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Composite Fabrication by Stir-Cast for Al C355.0 With Particulates Hematite Reinforcements at Different Weight Percentages in Copper Chills with and Without Water Circulation for Mechanical and Fatigue Performance

Rajesh T R [1,*], B. Venkata Narayana [2], Santhosh N [3], S.K. Vutukuru [4], Jaganraj R[5]

Abstract

This study investigates the fabrication of aluminum matrix composites using the stir casting method to analyze the mechanical characterization and fatigue behavior of Al C355.0 composites reinforced with varying weight percentages of hematite particulates. The hematite content was systematically adjusted from 0 wt. % to 12 wt. % in 3 wt. % increments, with the presence of constituent elements confirmed through Energy Dispersive Spectroscopy (EDS). The incorporation of hematite reinforcement significantly enhanced both tensile and compressive strengths compared to the base alloy. A steady increase in strength was observed from 0 wt. % to 9 wt. %, indicating effective load transfer and uniform dispersion of particulates within the matrix. The implementation of water circulation around the mold further improved mechanical properties by promoting better particulate distribution, reducing porosity, and enhancing solidification. Fatigue testing results revealed that composites containing 9 wt. % hematite exhibited superior fatigue resistance, with an increased number of cycles to failure compared to lower reinforcement concentrations. However, at 12 wt. %, excessive particle clustering led to weak interfacial bonding, negatively impacting both mechanical strength and fatigue life. These findings suggest that an optimal hematite concentration of 9 wt. % provides the best combination of mechanical strength and fatigue resistance, particularly when processed using water circulation in copper chills to improve material integrity and performance.

Keywords: Al C355.0, hematite, stir casting, copper chills, water circulation, EDS, tensile, compression, fatigue

***Author for Correspondence**
Rajesh T R

[1]Research scholar, Department of Mechanical Engineering, Visvesvaraya Technological University-Jnanasangama, Belagavi, Karnataka, India (Research Centre-SEA College of Engineering and Technology), Bengaluru, Karnataka, India
[1]Assistant Professor, Department of Mechanical Engineering, Gopalan College of engineering and Management, Bengaluru, Karnataka, India
[2]Principal and Professor, Department of Mechanical Engineering, SEA College of Engineering and Technology, Bangaluru, Karnataka, India
[3]Head of the Department, Department of Mechanical Engineering, MVJ College of Engineering, Near ITPB, Whitefield, Bangaluru, Karnataka, India
[4]Assistant Professor, Department of Aeronautical Engineering, Vel Tech Rangarajan Dr. Sagunthala R& D Institute of Science and Technology, Avadi, Chennai, Tamil Nadu, India
[5]Head, Department of Aeronautical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Avadi, Chennai, Tamil Nadu, India

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INTRODUCTION

Aluminium is extensively used in the aerospace and automotive industries due to its lightweight nature and high specific strength. Metal matrix composites (MMCs) are preferred because they offer superior strength compared to their base alloys while maintaining a low density. The inclusion of specific reinforcements, such as red mud, TiO_2, TiC, Al_2O_3, B_4C, and SiC, significantly enhances the properties of these composites relative to the

