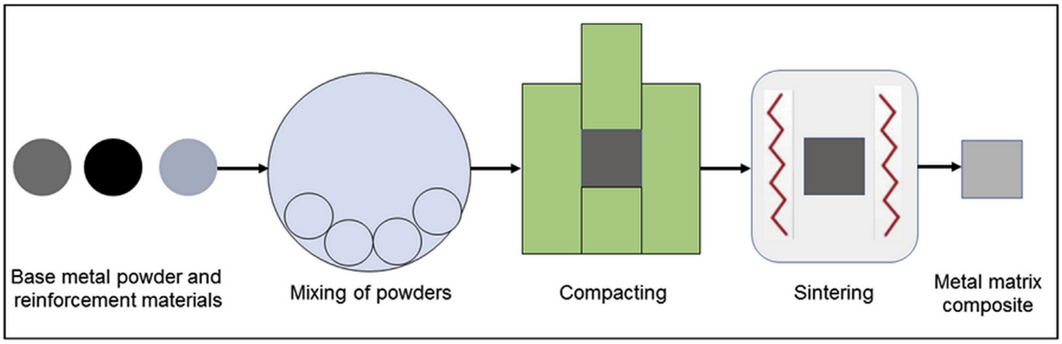

Fig. 1 – Schematic illustration of the powder metallurgy technique to prepare MMCs.

Blender. Agglomeration and clustering at local spots are the two main processing issues in mixing fine powders, affecting the mechanical properties of MMC. A specially fabricated barrel mixer is also utilized to mix the powders in which both barrel and agitator are rotated in the opposite direction. Slots in the ribbon of the agitator were provided to induce the shear during the mixing of powders. Both types of mixing devices used in this experimental study are shown in Fig. 2. Different batches of powder mix have been obtained in which SiC is added to the pure aluminium in the proportion of 15%, 20%, and 25%. After mixing, MMC material is fabricated through the powder metallurgy process. Each time 30 g of mixed powder is taken, it is compacted in a circular die with the help of a steel punch. The compaction of powder is carried out at the pressure of 200 MPa. To estimate density, green compacts are obtained and carefully weighed on a digital weighing machine. Figure 2 presents the die and punches used in this study and the green compacts obtained after the compaction of powders.

After that, in the inert atmosphere of argon gas, all the specimens are sintered at 598 °C for 90 min and water quenched. After quenching, all the samples are dried with the help of hot air. The sintering arrangement is shown in Fig. 2. For microstructural examination, the faces of all the specimens are cleaned, and their faces are prepared through a grinding and polishing machine. Emery papers of 200–1000 grit have been used. Furthermore, all the specimens are polished with a diamond paste of 1 μm and 3 μm. Micrographs are obtained to confirm the presence of SiC particles in the aluminium matrix and uniform dispersion.

2.2. *Surface characterization and mechanical properties*

Micorogrpah and SEM images of the fabricated specimens are obtained to analyze the effect of the proportion of reinforcement material and the mixing method. An image analyzer is utilized for obtaining the microstructure of the prepared samples. The compressive strength of all the samples is evaluated using a universal testing machine with a digital readout. The hardness of each sample is measured for the specimens prepared with different proportions of SiC. For each sample minimum of five readings are considered for each face. The specimens are machined, and hardness at the interior portion is also measured to see the uniformity of results.

2.2.1. *Microstructure of Al-MMC*

The microstructure of Al-MMC of various compositions is obtained through an image analyzer. For the comparison purpose, a few samples are prepared from pure aluminium powder, i.e., without reinforcement, and their microstructure is obtained. Fig. 3(a) and (b) present the Al-MMC made of pure aluminium only and the presence of porosity sites as dark regions resembling grain boundaries. The presence of SiC particles and porosity can be seen easily at various locations in the microstructure, as shown in Fig. 3(c) and (d) for the composition of Al-MMC with 15% SiC and 20% SiC. Uniform dispersion of SiC particles can be seen clearly when the powders are mixed through a barrel mixer.

