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Effect of Silicon Carbide Particulates on Mechanical Behavior of Al5052 Alloy Metal Matrix Composites for Mining Applications

V. Mohan[1], N. B. Doddapattar[2] and K. Sunil Kumar[1]

[1]*Department of Mechanical Engineering, R L Jalappa Institute of Technology, Doddaballapur - 561203, Karnataka, India; mohanv.dbpur@gmail.com*

[2]*Department of Mechanical Engineering, Cambridge Institute of Technology, North Campus, Bengaluru - 562110, Karnataka, India*

Abstract

In particular, the impact of Silicon Carbide (SiC) particles on the mechanical properties of stir-cast Al5052 alloy Metal Matrix Composites (MMCs) for rotor blade applications is examined in this work. The goal of integrating SiC particles is to improve mechanical characteristics including wear resistance, tensile strength, and hardness while preserving the ideal weight-to-strength ratio, which is essential for rotor blade performance. The Al5052 matrix was filled with SiC in a variety of compositions (0%, 2%, 4%, 6%, and 8% by weight), and the resultant composites underwent mechanical testing and microstructural examination. Due to the efficient load transfer and reinforcing processes, the results show a considerable improvement in tensile strength and hardness with the addition of SiC particles. Furthermore, microstructural analyses demonstrate a uniform dispersion of SiC in the matrix, which supports the improved performance attributes. Wear resistance of Al5052 alloy is greatly increased when Silicon Carbide (SiC) particles are added as reinforcement. This makes the composite material perfect for applications requiring great durability and longevity to survive hard mining conditions, such as wear plates, conveyor liners, and drill bits in mining machinery components.

Keywords: *Al5052 Alloy, Mechanical Characteristics, Mining Applications, Stir Casting, SiC*

1.0 Introduction

Because of its exceptional versatility, aluminum and its alloys have been greatly sought after in technical applications since the early 20^{th} century. These materials are very attractive for a variety of applications because they have exceptional mechanical and physical qualities and are reasonably lightweight. Aluminum is particularly positioned in the aerospace industry as a material for structural applications, automotive, and high-rise construction because of its high strength-to-weight ratio. Moreover, aluminum has great thermal and electrical conductivity, which is about half that of pure copper. It is a good option for power transmission cables because of its strong mechanical strength and combination of these qualities. Particulate-reinforced aluminium matrix composites are extensively utilized in the aerospace, automotive, and structural domains. They possess exceptional attributes such as a superior strength-to-weight ratio, exceptional resistance to wear and tear, increased stiffness, improved fatigue resistance, controlled thermal expansion, and improved stability at elevated temperatures. These qualities outperform those of conventional metals and alloys, which makes them perfect

**Author for correspondence*

for a variety of cutting-edge components[1-5]. Compared to materials processed using traditional methods, which have coarse grains, materials produced by the stir casting process frequently have high concentrations of flaws and finely separated grains, which adds to the materials strength. This kind of technique shows great potential for increased fatigue life, wear resistance, and strength in the materials that are developed. This can be further enhanced by controlling the viscosity within allowable bounds, using alloys that are not highly reactive to the reinforcement, using inert gas atmospheres to prevent oxidation, heat treating the reinforcement particles to remove gas layers that impede particle-melt wetting, and swirling the melt to stop particles from settling because of density differences. A large body of research highlights the importance of stirring speed as a critical process variable in the manufacturing of aluminium composites. As a result, traditional processes like extrusion, drawing, and rolling are unable to duplicate the qualities of materials produced using stir casting[6–10].

