Development of advanced hybrid ZA43–Gr–SiC composite with improved mechanical properties for sustainable transportation applications

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Abstract. The development of high-strength-weight ratio and wear resistant metal matrix composites (MMCs) has demanded due to the requirements imposed by the transportation sector for light, high-performance and environmentally friendly materials. Due to its good castability, the corrosion resistance and properties as bearing are excellent in zinc-aluminum alloy ZA43. However, ZA43 is known to have a strength that is too low, deteriorating under high temperature conditions. To address these issues, this work utilizes silicon carbide (SiC) and graphite (Gr) as reinforcements for ZA43. The microstructural analysis showed that the reinforcements were spread out evenly throughout the material. The mechanical testing showed that the tensile strength, hardness, and toughness were all higher than those of mono ZA43. The findings suggest that ZA43–Gr–SiC hybrid composites could be advantageous for environmentally sustainable transportation systems that necessitate durable, lightweight materials.

1 Introduction

Engineers are making strong, light, and eco-friendly materials to keep up with the fast growth of the auto industry. Reducing unnecessary weight has many benefits, such as improving fuel efficiency, lowering greenhouse gas emissions, and helping people follow environmental rules [1-3]. Due to their diverse design options, enhanced wear resistance, and exceptional strength-to-weight ratios, metal matrix composites have become a prominent field of research.

Among zinc-aluminum (ZA) alloys, ZA43 is distinguished by its remarkable castability, bearing properties, and intrinsic corrosion resistance [4,5]. Still, the monolithic ZA43 isn't strong enough and doesn't hold up well under high stress or heat, which limits its use in advanced transportation systems [6]. A successful approach to addressing these concerns is the utilization of reinforcements composed of ceramic and solid lubricant. The mechanical and tribological performance of hybrid composites is improved through the integration of reinforcements possessing complementary properties [7]. Reinforcing silicon carbide is an

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established technique that enhances toughness, load-bearing capacity, and complexity [8]. On the other hand, graphite works as a solid lubricant and makes a self-lubricating surface coating while rolling, which reduces wear and friction [9]. Adding these reinforcements to a ZA matrix makes the material stronger, more resistant to wear, and more stable in size, while still keeping its flexibility [6][10].

Despite the increasing interest in hybrid MMCs, the systematic examination of ZA43-based composites concurrently reinforced with graphite and SiC is still constrained. Understanding microstructural evolution, distribution of reinforcements, and the resulting mechanical behavior (tensile strength, hardness, and toughness) is critical to tailoring these materials for industrial applications. Although individual studies have explored ZA43–SiC and ZA43–Gr composites separately, but investigation on ZA43–SiC–Gr hybrid composites is limited. This study aims to fill this research gap by fabricating ZA43–Gr–SiC hybrid composites via stir casting and evaluating their mechanical properties under varying reinforcement contents.

2 Materials and methods

2.1 Materials selection

ZA43 alloy has been chosen as the matrix material due to its outstanding bearing and wear resistance characteristics, coupled with the high strength performance typical of zinc aluminum alloys. Composition of ZA43 is listed in Table 1. Silicon carbide and Graphite were used as reinforcement materials. SiC is incorporated for increasing the hardness, whereas Gr is utilized to improve the lubrication properties.

Table 1. Composition of ZA43 alloy [4].

Elements	Al	Cu	Mg	Fe	Zn
Weight %	43	2.5	0.02	0.012	Balance

2.2 Composites preparation

Stir casting is one of the best ways to make metal matrix composites because it is easy to do, does not cost much, and can be used for large-scale production. Figure 1 illustrates the stir casting process.

In the present study, ZA-43 alloy composites were synthesized via the stir casting route. The base alloy was first heated in a furnace to approximately 550 °C, exceeding its melting point, to ensure complete liquefaction. At the same time, 400 °C was used to warm up the SiC particles, which reduced temperature gradients and stopped flaws that could have been caused by water. The molten metal was mixed with a motorized stirrer that turned at 600 rpm. This made sure that the reinforcements were spread out evenly. In the end, this made a stable tornado. There is less pressure in one part of the melt than on its surface because of the vortex. This makes it easy to add reinforcements. At this point, graphite particles and silicon carbide (SiC) powder were both added at a controlled feed rate of 100 g/min. Table 2 shows a list of different mixtures of reinforcement materials. To ensure that the replacements were spread evenly in the ZA-43 matrix, stirring continued for another 4–5 minutes at the same speed.

