Impact of TiB_2 and SiC Reinforcements on Aluminum Alloys: A Comprehensive Analysis of Tribology, Mechanical Performance and Processing

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Abstract. Aluminum alloys based metal matrix composite have become a significant category of engineering materials due to their ability to provide an effective combination of light weight, decent strength to weight ratio and thermal stability. Despite these advantages, a good number of traditional aluminum alloys continue to be not sufficient in the highly challenging industries like automotive, aerospace, marine, and defense where the material has to endure extreme mechanical and tribological environments. The present review describes the impacts of each of the two materials, SiC and TiB_2, and their combination on the properties and performance of the metal matrix composites with aluminum. Combining the two types of reinforcements can result in improved uniformity, enhanced mechanical performance and increased wear resistance of hybrid composites compared to materials reinforced with a single ceramic phase. These composites have been fabricated using a number of methods including stir casting, in situ formation, powder metallurgy and friction stir processing and each has its own advantages and disadvantages. It is established that the addition of SiC may increase the hardness of aluminum composites by approximately 20-50% and the addition of TiB_2 may also increase it by approximately 25-50%. With the reinforcements applied concurrently, the gain in hardness can be as much as 40- 70% and correct proportions of the reinforcements have been discovered to boost tensile strength up to 45. Wear tests also indicate significant reductions in wear rate - usually of the order of 50-60% and reduced friction and increased surface stability. Another contribution to the literature, identified in this review, is the existence of a number of significant gaps in research, which can be addressed in future (through the investigation of nano-scale reinforcements and the creation of hybrid ceramics made of multiple particle types).

1. Introduction

Metal matrix composites (MMCs) made out of aluminum have gained enormous popularity

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over the past decades due to their low weight, high strength-weight ratio, excellent corrosion protection, and predictable thermal characteristics. These benefits render them applicable in applications where the weight reduction is significant yet high performance is needed e.g. in vehicles, aircraft, marine structures and defense components. Nevertheless, there are still limitations of normal aluminum alloys. They wear easily, they lose strength when subjected to high temperatures, and they are unable to support a lot of weight. Due to these problems, researchers have come up with aluminum composites which are reinforced with harder materials to enhance their mechanical and tribological behaviour[1].

Aluminum alloys are usually improved by adding several ceramic particles like silicon carbide (SiC) and titanium diboride (TiB_2). SiC also enables the alloy to become harder and more wear resistant, since it is a highly hard and stable material, which also transfers heat well. The other way through which TiB_2 is beneficial to the alloy is that it assists in creating a smaller grain structure and enables the load to be distributed more efficiently between the reinforcement and the aluminum. This occurs due to the fact that TiB_2 is very rigid, possesses high melting temperature and is bondable with aluminum [2]. This is primarily due to the fact that TiB 2 is very stiff, it melts at a very high temperature and also bonds very strongly with aluminum.

Each of the reinforcers has its own advantages when applied independently. However, when TiB_2 and SiC come together to form hybrid composites, it is even improved. These combined AMMCs typically display improved mechanical strength, smaller microstructure, and enhanced resistance of abrasion and can be used in strenuous engineering applications.

Aluminum composites with SiC and TiB_2 are produced by the use of a variety of methods. These are stir casting, squeeze casting, in-situ reaction processes, powder metallurgy and friction stir processing. These methods possess their advantages, including enhanced mixing of the particles, enhanced bonding of the interface, reduced energy consumption, or lower cost of production. With such techniques still, it is hard to disperse the particles uniformly, avoiding their concentrating in certain spots and to regulate the interaction they have with the aluminum during processing. Recent studies indicate that such parameters as the size of particles, the quantity of reinforcement provided and the ratio applied in hybrid composites should be closely chosen to achieve some desired better mechanical properties and wear resistance.

Since this field is rapidly expanding, it is necessary to learn the nature of the modifications in the characteristics of aluminum alloys with the help of SiC, TiB_2, and their combination. This review outlines the work done in the recent past, in relation to hardness, tensile strength, wear behavior, the microstructural changes, and the key challenges in the production of such composites. It also identifies the field where further research is still required and proposes future opportunities including the use of nano-sized reinforcements, better processing techniques in the solid state and multi- ceramic hybrid systems that can be used in more advanced lightweight applications.