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base metal alloy. For example, reinforcing aluminium with materials like SiC can notably improve its properties, especially at room temperature. [1]. Effect of single and multiple reinforcements on the properties of material matrix composites such as mechanical and wear properties are performed [2]. It is to be noted that a 5% , 10% and 15% TiO2 reinforcement in Aluminium composite led to the increase of the tensile and hardness properties of the MMC under consideration and also the compressive strength decreased with the increase in concentration of the reinforcement [3]. Mechanical properties of Die casting process is calculated using the equation 12 + X (La +Yb) alloy, where (X = 0, 0.3, 0.6 and 0.9). Mechanical properties improved with addition of rear earth materials. At 0.6 wt.% of rear earth materials, tensile strength of alloy increases from 280 MPa to 313 MPa and elongation from 4%-4.5% [4]. Al 6063 matrix composites (AMCS) using ZrO2 and nickel particles was developed. Ductility improved with % of nickel increased AMCs with 6% ZrO2 +6% Ni were found to bring balance in ductility and strength [5]. Mechanical properties at elevated temperatures for Zr modified Al-Si-Cu-Mg alloy was studied. There was improvement in the tensile strength by 34% -50% [6]. Effect of nano reinforcements were studied and it was concluded that nano particles improves base metal in terms of wear and mechanical properties [7]. During aging at 150ºC for aluminium C355.0 alloy a very good mechanical properties were observed [8]. The C355.0-T6 alloy demonstrated superior mechanical properties compared to the A356-T6 alloy, attributed to its higher thermal stability due to Cu-based strengthening particles [9]. Studies on aluminum matrix composites (AMCs) reinforced with micro and nano-sized Al_2O_3 particles revealed that as the weight percentage of nano Al_2O_3 particles increased, there was a corresponding increase in hardness, compressive strength, and porosity [10]. A composite was fabricated using low-cost, naturally available kaolin combined with 10% Al-SiC at varying weight percentages of kaolin. The optimal combination of mechanical properties was achieved with the hybrid composite containing 4% kaolin [11]. The incorporation of SiC reinforcements into the aluminum matrix resulted in significant improvements in hardness and ultimate tensile strength (UTS), increasing from 23 HV to 47 HV and from 84 MPa to 130 MPa, respectively. [12].

In the current work the particulate hematite is added in weight percentage in a step of 3% from 0-12%. The ALC355.0 is through stir casting method and hematite is added to the metal matrix composite in copper chills with and without water circulation (water circulation less than room temperature at 4^0C) the fabrication procedure could be seen in Figure 2. It is found that stir casting is a low straight forward technology for aluminum metal matrix components. Stir casting helps in achieving high production rate as well [13-14]. It is observed that water circulation is an alternative to cooling. It is anticipated that cooling of any MMC would result in increase in Tensile and compression strength along with improved hardness. The hardness of the MMC Al C355.0 has showed improvement and the present paper attempts to show that compression and tensile strength do increase with cooling and in the copper chills for the composite material [15].

MATERIALS AND METHODS

Constituent Materials

Al C355 alloy in the form of ingot are procured from Fenfe Metallurgical, Bangalore, India and used as matrix material. The composition of Al C355 is represented in Table 1. The EDS and SEM Images are shown in Figure 3 and Figure 4 which confirm the presence of hematite particulate reinforcement.

Table 1. Composition of C355.0 alloy.

S no.	Constituent	Percentage (%)
1	Si	5.5
2	Mg	0.6
3	Fe	0.2
4	Cu	1.5
5	Mn	0.1
6	Ti	0.2
7	Zinc	0.1
8	Al	91.65

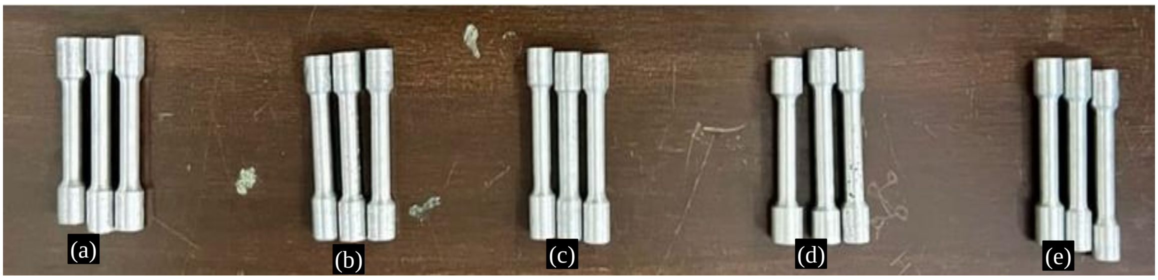

Figure 1. Tensile strength specimen, (a) 0 wt. % hematite with copper chills with water circulation, (b) 0 wt. % hematite with copper chills without water circulation, (c) 3 wt. % hematite with copper chills with water circulation (d) 6 wt. % hematite with copper chills with water circulation (e) 9 wt. % hematite with copper chills with water circulation (f) 12 wt. % hematite with copper chills with water circulation

Fabrication Procedure

SU-4949 surya motor of 12 V capacity that works with 3 A - 4 A having a flow rate of 5.5 LPM having a pressure of 115 PSI (9 bar pressure). The water is circulated at a temperature of 4^0C within the copper chills.