Fig. 4 (a) and (b) show the microstructure of Al-MMC with 15% SiC and 20% SiC. When powders are mixed through V-Blender, dispersion of SiC particles can be seen but mixing time is very high in the case of V-Blender. Hence subsequently, all the powders are mixed through a barrel mixer only. SEM micrograph is also obtained for the sample prepared through the barrel mixer and, these micrographs also confirmed the presence of SiC particles in the aluminium matrix. SiC particles can be seen with sharp edges, while aluminium particles can be seen with round edges. The SEM micrographs are shown in Fig. 5.

3. Results and discussion

3.1. *Assessment of mixing quality of powders*

A V-Blender and barrel mixer is utilized to mix the powders. Random samples are taken at regular intervals, and element testing is carried out to confirm the proportion of reinforcement in each sample. Mixing is carried out for various time duration, and mixing effectiveness is evaluated. Quality of mixing is better when powders are mixed in a barrel mixer; also, barrel mixer takes less time to achieve the desired quality of mixing. Powder-mix is found loaded with cluster and local agglomeration when mixed with V-Blender. This issue is resolved when steel balls are added to V-Blender. The random movement of the steel ball results in a tumbling effect and helps break the clusters and reduce agglomeration. Based on the mixing index, duration of mixing, and required quality,

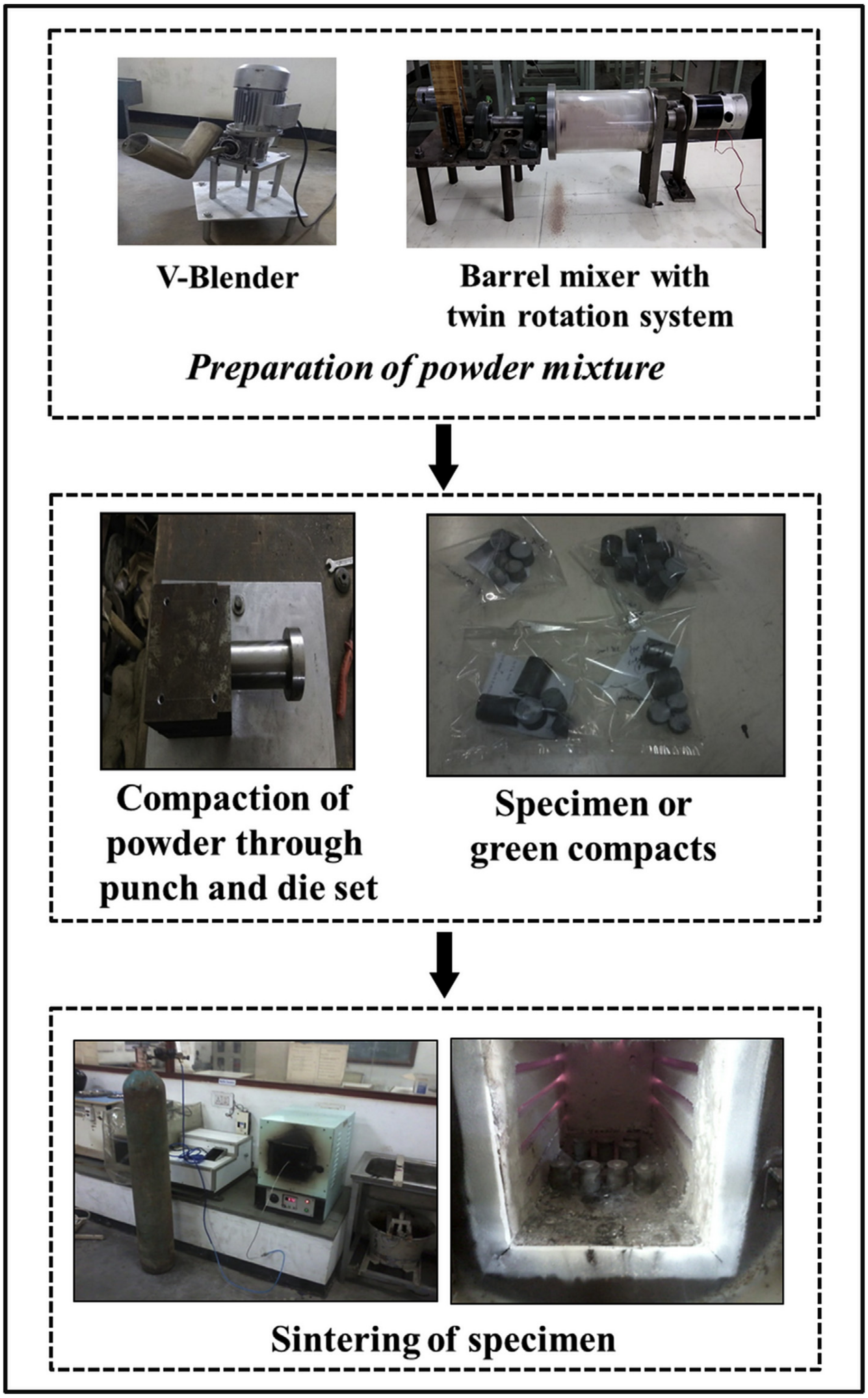

Fig. 2 – The experimental methodology adopted for the work.

the barrel mixer is found better. The performance of mixers is depicted in Fig. 6(a) and (b).

In this study, the lower bound value of the mixing error is set as 5%, i.e., if the aluminium powder is mixed with 20% of Sic powder, then at random in each sample, at least 18–19% SiC should be found. From Fig. 6, it can be seen that the barrel mixer requires only 35–40% of the time compared to V-blender. Hence twin rotation in barrel mixer with shear arrangement worked well for mixing powders.

3.2. *Hardness measurement*

Hardness is one of the target properties of metal matrix composite material that needs due attention. The presence of

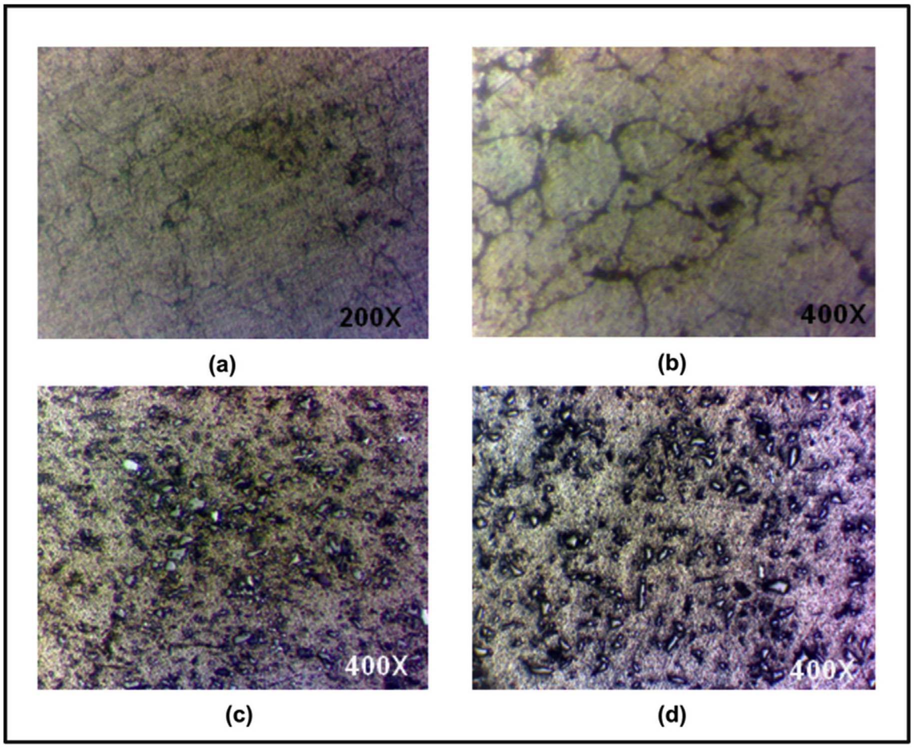

Fig. 3 – Optical images of Al-MMC (a) and (b) without reinforcement (c) 15% SiC and (d) 20% SiC mixed with barrel mixers.