Aluminum-based metal matrix composites (AMMCs) have gained immense popularity over the last few decades due to the following reasons: low weight, high strength-to-weight ratio, high corrosion resistance, and thermal stability. They are used in these applications because of their benefits of being needed in places in which there is a strong emphasis on a weight loss but a high level of performance is necessary, like in automobiles, airplanes, ships, and defense components. Nonetheless, the normal alloys of aluminum have certain limitations. They are not very wear resistant, strength is lost during high temperature and they have limited loads. These have prompted scientists to develop aluminum composites that are reinforced by harder particles so as to enhance their mechanical capabilities and wear ability.

Aluminum alloys are usually improved by adding several ceramic particles like silicon carbide (SiC) and titanium diboride (TiB_2). Since it is a very hard and steady material that is also a good conductor of heat, SiC contributes to the alloy being more resistant to wear and making it stronger. The other way TiB_2 enhances the alloy is by enabling a smaller grain structure and the load to be distributed better between the reinforcement and the aluminum. This is due to the fact that TiB_2 is very hard with high melting temperature and very strong bonding with the aluminum [2]. This can largely be attributed to the fact that TiB_2 is very stiff with very high melting point and that it bonds very well with aluminum.

In isolation, each of the reinforcements has its own positive sides. However, the outcomes are even improved when SiC and TiB_2 are mixed to create hybrid composites. The hybrid AMMCs are stronger, more uniform in microstructure and more resistant to wear thereby making them suitable in heavy-duty engineering applications. Various processes may be used to produce aluminum composite types which include SiC and TiB_2, including stir casting, squeeze casting, in-situ reaction, powder metallurgy and friction stir. With such processes, the distribution of the particles is nonetheless challenging to accomplish evenly, to avoid their aggregation, and to regulate their relationship with the aluminum in the processing. Some recent findings indicate that determining the correct particle size, the quantity of reinforcer applied and the proportion of reinforcer in hybrid composite is significant in attaining improved strength and wear resistance. Since the process of work in the field is still developing, it should be known how the effects of the use of SiC, TiB_2 and a combination of these two materials on the characteristics of aluminum alloys are expressed. The present review provides a summary of recent data on hardness, tensile strength, wear behavior, microstructure, and the major problems encountered during the manufacturing of such composites. It also reveals the areas that remain to be researched further and the applications in the future, which could be using nano-sized reinforcements, improved solid-state processing techniques, or hybrid systems which use more than one type of ceramic reinforcement to lightweight products.

2. Literature Review

The inclusion of both SiC and TiB2 rendered the aluminum harder, denser, and even with the structure [1]. They mentioned that the TiB2 served to tear the grains into smaller sizes whereas, SiC served to wear the material. Similar findings were found among Singh et al. [10]. Al-Zn-Cu alloys with SiC and TiB2 reinforcers in their work demonstrated greater tensile strength and could assume loads more in comparison with alloys that lacked these reinforcements. Such findings are consistent with the previous research by James et al. [12], who established that composite reinforcements that used both were more effective than the ones that utilized one.

TiB_2 particles which form within the metal during processing have also consumed a significant amount of time to be studied by researchers. In 2019, Sahoo et al. [2] reported the use of in-situ methods to make an Al -Si -TiB_2 composite, and found that this technology created stronger bonding regions, reduced porosity, and provided a more homogenized dispersion of the particles. A Seshappa et al. [9] reached the same conclusion. They also reported that in-situ TiB_2 enhances the ease with which the material can be worked and lowers the cast defects resulting to stronger components.

Aluminum composite wear is still being researched extensively. Dey et al. [11] discovered in 2021 that incorporation of TiB_2 assists the metal to resist wear owing to the fact that it is extremely hard and adhesive to the aluminum. In 2024, Bhowmik et al. [5] demonstrated that (TiB_2 + SiC) will allow a reduction of wear by up to 60 percent and render the surface smoother. Other works using only one reinforcement, such as Muthu et al. [14] with SiC in LM25 or Bhowmik et al. [5] with Al7075/SiC, had SiC alone also reduce the wear, but a combination of both is better and helps the metal to stay strong in harsh conditions. Single-reinforcement studies such as the ones by Muthu et al. [14] of SiC and Bhowmik et al. [5] of Al7075/SiC demonstrate that SiC benefits wear, however, dual reinforcement is more