The reinforcement is added to aluminium matrix using stir casting and the specimen is prepared using sand casting method with the copper chills.

The water circulation is taken for cooling process and it was anticipated that this cooling will be responsible for the increase in tensile and compression strength of the stir casted Al C355.0. The particulate hematite are later added to the stir cast (AL C355.0). The copper chills cooling rate is 25 ^{0}k / sec and the cooling rate with water in the copper chills is 5^0k / sec. The crucible is of 4kg capacity and can be scalable upto 6kg.

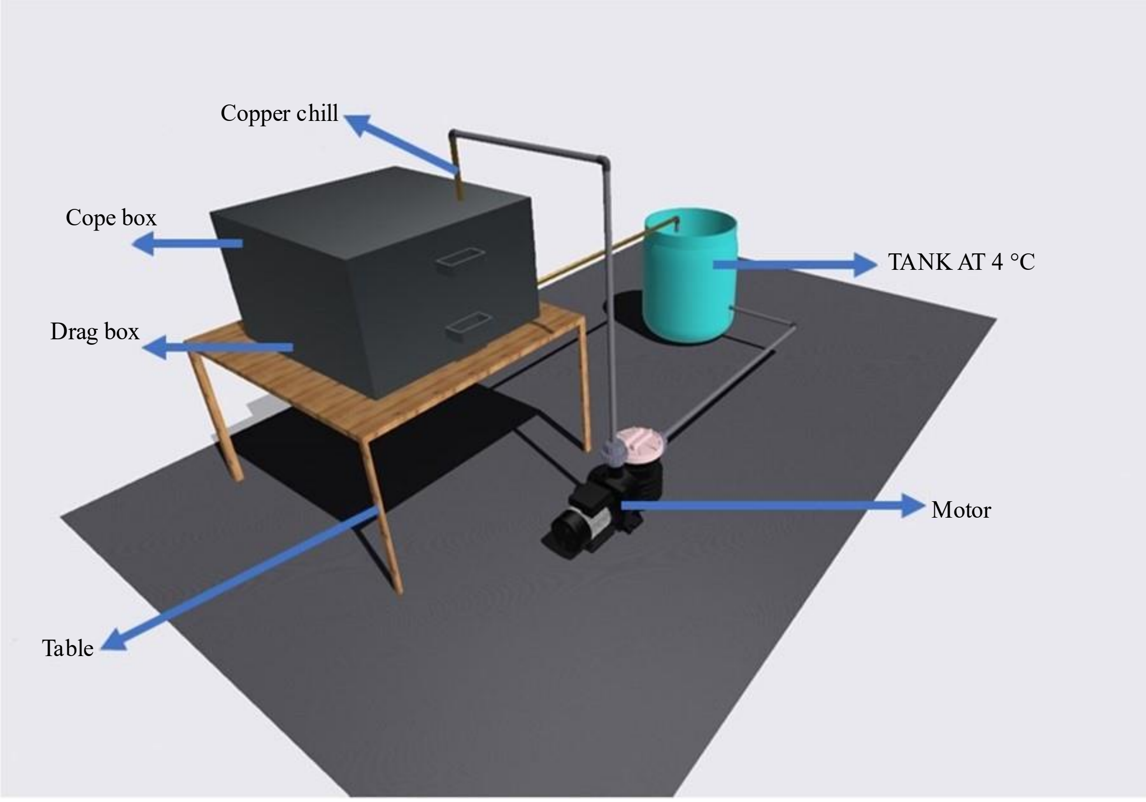

Figure 2. Fabrication of AL C355.O along with the water circulation in copper chills