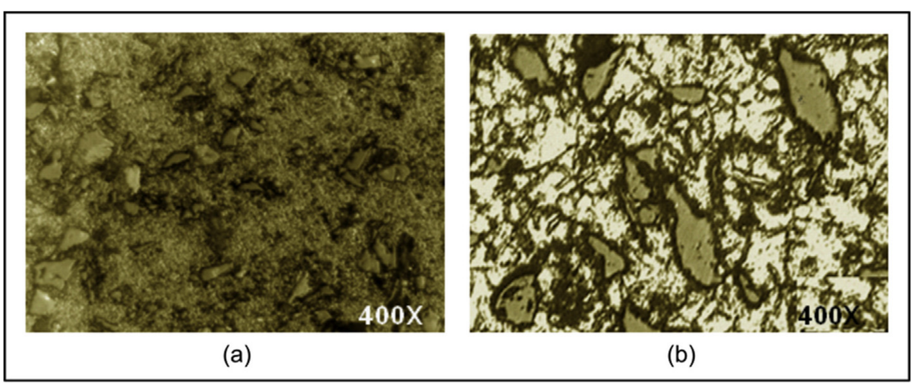

Fig. 4 – Microstructure of Al-MMC with (a) 15% SiC and (b) 20% SiC mixed with V-blender.

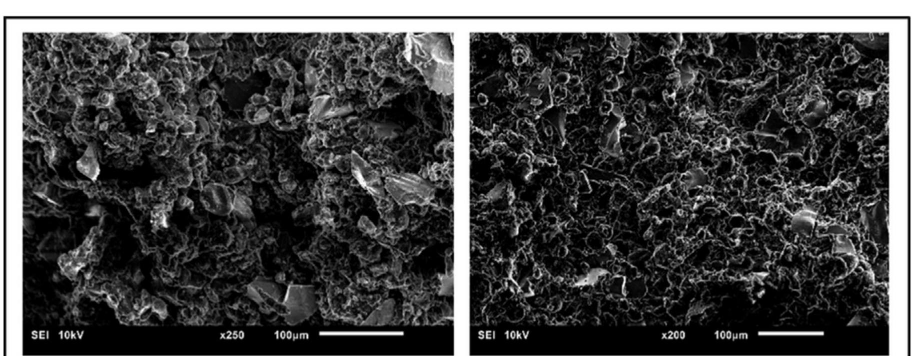

Fig. 5 – SEM images of prepared Al-MMC.

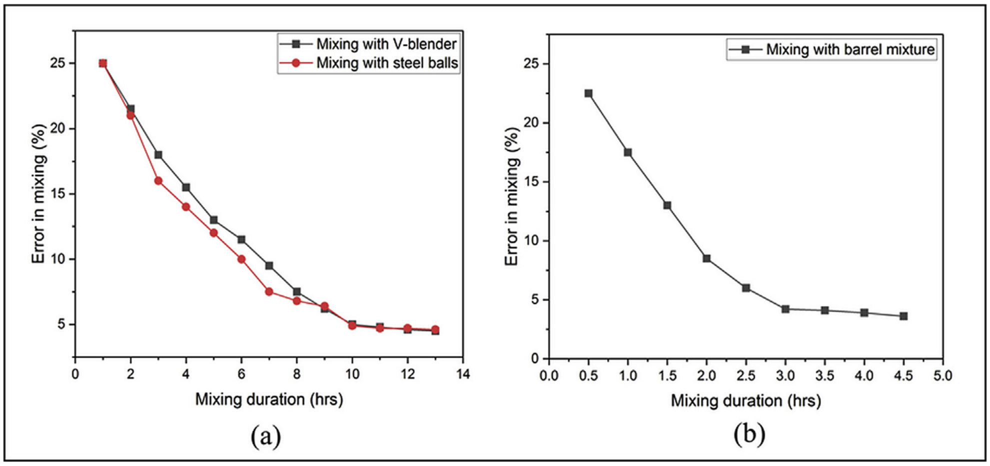

Fig. 6 – (a) Mixing of powders with v-blender (b) Mixing of powders with barrel mixer.

hard particles in a soft matrix-like aluminium always promotes hardness. The hardness of composite material [36] also increases with the increased proportion of hard particles. Many studies [37] reveal that increased reinforcement content increases the hardness [38] of the composite material. In many cases, where the powders of matrix material were prepared by ball milling or similar techniques [11], ball milling powders [18] are subject to severe deformation, grain refinement, and solid dispersion [23]. This leads to the enhancement of the hardness of MMC. Interestingly, the high hardness of ceramic particles contributes to the enhancement of hardness as the load transfer is done to them through the particles of the matrix material. However, where the particle size of matrix material is too fine, then a significant contribution to the enhancement comes from the hard-reinforcement particles, where the bond between matrix and reinforcement, porosity, and voids may affect the resultant hardness.