effective and long-lasting in hard environments.
A lot has been done in comparing the various ways of making these composites as well. Soltani et al. [28] considered the stir casting and concluded that stirring speed, temperature and wetting agent use are highly significant in the distribution of the particles. Later works based on the friction stir processing and friction stir welding demonstrated that the heavy plastic deformation reduces the grains to a smaller size and strengthens the SiC/TiB_2 composites. Research on the powder metals, such as Li et al. [12], concluded that the inclusion of nanoparticles may enhance the behavior of the substance in various directions and increase its ductility.
Some have also examined the corrosion handling, machining and new hybrid designs of these composites. Chebolu et al. [30] observed that the incorporation of hard ceramic particles can be used to make aluminum resistant to rust. It also discovered that hybrid composites require additional force to cut but provide a smooth surface. Other applications, such as multiple varieties of ceramics or microscopic TiB_2 particles Li et al. [12], demonstrate that the materials may be made even stronger and longer-lasting. There is a definite enhancement of the overall performance when various reinforcements are used.
A number of review literature, such as Singh et al. [3], Ujah et al. [21], Mathivanan et al. [22], and the 2024 AMMC review indicate comparable trends in aluminum composites. They emphasize that it is necessary to regulate the microstructure, identify how better to distribute reinforcing particles uniformly, and how to establish optimal combinations of ceramic materials. Other gaps in research are also observed in the reviews, such as the performance of such composites in the real working environment, their behavior to various temperatures, and their long-term stability during the regular course of operations.
Aluminum alloys are strengthened, harder and more resistant to wear out by adding SiC and TiB_2 either separately or in combination. This is brought out clearly in the literature. The techniques of production and experimentation have been improved over the years, and work is still required, which can satisfy the requirements of more recent and harder technical applications. Future research should focus on improving solid-state processing methods, making good hybrid combinations, and using fine-scale reinforcements to make performance more reliable and consistent.

3. Processing Techniques

There are many different ways to process SiC- and TiB_2-reinforced aluminum matrix composites, and each one has its own benefits in terms of particle distribution, interfacial bonding, microstructural refinement, and mechanical performance. The literature identifies several primary fabrication methods, including melt-based processes, solid-state processing, in-situ synthesis, and powder metallurgy. Stir casting is the most widely used technique because it is cheap and easy to use.

3.1 Stir Casting and Melt-Based Routes

According to the work of Bhowmik & Dey [1] and Seeniappan et al. [7], stir casting continues to be the most widely used method for producing AMMCs. During this, molten aluminum is stirred mechanically in order to have the added SiC, TiB2 or even a mixture of the two to evenly spread through the molten mass. The reason why the method is popular is that it is cheap, can be used in large production volumes and can be reinforced with various materials. Even so, there are issues like the clustering of particles, ineffective wetting, and creation of porosity.
The research on hybrid composites prepared using melt-based processes demonstrates a definite change in strength and wear behavior. According to Singh et al. [4] and James et al.

[13], the combination of SiC and TiB_2 is used to refine the grains and enhance the method of transferring the load between the reinforcement and the matrix. Seeniappan et al. [7] also demonstrated that melt processing could be used to create more hard composites and that the harder the reinforcement, the harder the composite.

3.2 In-Situ Synthesis of TiB_2 Reinforcements

In-situ processing has garnered significant interest due to its capacity to produce TiB_2 particles directly within the aluminum melt via chemical reactions, commonly involving potassium hexafluorotitanate (K_2TiF_6) and potassium tetrafluoroborate (KBF_4). Sahoo et al [2] stressed that in-situ formation leads to better bonding at the matrix–particle interface, less agglomeration, and smaller reinforcement sizes than adding particles from the outside. Previous experimental studies cited in the same review [2] validated that in-situ TiB_2 produces uniformly distributed particles, resulting in enhanced strength and wear resistance. In the same way, the conference study by Seshappa et al. [9] found that TiB_2 produced in-situ makes the material more fluid and reduces casting flaws such as shrinkage and micro voids. These benefits make the in-situ method good for making high-performance composites with more complex microstructures.

3.3 Solid-State Processing and Friction Stir Techniques

Friction stir processing (FSP) and friction stir welding (FSW) are solid-state methods known to improve how evenly SiC and TiB_2 particles are spread in aluminum composites. Ali et al. [6] noted that the stirring action during FSW moves the metal enough to distribute the particles properly and form much finer grains in hybrid composites. Since the metal stays solid, common melt-related issues like porosity and segregation are mostly avoided.

These methods also cause dynamic recrystallization, which increases the material’s strength, hardness, and joint stability. Due to this reason, FSP and FSW are employed in the enhancement of surfaces, restoration of damaged portions, and welding reinforced aluminum components without negatively affecting their useful mechanical characteristics.