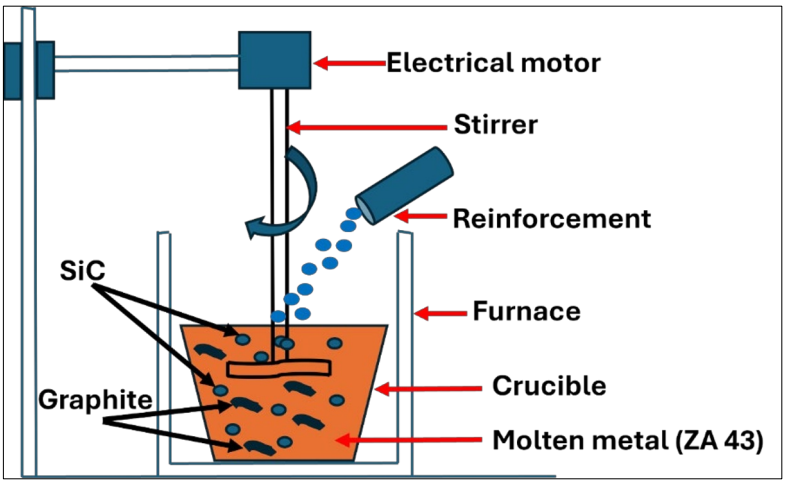

Fig. 1. Schematic diagram of stir casting process.

Table 2. Combination of reinforcement materials.

S. No.	Gr (%)	SiC (%)
1	0	1
2	1	3
3	3	3
4	5	3

The molten mixture was poured into a preheated die (steel). During the controlled cooling process, external pressure was applied for two to three minutes to densify the material and reduce the number of holes within it. When the mixture was completely solid, the pressure was released, and the cast was removed and cut to the correct size. Before casting, the die and mixer were preheated to avoid sudden temperature changes and ensure even microstructural development.

2.3 Evaluation of mechanical properties

Test specimens that were 10 × 10 mm in cross-section and 55 mm in length subjected to the Charpy impact test for the toughness evaluation. A swinging pendulum hits the specimen across from the notch in this way, breaking it. The impact is made when the 250 N pendulum falls from a height of 1.457 meters at an angle of 140°. The notch impact strength is measured by breaking a V-notched specimen and figuring out how much energy was taken compared to the cross-sectional area of the specimen. Before the test, the equipment was set up so that the zero-reference point meant that the pendulum blade barely touched the specimen when it was free to swing. During the tests, each object was securely held in place in a square-shaped support.

A universal testing machine (UTM) was used to find out the tensile properties of the composites. The tests were done with a crosshead speed of 1 mm/min, which is about the same as a theoretical strain rate of 0.001 s^{-1}. Load–elongation data were continuously recorded using dedicated software for detailed post-test analysis. As illustrated in Figure 2, cylindrical specimens were subjected to uniaxial loading, with force applied simultaneously at both ends during testing.

Fig. 2. Specimens for tensile testing.

For the Brinell hardness evaluation, specimens with an 18 mm diameter were prepared and carefully polished using Emery paper. The hardness of the composite samples was measured using a Brinell hardness testing machine. A load of 187.5 kgf was applied for 3 seconds to assess the micro-hardness of each specimen, and readings were recorded individually for all samples.

3 Results and discussion

3.1 Microstructure of composites

Figure 3 shows the optical microstructure of composites. It is observed that when Gr is reinforced up to 1%, SiC dominates in composites, while when Gr is increased to 3 % and 5 %, Gr dominates in composites due to lower density of graphite as compared to SiC. Presence of both particles in composites is anticipated to better mechanical and tribological properties due to synergistic effect of both particles (SiC and Gr).