In the current experimental work, an increase in the hardness of composite material with the increase of reinforcement is evident in Fig. 7. MMC with 25% SiC content is found with the highest hardness value. However, the effect of the mixing method can be seen very clearly. The hardness value is lowest for each composition when powders are mixed through V- blender due to the inherent ineffectiveness of mixing. At the same time, it is better to mix with steel balls, and the best results are obtained when powdered mixed through a barrel mixer. To some extent, steel balls cause work hardening on the particles, especially on ductile particles, which contributes to enhanced hardness and strength. Less dispersion of SiC particles can be responsible for the lower value of hardness, while the degree of dispersion is highest when the powder is mixed through the barrel mixer. As in barrel mixer, SiC particles are mostly uniformly distributed in the aluminium matrix; higher hardness of MMC is observed.

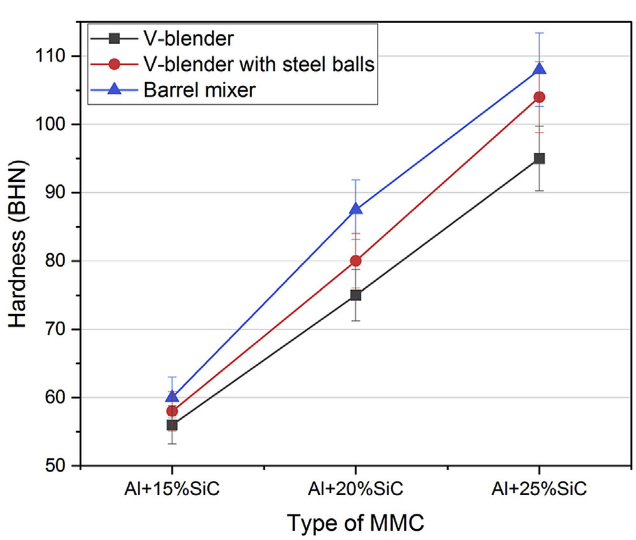

Fig. 7 – The hardness of Al-MMC with varying content of SiC and mixing methods.

Ansary et al. [39] demonstrated that the presence of hard particles like MgO could enhance the hardness of composite material; according to them, there is a difference between thermal expansion of soft and ductile matrix material like aluminium and reinforcement material, which is: in turn, causes an increase in hardness. Tosun and Kurt [25] suggested that the presence of secondary phases in microstructure increases the hardness of MMC, and due to the presence of intermetallic phases which were formed near grain boundaries, strong bonding between reinforcement particles and matrix material were observed, which is clear evidence of enhanced hardness of MMC. In work reported by Nassar et al. [40], titanium dioxide in nano form to reinforce the pure aluminium, and MMC was fabricated by powder metallurgy route. They also confirmed that with the increased content of hard particles, the hardness of MMC increases. In their experimental work, the hardness of titanium dioxide-based Al-MMC was obtained in the range of 52–82 BHN. They found that nanoparticles of reinforcement material hinder the dislocation of the matrix material, and there is an increase in hardness and strength. Mimoto et al. [29] added carbon nanotubes to titanium powder to study the strengthening mechanism and other mechanical properties. They found that incorporating carbon nanotubes in the titanium matrix could significantly increase the hardness, and they achieved a micro-hardness of more than 300 HV.

The Higher degree of dispersion eliminates the probability of such sites where only aluminium is present, and SiC particles may be a little away from such sites when hardness is measured. When repeated readings are taken, the range of hardness among all the observations is least in the case of barrel mixing, which is another attribute for getting the highest value of hardness when powders are mixed through a barrel mixer. The range of hardness measurement decreases when SiC particles are uniformly distributed, and at any random site, SiC particles are found in the vicinity of aluminium particles. Compaction pressure also affects the hardness and gives rise to it, and at higher compaction pressure, sintered porosity is less, and more densification is observed. At the same time, bonding at the interfacial region is also improved, and better load transfer happens, which results in higher hardness.