With the goal of generating active flow patterns for even solid particle distribution within the molten liquid, Hashim *et al.*, used finite element analysis to recreate fluid current and ascertain the beliefs for stirring speed and impeller position[11]. Parallel to this, Naher *et al.* carried out leveled-up stirring experiments using SiC particles serving as reinforcements and fluids that resembled the melt characteristics of aluminum. These tests, which were carried out in clear crucibles, made it easier to visually record run designs[12]. In order to create Al-SiC composites by stir casting, Ravi *et al.,* investigated mixing parameters utilizing a water prototupe, taking into account variables like speed, blade angle (impeller), and rotation direction[13]. In order to replicate flow patterns and comprehend the effects of stirring limitations such blade angle, speed, impeller size, and geometry, Lu and Lu used finite element modeling[14]. Sahu and Sahu optimized stirring parameters such blade angle, impeller size, and stirring speed using the Grey Taguchi technique and computational fluid dynamics to simulate fluid flow. This chapter examines a number of readings that investigate the effects of stirring and additive parameters, as well as how to optimize them, when producing Aluminum Matrix Composites (AMCs) and Hybrid Aluminum Matrix Composites (HAMCs) using the stir casting process[15]. Prabu *et al.*, looked into how stirring procedures affected the creation of Al/105 SiC composites. Their investigation showed that different stirring times and speeds affected the composite's toughness and fundamental structure. Particle agglomeration was caused by lower stirring speeds and shorter stirring times, whereas improved particle distribution was made possible by higher stirring speeds and longer stirring times[16]. Furthermore, Prasad *et al.* use a twofold stir casting method to investigate mixed matrix metal compositions using 8% rice husk ash and SiC particles. Their results showed that SiC and Rice Husk Ash (RHA) were distributed uniformly throughout the matrix phase. They observed enhanced yield and ultimate tensile strengths correlated with the quantity of RHA and SiC, as well as increased porosity and hardness with greater percentages of reinforcement[17]. Kumar *et al.* used varying weight fractions and particle sizes in stir casting to produce Al6061 composites with fly ash. Their results show that the samples ductile strength, hardness, and compressive strength were all impacted by the fly ash's particle size. Even though the smallest amount of fly ash increases ultimate and compressive strength while decreasing ductility[18]. Rajani *et al.* investigated a variety of casting concepts for Al-Si-Mg composites supplemented with wing powder particles. They found that by using a modified compo casting procedure, a porosity-free composite with the right particle distribution was produced[19]. Jayaseelani and colleagues evaluated the extrusion behavior of stir-cast and powder metallurgy-produced Al-SiC in a different investigation. When compared to specimens made using powder metallurgy, they discovered that stir casting generated specimens with finer microstructures, higher hardness, and greater strength[20]. Moreover, stir casting was used by Keshavamurthy and colleagues to create Al7075-TiB2 *in-situ* composites, which showed significantly greater microhardness, yield strength, and ultimate tensile strength than the unreinforced alloy[21].

2.0 Materials and Methods

Because aluminum 5052 alloy is so versatile, it may be alloyed into a wide variety of series. These series are classified by the Aluminium Association (AA Inc.) according to the alloying elements they contain, and each series is assigned a four-digit designation. The 5xxx series, which mostly uses magnesium as the primary

(a)

(b)

Figure 2. **(a).** Al5052 alloy. **(b).** Silicone carbide.

alloying element, is notable among them. Magnesium and manganese together form a work-hardenable alloy that is moderately to extremely resistant. Interestingly, magnesium is a far better hardener than manganese; Around 0.8% of magnesium is equal to 1.25% of manganese, meaning that much larger amounts can be added[22–27].

Particulates of Silicon Carbide (SiC) are being used more often as reinforcement in Al5052 alloy to improve its mechanical characteristics. SiC is a hard, lightweight material that greatly increases hardness, wear resistance, and tensile strength. As such, it is perfect for applications that need to be durable, like rotor blades. SiC particles are added to improve load distribution and reduce deformation under stress. SiC's tiny particle size also makes it easier for the SiC to disperse uniformly throughout the Al5052 matrix, which improves interfacial bonding. The aerospace and automotive industries can benefit from the development of innovative metal matrix composites with improved performance thanks to the synergy between SiC and Al5052 alloy[28–32].

In order to help mix reinforcing ingredients into the matrix material, a mechanical stirrer is introduced during the casting process, a method known as "stir casting." Because of its affordability, mass production suitability, ease of shape, and enhanced control over the composite structure, this approach works well for creating MMCs. Using this technique, the furnace has a bottom hole in the melting crucible that allows for bottom pouring and is protected by a metal shell that is cylindrical. The Al 5052 alloy matrix melts during the stir-casting process and is held at a particular temperature in this furnace for two to three hours at 650 ^{o}C. Simultaneously, a second furnace is used to warm silicon carbide reinforcements at varying percentages of 2%, 4%, 6%, and 8%. The process of churning to form the vortex starts as soon as the matrix material melts[33].

3.0 Testing of the Composite's Materials

As seen in Figure 3(a), the Brinell Hardness tester was used to determine the hardness of the research materials. As seen in Figures a and b, the surfaces of the microstructure sample were further polished using 400, 600, 800, and 1000 grain sand sheets. After this process, the samples were polished to a mirror-like sheen and any scratches on the work surface were removed using a disc polisher[34]. Clemax Image software was used to examine the composite specimens under a microscope. This microscope's computer interface, high-resolution camera, and 50–100X magnification range, when combined with Clemax software, enable it to analyze updated programs and assess and save data. The polished samples were

Figure 2. Sequence of composite preparation: (**a**) Temperature measurement using pyrometer, **(b)** Nitrogen gas cylinder and pressure control valves, **(c)** Nitrogen degassing, **(d)** Mechanical stirrer system, **(e)** Stirring the molten Al5052 alloy, **(f)** Warming of reinforcements, **(g)** Metal die casting, **(h)** Finger moulding die, **(i)** Chalk powder coated die, **(j)** Pouring composite slurry into die, **(k)** Developed casting, **(l)** Different composites materials.