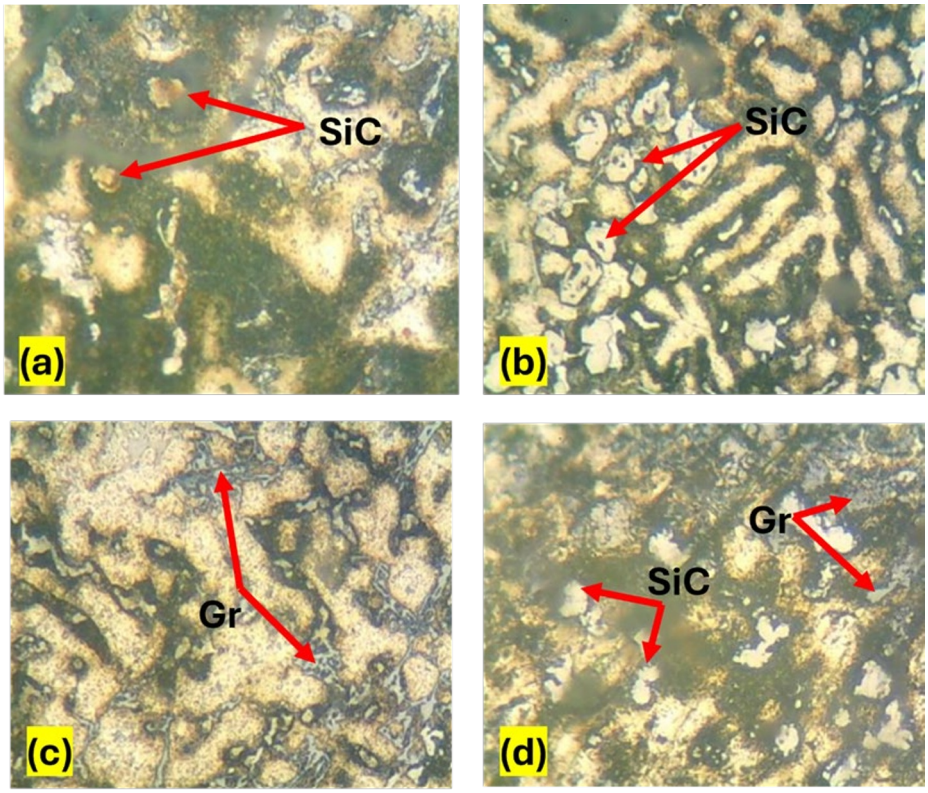

Fig. 3. Microstructure of composites: (a) ZA43 + 1% SiC, (b) ZA43 + 3% SiC + 1% Gr, (c) ZA43 + 3% SiC + 3% Gr, and (d) ZA 43 + 3% SiC + 5% Gr.

3.2 Toughness of composites

The Impact strength refers to the capability of a material to withstand sudden shocks or impacts by absorbing and dissipating energy. Not only do standard design parameters determine whether or not a composite is good for a job, but so does its ability to absorb energy. Figure 4 illustrates the impact energy of ZA-43 metal matrix composites reinforced with SiC and graphite particles, showing a consistent rise in impact energy as the filler content increases.

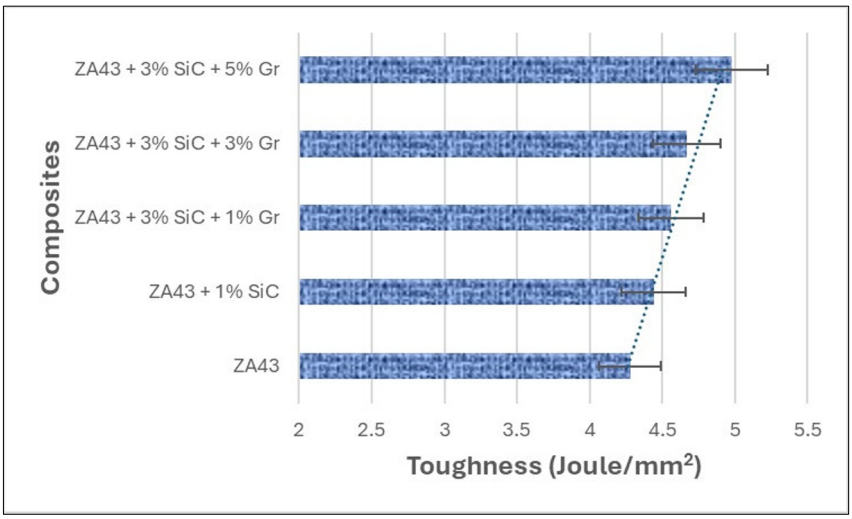

Fig. 4. Toughness of different composites.

3.3 Tensile strength of composites

Figure 5 shows the tensile strength test results for ZA43–SiC–Gr composites. No matter what kind of reinforcement is used, the tensile strength goes up as the filler percentage goes up in all specimens. This is because the hard particles can transfer loads from the softer matrix to the reinforcement phase, thereby increasing the composite's load-bearing capacity. As the percentage of fillers' weight increases, the support must carry more weight, which makes the structure even stronger. Additionally, hard ceramic particles, such as SiC, prevent plastic deformation by blocking the flow of the matrix, thereby contributing to the higher tensile strength.