3.3. *Compressive strength of MMC*

Matrix material, when reinforced by particulate or particle, can enhance the strength of the resultant MMC. According to the micromechanical model [29,30].

$$\Delta R_{p.C} = \Delta\sigma_{\alpha} + \sigma_{KG} + \sigma_{SKG} + \sigma_{KF} \tag{1}$$

The $\Delta R_{p.C}$ is the increase in strength due to the addition of hard particles to the aluminium matrix, which causes enhancement in strength. Shear modulus, Berger vector, and dislocation density are also important elements that affect the MMC's strength. $\Delta\sigma_{\alpha}$ represents the measure of induced dislocations using the following formula:

$$\Delta\sigma_{\alpha} = \alpha.G.b.\rho^{1/2} \tag{2}$$

Hence, if reinforcement material with a higher value of shear modulus is added to the matrix, it will directly impact strength. $\Delta\sigma_{\alpha}$ is considered yield strength contribution, and it occurs due to geometric dislocations and inner tensions. Grain size also influences the stretch of MMC, σ_{KG} Provide the contribution to strength measured due to grain size, estimated through the Hall patch equation. σ_{SKG} Contributes to the yield strength and compressive strength due to changes in grain size during processing. It is immediately affected by the particle size, which decides the grain size. σ_{KF} suggest the effect of work hardening. Generally, in powder metallurgy, when powders are mixed, hardening is introduced in the particles depending on the type of mixer work; the particle of ductile material is greatly influenced by work hardening. Small particles contribute more work hardening effect than coarser particles; as a result, MMC with finer particles may have high strength. In the light of the above facts, the compressive strength of Al-MMC is experimentally investigated. The average compressive strength of Al-MMC is highest when reinforcement content is 25%. The experimental results are shown in Fig. 8, where it can be seen that with the increase of SiC content compressive strength of Al-MMC increases. Sic particle and Al-based solid solutions can readily restrict the propagation of cracks under loading. As a result, more stress would be needed to cause further plastic deformation. Hence with increased content of SiC, compressive strength increases. Also, at the same time, strength is even higher when powders are mixed through a barrel mixer, which is a very effective mixer for uniformly mixing the powders. The uniform mixing ensures that at each location in the Al-MMC, reinforcement particles are dispersed with a great degree of homogeneity; hence no clusters of reinforcement particles are formed, no agglomeration happens, hence, all the SiC particles are uniformly surrounded by the aluminium matrix, and as a result, better strength is observed.

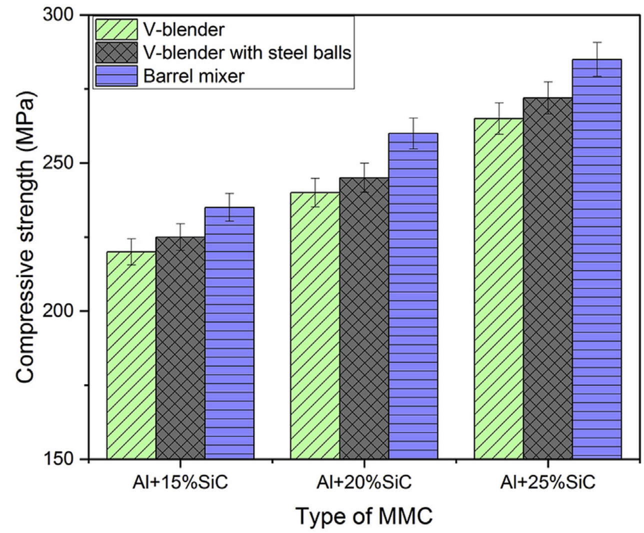

Fig. 8 – Impact of particle size on compressive strength of Al-MMC.