cleaned for 10–20 seconds with a Kroll reagent (2 ml of hydrofluoric acid, 6 ml of nitric acid, and 92 ml of distilled water) before being scanned with a Japan optical metallurgical microscope[24]. The ASTM D638 procedure was used to assess the tensile strength. Figures 3(c) show the testing specimens that were utilized. According to ASTM E8/E8M-11 criteria ta M/s, tensile tests for the Al5052 alloy and composites were carried out using the INSTRON-5560 tensile testing instrument. Utilizing an automated mechanical testing machine (DAK UTB9103) with a crosshead speed of 0.04 mm/min, the compressive responses of the as-cast were investigated. The test was conducted at room temperature, and as indicated in 3d, round samples with a diameter of 10 mm and a height of 25.5 mm were made in compliance with ASTM standard E9-09. The equipment guarantees a clean and moisture-proof environment and resets to the home position prior to every test. The close contact between the specimen surface and jaw face has been ensured with great care. Five typical samples were used for the testing, and the average reading was noted along with the value.

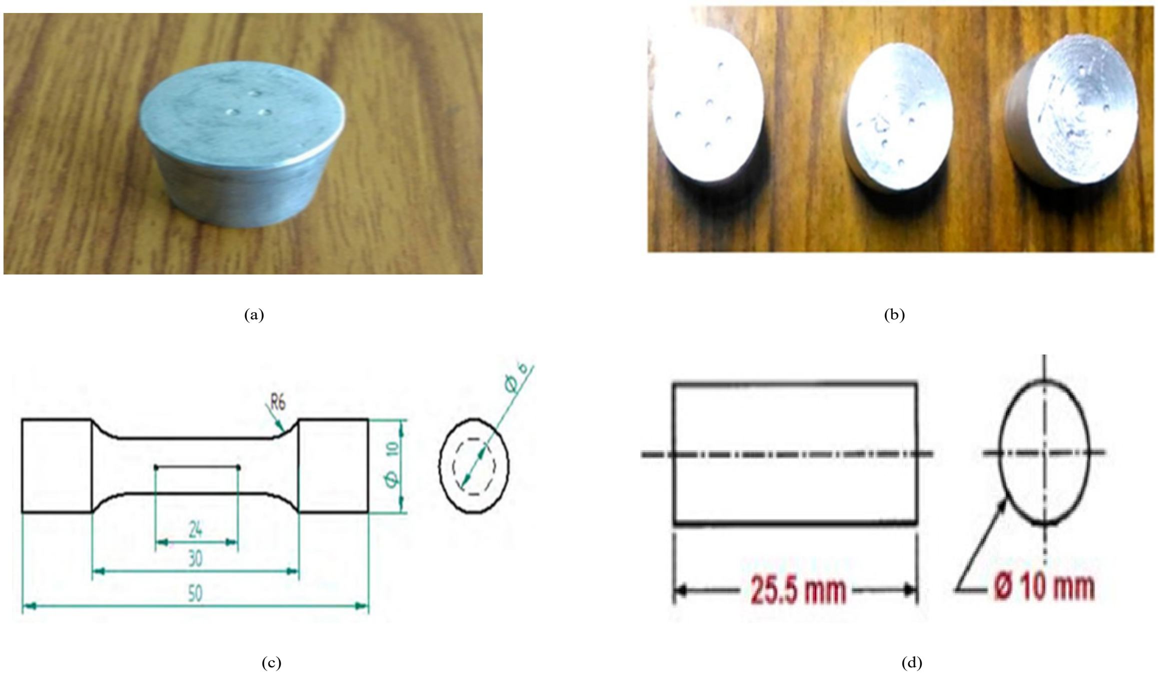

Figure 3. **(a).** Microstructure and hardness specimens for Al5052 alloy. **(b).** Microstructure and hardness specimens at different compositions. **(c).** Tensile strength specimens. **(d).** Compression test samples.