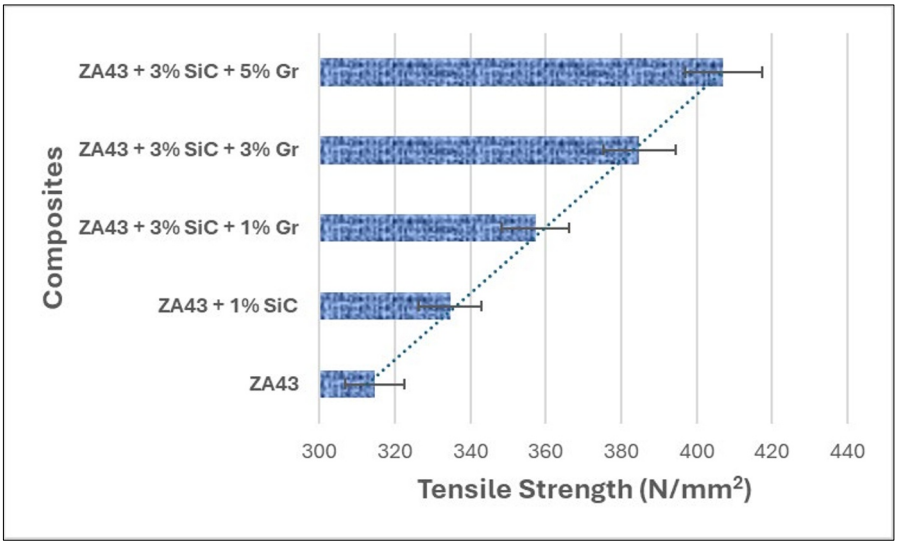

Fig. 5. Tensile Strength of different composites.

3.4 Hardness of composites

Figure 6 shows how changing the amount of graphite in cast ZA43–SiC–Gr particle mixtures change how hard they are. It appears that the hardness decreases as the amount of graphite increases. In particular, the hardness decreases noticeably when the graphite level increases from 1% to 5%. This trend is likely to continue, as graphite is a soft phase that does not contribute to making the material harder. As previously mentioned regarding ductility, the graphite in the material acts as a solid lubricant, permitting the grains to move more easily and therefore increasing the material's flexibility under the hardness tester's indenter. The composite's hardness consistently goes down as the amount of graphite added increases. This limits the amount of graphite that can be added to improve the composite's other mechanical properties. Therefore, determining the optimal amount of graphite to add in order to enhance the composite's final tensile strength and compressive strength while minimizing its hardness as much as possible is necessary.

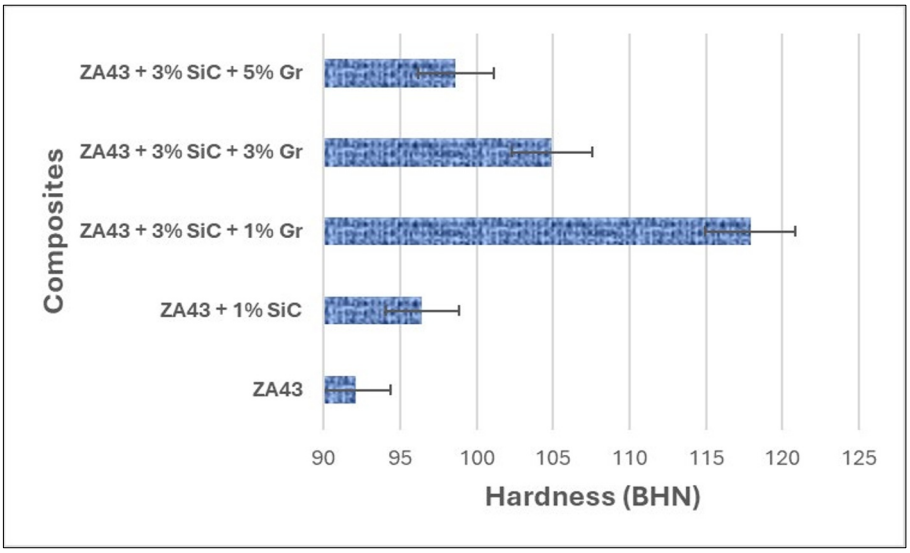

Fig. 6. Hardness of different composites.

4 Conclusion

Adding silicon carbide and graphite to ZA43 alloy through the stir casting method improves its mechanical properties, as the study shows. The even spread of reinforcements and improved bonding between surfaces resulted in significant improvements in tensile strength, hardness, and toughness compared to ZA43, which was a solid material. In these improvements, the alloy's natural weaknesses are lessened under heavy loads. This demonstrates that ZA43–Gr–SiC hybrid composites can be utilized in transportation as lightweight, strong, and eco-friendly materials.

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