3.4 Powder Metallurgy and Mechanical Alloying

Powder metallurgy can be applicable to produce aluminum composites containing insignificantly small particles of TiB_2 or SiC. Li et al. [12] discovered that the addition of TiB_2 nano-particles to 2024Al enhanced the ductile quality of the substance, caused the structure to become more homogenous, and increased a set of directions in terms of performance. The reinforcement can be carefully controlled by this method and the size and placement of the particles can be controlled, which is important when a particular mechanical property is required. Other steps which must be taken so that the process can be completed include pressing or sintering the material to solidify it.The bonds are stronger and the particles are more evenly distributed when mechanical alloying is combined with powder metallurgy. However, the technique requires accurate equipment, regulated conditions of working, and additional measure such as hot pressing or sintering to convert the powder into a solid object.

3.5 Advanced and Hybrid Processing Approaches

Recent development has been on the merging of various types of reinforcements in ceramics, novel sintering, and better processing of techniques. According to Chinababu et al. [31], with the inclusion of several reinforcement steps, which is achievable by controlled casting or other composite technologies, the structure of the material could be modified, to fit a given engineering need. Research concerning AA7475/TiB_2/ SiC hybrid composites (Taylor and Francis, 2025) has also considered the environmentally friendly production processes that do not use much energy but do not compromise performance. It was demonstrated by Muthu et al. [14] that stirring speed, preheating, the treatment of the reinforcing particles, and the sintering steps are the issues that influence wear resistance of the material strongly.

4. Mechanical Properties

The behavior of aluminum with the addition of SiC, TiB2 and the two alloys has been studied by many researchers. The nature of the particle, its size, a portion of it utilized as well as the dispersal of the same through the metal all affect the hardness, strength, stiffness and the manner in which the material fractures. Using a combination of the two types of reinforcement SiC and TiB2, the composite tends to maintain higher performance since each reinforcement is supported and the other in order to allow the metal to move the loads more efficiently.

SiC is also a material that is considered to be very hard and stable at high temperature, the characteristics also transfer to aluminum when it is incorporated. A review of literature on the topic by Singh et al. [3] and Bhowmik et al. [5] found significant improvements in hardness, with a range of improvements of approximately 20-45 % depending on the amount of SiC utilized and particle size. Figure 1 illustrates that reinforced alloys based on SiC have a continuous increase in value of hardness, in comparison to the base material, which substantiates the findings of such studies.

TiB_2 also gives good enhancements. According to research provided by Dey et al. [11] and the 2021 publication of Wiley, hardness has increased approximately 25-55%, and tensile strength and elastic modulus have also been reported to gain noticeable. TiB2 has a good affinity to aluminum and this aids in better transfer of loads. Figure 2 illustrates this phenomenon and TiB2 composites exhibit greater tensile strength compared to samples of SiC only.

Composites that are reinforced with both TiB2 and SiC always perform better as compared to those reinforced with single ceramics. Hardness improvements of 40-70% James et al. [13], 45% Singh et al. [4], and 45% Seeniappan et al. [7] and strength improvements of approximately 45 were found. The combined reinforcements help refine grains, limit porosity, and reduce early crack formation. Figures 1–3 reflect this, as hybrid systems show the best hardness, strength, and wear behaviour across all groups.

Hybrid AMMCs generally perform much better in terms of wear. Bhowmik et al. [5] and Muthu et al. [14] noted that when SiC and TiB_2 are used together, the material often loses only about half as much during wear tests. The ceramic particles help cut down scratching and keep the surface steady when the parts slide against each other. Because of this, the hybrid samples in Figure 3 show the least amount of wear.

Most studies report the same outcome. When SiC and TiB_2 are used together, the material becomes stronger, harder, and better at resisting wear than when either one is used alone. When quantity of individual particles is adjusted accordingly and processing of the material is done in the right manner, the advantages are even more. Due to this reason, these hybrid AMMCs are increasingly making use of them in car, aircraft, and defence parts where the material must be capable of handling large loads and is in constant operation.