4.0 Results and Discussion

4.1 Study of Microstructure

There are notable variations in the microstructure of Al5052 alloy reinforced with silicon carbide (SiC) particles when the SiC percentage ranges from 2% to 8%. As seen in Figure 4(a), Al5052 is an aluminum-magnesium alloy renowned for its good resistance to corrosion and moderate strength. Because SiC is hard and stable, adding SiC particles improves the characteristics of the composite material. Particulates are evenly dispersed throughout the aluminum matrix at 2% SiC, which leads to a minor improvement in hardness and strength over the basic alloy. There is little interfacial reactivity and strong interaction between the SiC particles and the Al5052 matrix at their clean interface. Particulate matter is more prominently seen in the microstructure when the SiC level rises to 4%, which results in better load transfer between the reinforcement and matrix. As seen in Figure 4(b), this further improves the mechanical qualities of the composite, such as enhanced wear resistance and stiffness. Particulate clustering starts at 6% SiC and can lead to stress concentration spots. The probability of crack initiation at these clusters may rise even while the overall strength and hardness are becoming better. As demonstrated in Figure 4(c), appropriate processing methods are essential to guarantee uniform distribution and reduce clustering. The microstructure has a high particle density with 8% SiC, which could cause agglomeration and porosity. While the composite's stiffness and hardness may increase, its ductility may decline. To keep a balance between the possible disadvantages of high particle content and the enhanced mechanical qualities, careful supervision of the manufacturing process is necessary. The peaks corresponding to the SiC particles and the Al5052 matrix are found by analyzing the XRD pattern. The International Centre for Diffraction Data (ICDD) database's standard diffraction patterns are consulted. Both Al5052 (usually at $2\theta = 38°, 44°, 65°$ corresponding to the (111), (200), and (220) planes) and SiC (usually around $2\theta = 35°, 41°, 60°$ corresponding to the (111), (220), and (311) planes) have notable peaks that are detected. As seen in Figure 5a, the phase composition is ascertained by analyzing the relative intensities and peak positions. The Scherrer equation (1) is used to estimate the crystallite size of the phases.

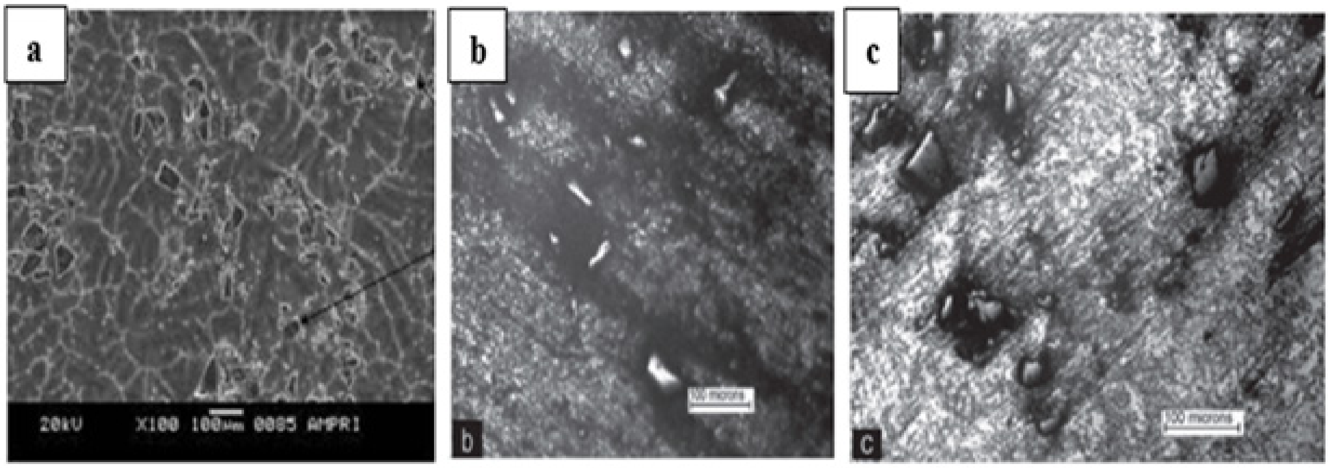

Figure 4. Microstructure of Al–SiC MMC fabricated at 600 rpm: **(a)** Al5052 alloy, **(b)** Al5052+4 wt.% SiC **(c)** Al5052+6 wt.% SiC stirring.