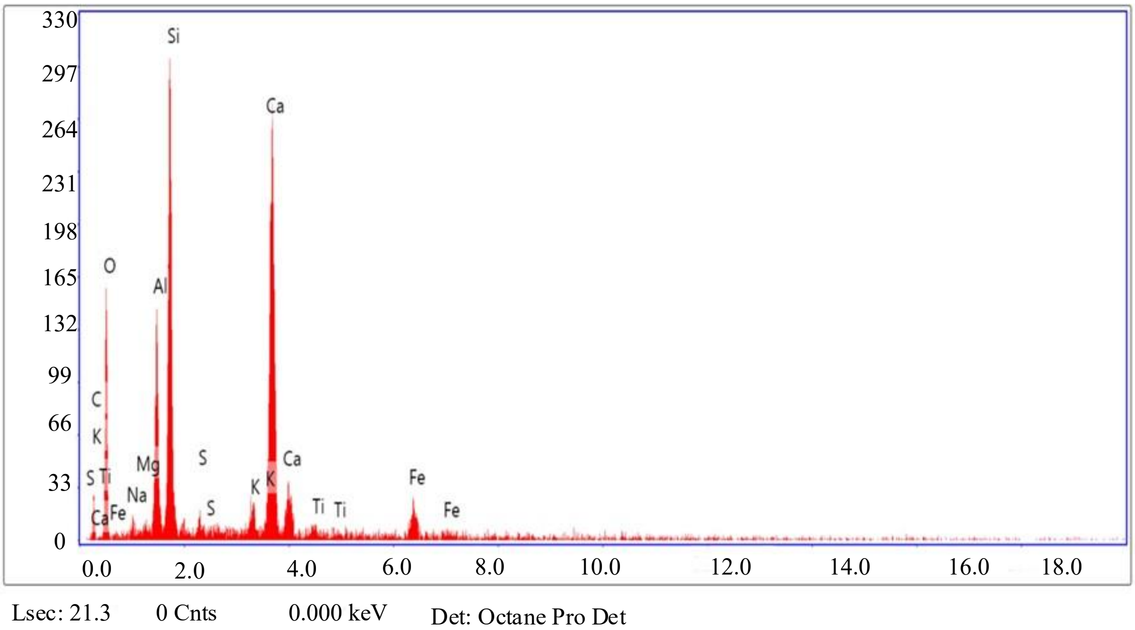

Figure 3. EDS image of hematite reinforced particulate.

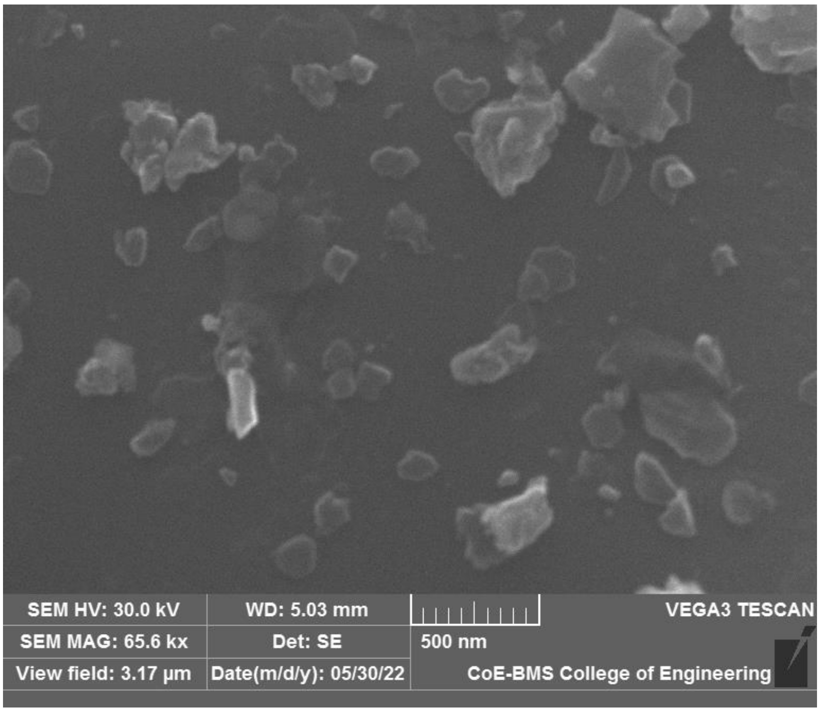

Figure 4. SEM image of hematite reinforced particulate.