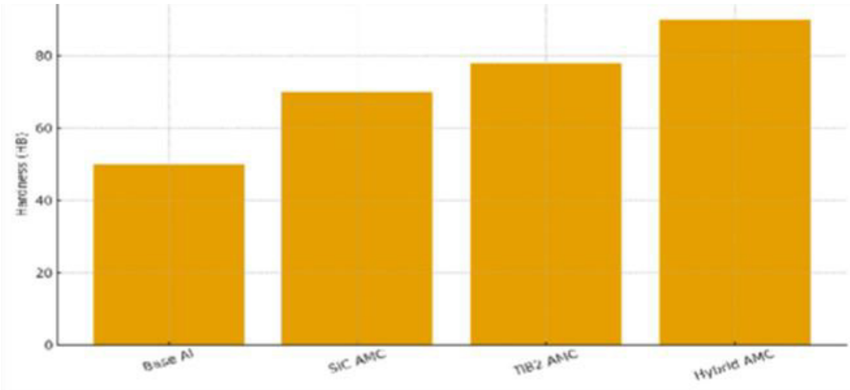

Fig. 1. Hardness improvement.

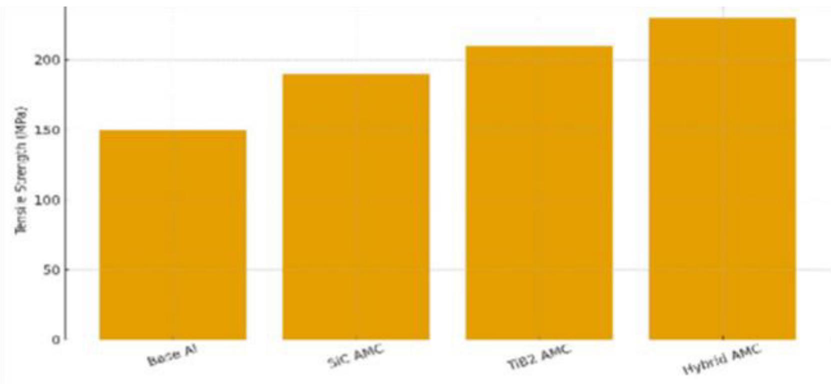

Fig. 2. Strengthening of the tensile strength.

5. Tribological Behaviour

The way an aluminum composite wears is significant when it is to be utilized in such applications as brakes, aircraft linkages, marine components, or defence apparatus. The sliding surface does not behave in the same way when a mixture
of SiC or TiB_2 is introduced into the metal. Most of the researchers who experimented with the two reinforcements hand in hand found that the outcome was normally enhanced, solely due to the fact that every material has a distinct role to play within the alloy.

SiC is also very hard and hence it assists in reducing scratching which would usually occur during sliding. According to Singh et al. [3] and Bhowmik et al. [5] and Muthu et al. [14], the wear decreased significantly, about a third or even half when compared to plain aluminum. The same is observed in Figure 3: the SiC composites wear less, but still the hybrids win the race. TiB_2 works differently. It glues itself to the aluminum to a greater degree and forms a rigid internal structure that supports some of the load during the rubbing of the surface. A 2021 review and Dey et al. [11] noted that this reduces wear as well as makes the friction more reliable as the material is not that easy to bend or break. That is equal to what is shown by Figure 3.

The best results come when SiC and TiB_2 are used together. Studies by Bhowmik et al. [5], James et al. [13] and Seeniappan et al. [7] showed that the wear can drop by around half, sometimes even more, and the friction also goes down. SiC adds hardness, while TiB_2 helps

the particles stay bonded and stops tiny cracks from spreading. Figures 3 and 4 show this clearly, with the hybrid composites performing the best overall.
If the amount of each particle, the way they are spread, and the processing steps are adjusted carefully, the hybrid composites can be made even more resistant to wear. Because of this, they are becoming a realistic option for parts that have to deal with constant rubbing and heavy surface loads.

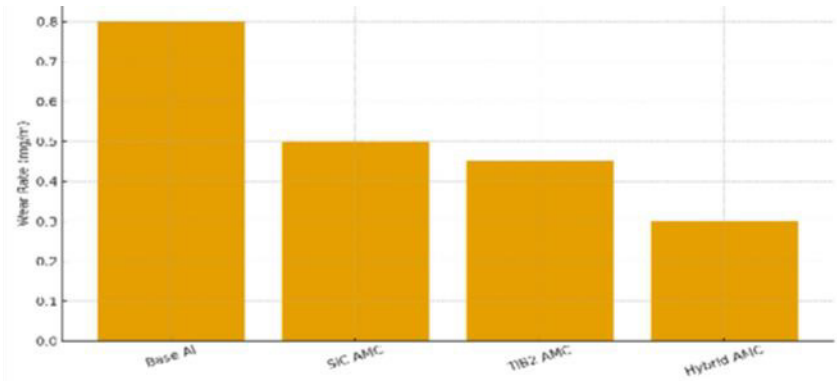

Fig. 3. Wear rate reduction.