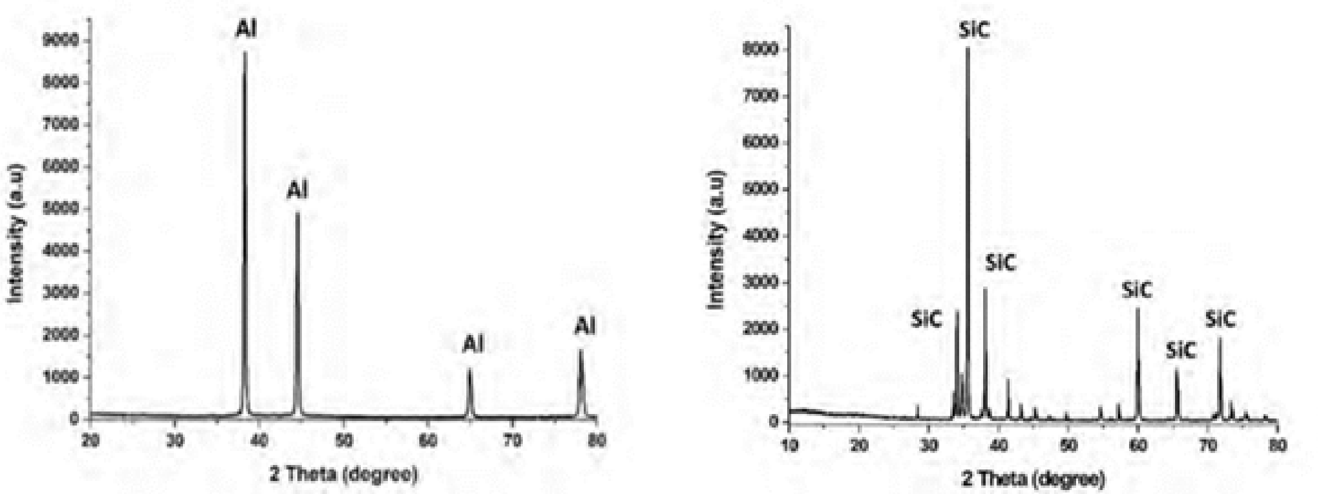

Figure 5. **(a).** XRD analysis of Al5052 alloy. **(b).** XRD analysis of SiC.

$$D = \frac{K\lambda}{\beta \cos\theta} \quad \text{Eq. (1)}$$

Where D is the crystallite size, K is the shape factor (typically 0.9), λ is the wavelength of the X-ray, β is the full width at half maximum (FWHM) of the peak, and θ is the Bragg angle.

Lattice strain and material flaws may also be indicated by the peaks widening, on distinguish between the effects of strain and size on peak broadening, utilize a Williamson-Hall plot. Al5052 and SiC-corresponding peaks are found. If there are any more peaks, they are examined to see if any inter metallic compounds or secondary phases have developed. Using the Scherrer equation, the crystallite size of the SiC particles and the Al5052 matrix are determined. For instance, the crystallite size can be determined if the FWHM of a peak located at 2θ = 38° (Al (111) plane) is 0.1°. The lattice strain and the existence of defects are shown by the broadening of the peaks. The XRD pattern verifies the existence of SiC particles. The XRD data suggest the nature of the interaction, including load transfer and bonding, between the SiC particles and the Al matrix. The

Al5052-SiC composite's phase composition, crystallite size, lattice strain, and overall structural integrity are all well-informed by the XRD investigation. Understanding the material's characteristics and possible uses in a variety of industries requires knowledge of this data. As seen in Figure 5b, additional investigation, such as Transmission Electron Microscopy (TEM) or Scanning Electron Microscopy (SEM), can supplement the XRD results for a thorough evaluation.

4.2 Density Analysis

The alloy aluminium 5052, or Al5052, is renowned for having a high fatigue strength, exceptional weldability, and outstanding corrosion resistance. It is extensively employed in many different industries, including as the aerospace, automotive, and marine sectors. Metal Matrix Composites (MMCs) are created by mixing Silicon Carbide (SiC) particles with Al5052 alloy to improve the material's mechanical characteristics and overall performance. The variations in density of Al5052 alloy with varying weight percentages (2%, 4%, 6%, and 8%) of SiC particles are the main focus of this investigation. SiC particles were added to the Al5052 alloy in different weight percentages (2%, 4%, 6%, and 8%). A typical stir casting procedure was used to manufacture the composites in order to guarantee that the SiC particles were distributed uniformly throughout the Al5052 matrix. The theoretical density of the composites was calculated using the rule of mixtures:

$$\rho_c = \frac{W_m \rho_m + W_p \rho_p}{W_m + W_p} \quad \text{Eq. (2)}$$

where:

ρ_c is the density of the composite.

Wm and Wp are the weight fractions of the matrix (Al5052) and particulate (SiC), respectively. ρ_m and ρ_p are the densities of the matrix and particulate, respectively. The Archimedes principle was used to determine the composites real density. Based on the densities of Al5052 (2.68 g/cm³) and SiC (3.21 g/cm³), the theoretical density of the Al5052-SiC composites was computed. Because of porosity and other flaws induced during the composite fabrication process, the actual densities were found to be somewhat lower than the theoretical values.

When SiC particles were added, the density of the composites rose. The difference between the theoretical and actual densities suggests that porosity or voids may

- 2% SiC:

$$\rho_{2\%} = \frac{0.98 \times 2.68 + 0.02 \times 3.21}{0.98 + 0.02} = 2.692 g/cm^3$$

- 4% SiC:

$$\rho_{4\%} = \frac{0.96 \times 2.68 + 0.04 \times 3.21}{0.96 + 0.04} = 2.704 g/cm^3$$

- 6% SiC:

$$\rho_{6\%} = \frac{0.94 \times 2.68 + 0.06 \times 3.21}{0.94 + 0.06} = 2.716 g/cm^3$$

- 8% SiC:

$$\rho_{8\%} = \frac{0.92 \times 2.68 + 0.08 \times 3.21}{0.92 + 0.08} = 2.728 g/cm^3$$