EXPERIMENTATION

The tensile specimens are as shown in the Figure 1. Tensile testing was conducted using an electronic tensometer, specifically a compact model designed for horizontal tensile tests with a capacity of 20 kN. This equipment is also suitable for conducting tensile, compression, and fatigue tests. The PC2000 model tensometer, utilized in this study, is equipped with DC servo motors, a drive system, and material testing software. Tensile test specimens were prepared following ASTM E8 standards, featuring a gauge length of 25 mm and a gauge diameter of 12.7 mm. For compression tests, the specimens were prepared according to ASTM E9 standards, with a diameter of 12.7 mm and a length of 25 mm. A photograph of the test equipment is shown in Figure 5.

Fatigue tests were carried out using a Ducom rotating-bending low-cycle fatigue testing machine, operating at room temperature and in compliance with ASTM E606 standards. The machine features a 12 mm collet size for securely holding specimens during testing. It offers a range of adjustable normal loads from 50 N to 100 N, providing flexibility in the force applied to the specimen. The machine operates at variable speeds from 1000 to 5000 rpm, with a speed accuracy of ±1% of the measured speed, ensuring precise control. It is capable of generating a bending moment of up to 500 Nm and can run tests for up to 999,999 cycles, supporting extensive fatigue evaluations. The dimensions of the machine are 950 mm in length, 500 mm in width, and 1140 mm in height, with the controller measuring 300 mm by 290 mm by 135 mm, making it compact and well-suited for laboratory use.

Fatigue test specimens, with a diameter of 6.35 mm and a length of 101.6 mm, were machined from cast composites. Tests were conducted at a constant cyclic frequency of 50 Hz (3000 rpm) and a stress ratio ® of 0.1. Fatigue life (Nf) was defined as the number of cycles until the specimen experienced complete failure. The gauge section of the specimens was polished to a surface finish of 1 μm using progressively finer grades of emery paper to reduce the impact of surface irregularities. During testing, maximum stress levels ranged from 40 Mpa to 200 Mpa, representing 20% to 90% of the material's yield strength. The average fatigue life (Nf) was calculated from three test results for each sample.

RESULTS AND DISCUSSION

SEM Microstructure

It is inferred from the SEM images that voids formation is a result of fracture of the reinforcing particles and failure of the surrounding matrix. There are increased local stress concentration locations that leads to loss in ductility. Majority of the damage is due to clustering of the reinforcement and development of particle cracking through generation of voids [15].

Figure 5. Tenso meter test machine (PC2000).

The Figure 6 gives the SEM of fractured as cast specimen without hematite and without water circulation. The cracks formed are predominantly seen majorly due to the striations and slip bands formed due to ductile fracture. The cup and cone fracture is evident in this specimen. The Figure 7 gives the SEM of fractured as cast specimen without hematite and with water circulation. The water circulation has caused the discretization of the slip bands thereby making the fracture of the specimen difficult. Similarly, the Figure 8 and Figure 9 gives the SEM of the fractured surfaces of composite specimens with 9 wt. % hematite with and without cooling. The effect of cooling is clearly seen in the Figure 9, wherein the slip bands and fracture planes are lesser as compared to the figure 8, with relatively more number of slip bands and fracture planes evident.