The effect of particle size on compressive strength is illustrated in Fig. 9. The compressive strength decreases as the particle size of SiC increases from finer to coarser. MMC with the finer size of reinforcement is found to be of higher strength, which agrees with the Hall-Patch model, i.e., finer size of reinforcement contributes more strength. Due to the lower size of particle interaction, dislocation also increases [34], which increases the strength of MMC [41]. The coarser particle size does not allow the whole engulfing of reinforcement particles to the maximum extent, the presence of nano and micropores, formation of oxides, and formation of high

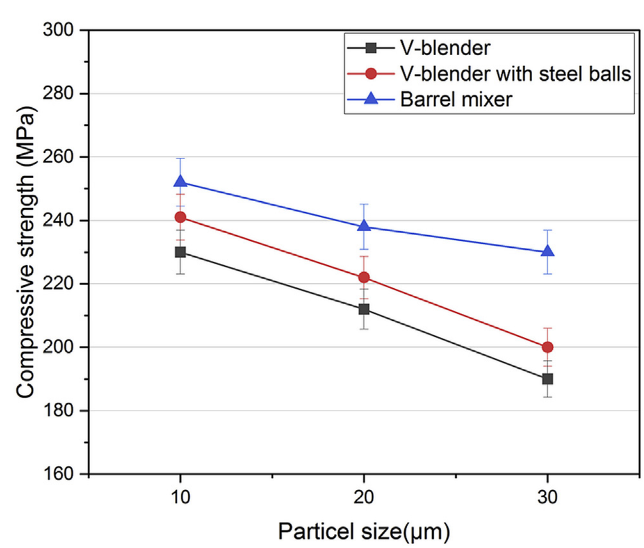

Fig. 9 – Impact of particle size on compressive strength of Al-MMC.

grain angle boundaries result in lowering of strength, which is evident in this experimental study. Rahiman et al. [42] also reported similar results of reduction in the hardness and strength, when the particle size of reinforcement material was increased. They reported a nearly 30% reduction in strength for the increase of particle size by 10–25 μm. The effect of the mixing method is also depicted; compressive strength is higher when barrel mixers are used. Due to uniform dispersion of reinforcement, hard particle availability is ensured at each portion of MMC, and better load transfer takes place from the softer to harder phase.

4. Conclusions

Mixing of powders is very crucial in powder metallurgy, as the quality of mixing directly affects the target properties of the material. Three different approaches are attempted to mix the powders effectively; the mixing quality is of concern when V-blender is used. Its major limitation is the total time required and particle size. As the partial size of the given particle reduces, mixing effectiveness decreases. Powders must be mixed for a prolonged duration to obtain the desired level of mixing. This, in turn, also affects the productivity of the overall process. Following important conclusions can be summarized.

1. When added to the V-Blender, steel balls could improve the mixing process by reducing the cracking effect and random tumbling of balls. When powders are mixed through a barrel mixer, the mixing of powder improves significantly, as high-quality mixing with the desired effect is achieved in less time. Improvement in hardness with the increased content of SiC particles is observed at the same time.
2. The hardness of the developed material is better when powders are mixed with a barrel mixer. As mixing with barrel mixer ensures uniform dispersion of reinforcement, at every location, a combination of hard particles boned by the soft matrix is observed, and enhancement in the hardness is the effect which is observed. Compressive strength of developed material is investigated, and, in line with the concept of hardness, compressive strength is also found increasing with increased content of SiC. The contribution of strength through hard particles can be seen.
3. The hardness of Al-MMC with 20% SiC is more than that of Al-MMC having 15% SiC. An increase in SiC proportion by 5% resulted in an increase in hardness by almost 14%, while another increment in hardness was also observed in Al-MMC, which has 25% of SiC by weight.
4. The experimental results align with the theoretical models as suggested by several researchers. However, an increase in the particle size of reinforcement becomes a matter of concern. The bond of SiC particles by the matrix material is greatly affected by particle size, which is evident. Hence it can be concluded that with the large particle size, the compressive strength of Al-MMC is compromised, which is in line with hall patch equations also.
5. In order to further explore the work, the sintering time and sintering methods can be changed, and the effect on the strength of Al-MMC can be investigated. For future work, it is proposed to analyze the machinability of MMC concerning various parameters like type of reinforcement and their size, cutting forces, tool wear, and sustainable manufacturing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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