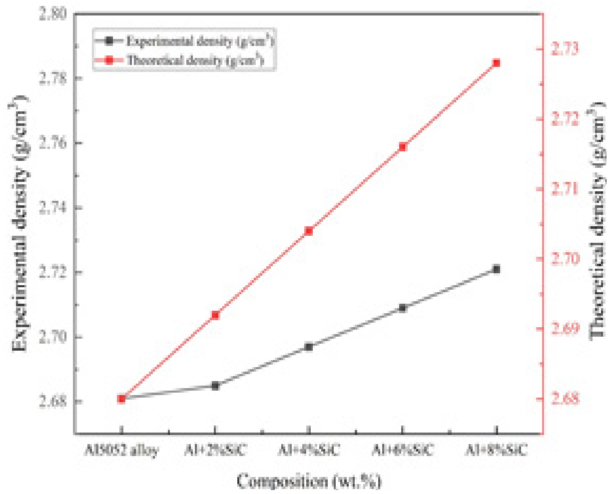

Figure 6. Density of the Al5052-SiC metal matrix composites.

have been present, as well as the impact of processing conditions. The efficiency of SiC as a reinforcing material in raising the overall density of the composite is demonstrated by the gradual increase in density with greater SiC content. Figure 6 illustrates the positive association between the amount of SiC applied and the final composite density in the density study of Al5052 alloy reinforced with SiC particles. The measured densities were marginally lower than the theoretical values, which emphasizes the significance of processing technique optimization for defect minimization. The investigation validates that adding SiC particles to Al5052 alloy can significantly improve its density and possibly its mechanical characteristics, qualifying it for use in cutting-edge engineering applications.

4.3 Hardness

Magnesium content and the microstructure have the most effects on hardness. By adding 2% SiC particles, hardness is marginally increased by adding more barriers to dislocation movement. Particle dispersion improves with 4% SiC, leading to a notable increase in hardness as a result of better load transfer between the reinforcement and matrix. The composite exhibits a significant increase in hardness at 6% SiC. SiC particles have a more uniform distribution, hence improving reinforcing and impeding dislocation movement even more. The composite with 8% SiC has the maximum hardness. But an increase in SiC concentration might also cause particles to cluster, which could bring in stress concentrators and have a detrimental effect on other mechanical qualities like toughness. SiC particles are added to the Al5052 alloy, increasing its hardness. As Figure 7 illustrates, the reinforcement effect is noticeable even at lower weight percentages, with notable improvements noted at greater SiC levels. According to this investigation, SiC reinforcement successfully raises the hardness of Al5052 alloy, making it appropriate for uses that call for increased mechanical strength and wear resistance.

SiC particles are frequently added to Al5052, a non-heat-treatable aluminium alloy that is well-known for its good corrosion resistance and moderate strength, in order to improve its mechanical qualities. The composite material typically has a higher compression strength as the SiC percentage rises. The hard, brittle SiC particles, which serve as reinforcement within the softer aluminium matrix, are responsible for this improvement. The Al5052 alloy displays its baseline compression strength at 0% SiC. Because of the first reinforcement action, the composite exhibits a discernible increase in strength when 2% SiC is applied. As more SiC particles are added, the compression strength increases with 4% and 6% SiC, offering better resistance to deformation. Generally, the compression strength peaks at 8% SiC. But as Figure 8 illustrates, these advantages may be somewhat outweighed by potential negative effects including increased brittleness and possible problems with particle agglomeration caused by the high SiC content. To sum up, Al5052-SiC metal matrix composites show improved compression strength as SiC concentration increases that is, until an ideal point is reached, after which brittleness and dispersion issues may cause the material to lose some of its benefits.

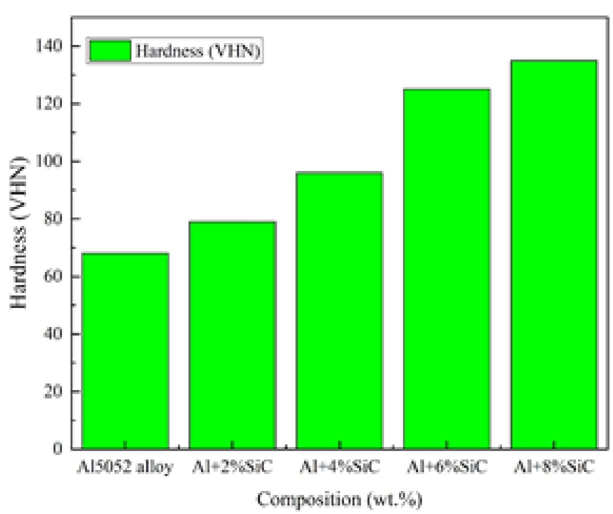

Figure 7. Hardness analysis of composites.