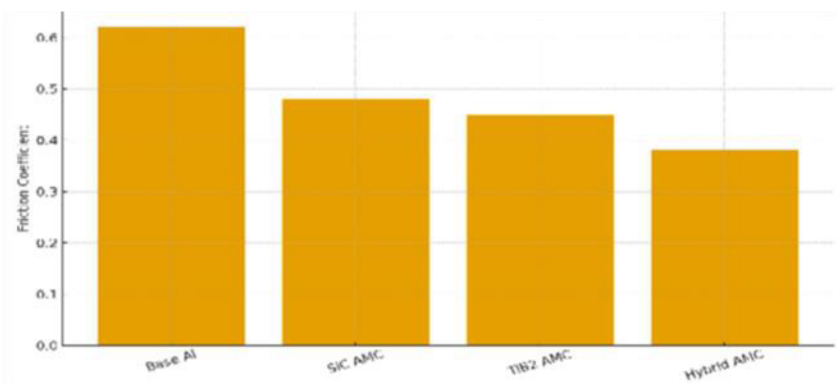

Fig. 4. Coefficient of friction.

6. Research Gaps and Future Scope

Although a lot of work has been carried out on aluminum composites reinforced with SiC, TiB_2, and their mixtures, several important issues still remain. A typical challenge is the maintenance of the particles that are distributed well in the metal. At large reinforcement, the particles will form clumps and this will form pores and reduce the strength. This is usually not easily attained with conventional stir-casting and other melt-based techniques particularly when the shape is complex. More effective processing techniques that provide enhanced mixing and enhance wetting of the particles are yet to be developed. Another gap is the limited understanding of how hybrid AMMCs behave over long periods in real working conditions. Only a few studies look closely at how these materials respond to repeated loading, high or changing temperatures, corrosive environments, or fast impact. Many papers report improvements in hardness and wear, but far fewer examine fatigue strength, thermal stability,

or how the material breaks down after long service.
The use of nano-sized SiC and TiB_2 is another area that has not been explored enough. Early work suggests that very small particles may produce stronger and more wear-resistant composites because of their higher surface area. However, it is still difficult to keep these particles from clumping together and to understand how they interact with larger particles inside the metal. Most available studies also focus on only a few aluminum alloys, such as AA6061 and some Al-Si and Al-Zn-Cu grades. There is still plenty of scope to test hybrid reinforcements in other types of aluminum, including aerospace-grade, marine- grade, and high-temperature alloys. This would give a clearer picture of how hybrid systems behave across a wider range of materials. New processing techniques are becoming important for improving hybrid AMMCs. Methods such as ultrasonic-assisted casting, high-shear melt treatment, additive manufacturing, and repeated friction stir processing can give much better control over how the material forms and help reduce common casting problems. There is also a tendency of researchers to employ computer tools to determine the impact of various particle sizes, reinforcement levels and processing conditions on the final material. Experiments can be planned and better hybrid composites developed within a reduced period using these tools.

7. Conclusion

This review has combined what various researchers have documented about aluminum matrix composites reinforced with SiC, TiB_2, or a mixture of both. All in all, there is one commonality between the studies this is that the addition of these ceramic particles makes the alloy tougher, harder and much more resistant to wear. SiC plays its main role in enhancing hardness and minimizing surface damage and TiB2 aids in strengthening the metal by enhancing grain structure and bearing heavier loads. Combining both the particles in a single experiment yields significantly more improvements than either of the two reinforcements can do individually.
Despite these positive results, there are still some practical issues on which attention should be paid. Diffusion of the particles in the melt, the limitation of the porosity and durability of the material at actual service conditions are still the challenges. Furthermore, few aluminum alloys have been investigated up to date with hybrid reinforcement, and a great number of systems remain uninvestigated. The future work should be aimed at better processing ways, selection of appropriate mix of reinforcements, and investigations of micro- and nano-scale additions to create more sophisticated composite.
In conclusion, SiC and TiB_2 are promising combinations that can be used to improve the characteristics of aluminum alloys. Future studies of alternative processing paths, alternative alloy matrixes, as well as more realistic durability assay, will contribute to making these hybrid composites increasingly applicable to large-scale engineering applications.

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