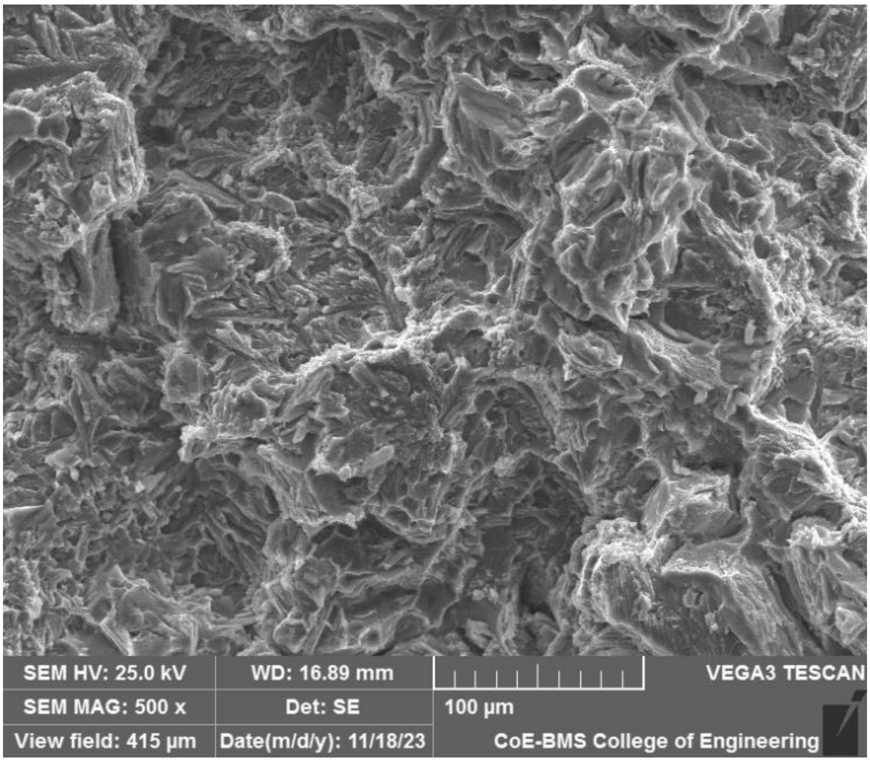

Figure 6. SEM of specimen in fracture (0 wt.% Hematite without water circulation).

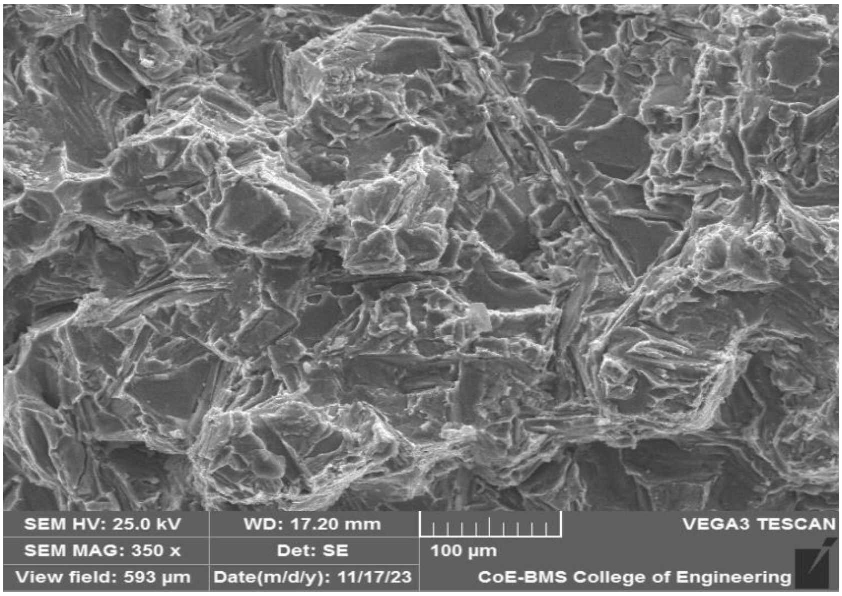

Figure 7. SEM of Composite in fracture (0 wt.% Hematite with water circulation).