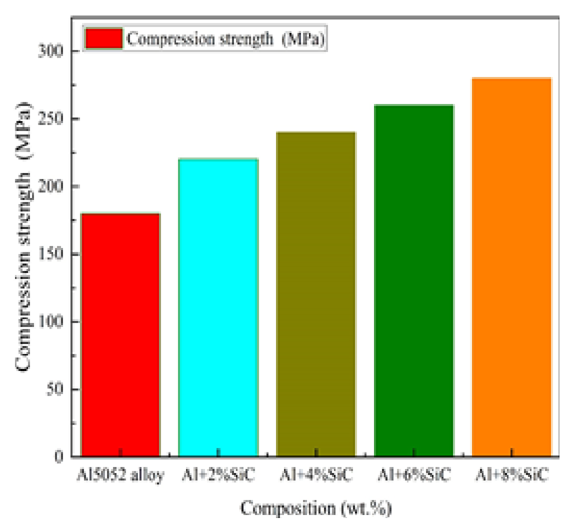

Figure 8. Compression strength of the composites.

4.4 Compression Strength

One important factor to consider while assessing the mechanical performance of Al5052 alloy reinforced with different weight percentages of SiC particles (0%, 2%, 4%, 6%, and 8%) is the compression strength of the material.

4.5 Tensile Strength

When compared to the unreinforced alloy, the tensile strength of the Al5052 alloy reinforced with Silicon Carbide (SiC) particles at different weight percentages (0%, 2%, 4%, 6%, and 8%) significantly improves. SiC

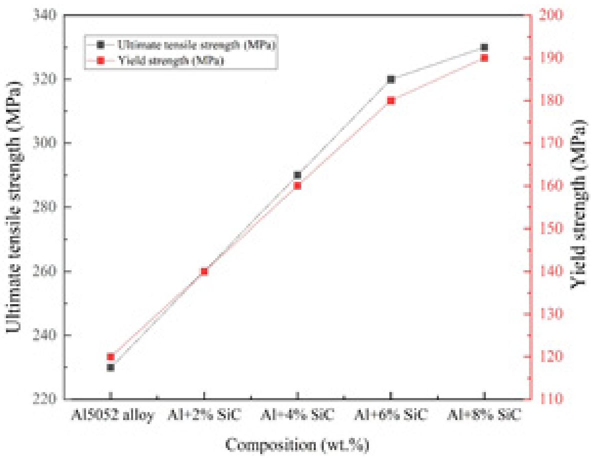

Figure 9. Ultimate tensile strength.

particles are added to Al5052, which is well-known for its good resistance to corrosion and moderate strength. This reinforcement helps to improve the mechanical properties of Al5052. The pure Al5052 alloy's tensile strength acts as the benchmark when there is no reinforcement. The load transfer from the softer aluminum matrix to the harder SiC particles is responsible for the appreciable increase in tensile strength observed with the addition of 2% SiC particles.

The tensile strength improves even higher as the SiC content rises to 4% and 6% because of the improved dislocation density and more effective stress dispersion surrounding the particles. At 6% SiC reinforcement, where the matrix and reinforcing particle equilibrium is at its best, the optimal tensile strength is frequently found.

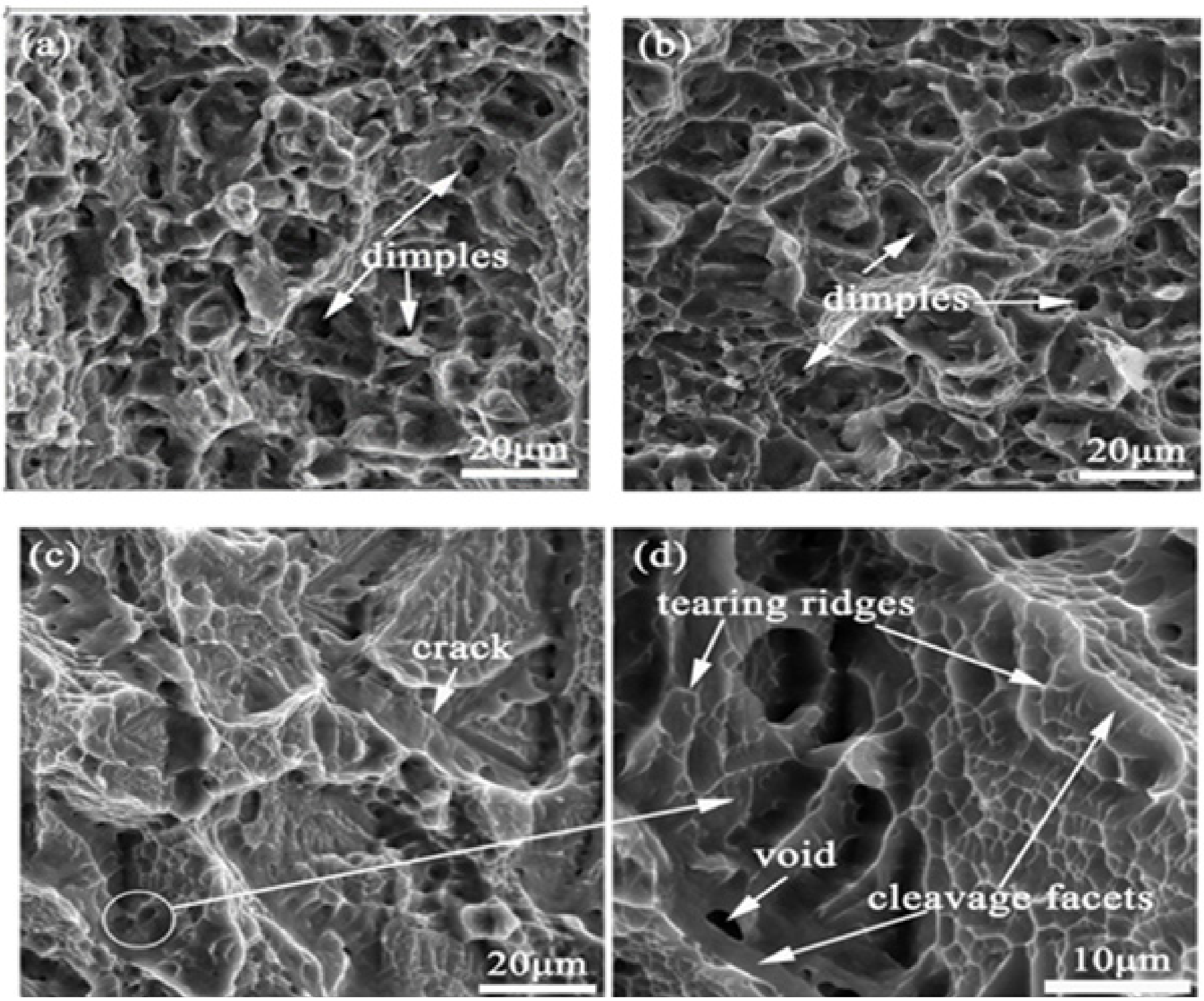

Figure 10. Tensile fractured surfaces of Al5052-SiC composites.

However, because of the likely agglomeration of SiC particles, which could result in stress concentration sites and potential flaws in the composite structure as shown in Figure 9, the tensile strength at 8% SiC may not increase considerably or may even slightly decrease. The present work underscores the promise of Al5052 composites reinforced with SiC for applications that necessitate enhanced mechanical performance and greater tensile strength.

4.6 Fractured Surface Analysis

Tensile strength in Al5052 alloy reinforced with SiC particles of different weight percentages (0%, 2%, 4%, 6%, and 8%) was analyzed using fractured surface methodology, which provides important insights into the failure mechanisms and mechanical behavior of these metal matrix composites. Tensile strength usually increases with increasing SiC content because of the ceramic particles hardening action. As seen in Figure 10a, the Al5052 alloy shows ductile fracture with prominent dimples at 0% SiC, indicating considerable plastic deformation. Smaller dimples and sporadic cleavage facets, as seen in Figure 10b, indicate that the fracture surface exhibits a mixed mode of ductile and brittle properties with the addition of 2% SiC.

Because there is improved load transfer between the matrix and the reinforcement at 4% SiC, the fracture surface exhibits a more homogenous distribution of SiC particles, leading to finer dimples and increased strength. As demonstrated in Figure 10c, the fracture becomes primarily brittle at 6% SiC, with apparent particle pull-out and crack propagation at the particle-matrix interface, indicating a higher stiffness but decreased ductility.

Ultimately, the composite shows significant particle clustering and brittle fracture at 8% SiC, which causes stress concentration and early failure. As seen in Figure 10d, this development emphasizes the crucial harmony between mechanical performance and reinforcement content in metal matrix composites.

5.0 Conclusions

The following research out are drawn in below:

- Stir casting is a reliable procedure for making hybrid composites because it produces composites with outstanding strength and bonding as well as great ingredient integrity with the matrix.
- Al5052-SiC metal matrix composites show improved compression strength as SiC concentration increases, but only to a certain extent. After that, brittleness and dispersion issues may cause the material to lose some of its benefits.
- The research indicates that the tensile strength of Al5052 alloy can be considerably increased by reinforcing it with Silicon Carbide (SiC) particles. The benefits may plateau or decrease beyond 6% SiC content because of particle aggregation and related flaws, while the improvement is most noticeable up to that point. These results highlight the SiC-reinforced Al5052 composites potential for applications requiring higher mechanical performance.
- The investigation indicates that the hardening effect of ceramic particles in Al5052 alloy increases tensile strength when the SiC percentage is increased. Higher SiC percentages cause a shift in fracture modes from ductile to brittle, which indicates that ductility is lost as a result.
- It's critical to strike the ideal balance between mechanical performance and reinforcement content since too much SiC can concentrate stress and cause early failure.

6.0 Acknowledgements

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