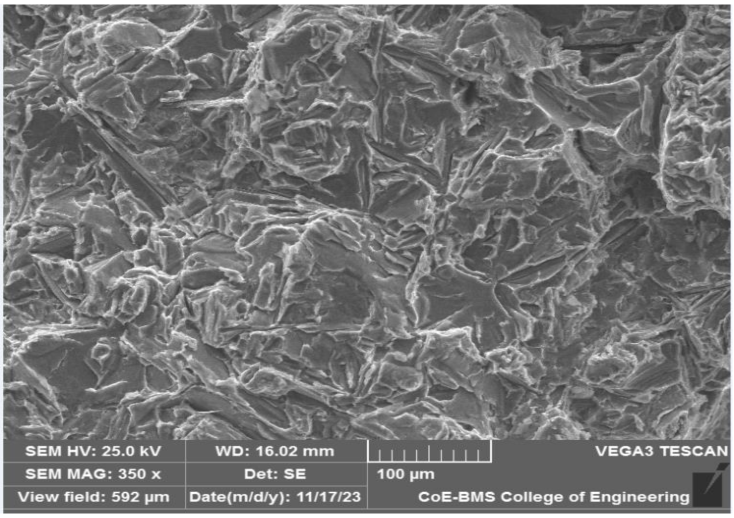

Figure 8. SEM of Composite in fracture (9 wt.% Hematite without water circulation).

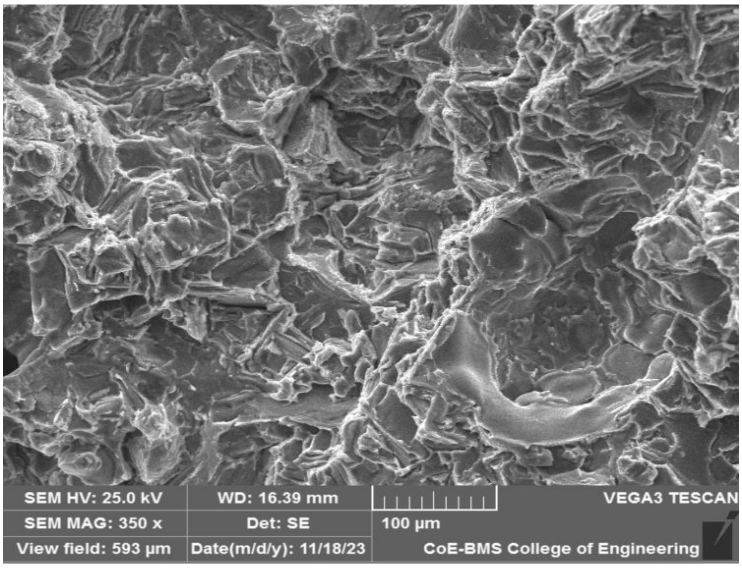

Figure 9. SEM of Composite in fracture (9 wt.% Hematite with water circulation).

The number of voids and dimples in the water circulated MMCs are comparatively lower compared to without water circulation (Figure 9). Good tensile strength was shown by the MMCs that undergo water circulation in copper chills.

A similar observation was made which shows an increase in the UTS of the specimen with the presence of hard hematite particles that impart strength to the matrix under consideration. The results were similar to the results as mentioned [14-17].

Tensile Test Results

The results of tensile test are presented in table 2 and table 3 for different conditions, viz., with copper chills and without water circulation, and with copper chills and without water circulation respectively.

As can be seen from table 2 and table 3, the UTS and YS is more when circulated with water in the presence of copper chills. Initially with the increase in Hematite up to 9 wt. % in the matrix there is an increase in the UTS by using water circulation in copper chills. There was also good bonding of the reinforcement in the matrix. As the weight of the hematite reinforcement increased further to 12% W in the matrix the particle hematite formed more voids as a result of particle cracking.

Table 2. Tensile test results for specimens cast with copper chills and with water circulation.

Hematite reinforcement	Yield strength (MPa)	Percentage enhancement	Ultimate tensile strength (MPa)	Percentage enhancement
0%	209	-	238	-
3%	220	5%	253.47	5.9%
6%	231	9.5%	276	13.7%
9%	256	18.3%	320	25.6%
12%	240	12.9%	291.34	18%

Table 3. Tensile test results for specimens cast with copper chills and without water circulation.

Hematite reinforcement	Yield strength (MPa)	Percentage enhancement	Ultimate tensile strength (MPa)	Percentage enhancement
0%	227	-	258	-
3%	232	2%	266.14	3%
6%	261	13%	311.88	17%
9%	287	21%	359	28%
12%	266	15%	317	18.6%

In summary, the tensile strength is more for the water circulated MMCs with the hematite up to 9 wt. %. This is in agreement with [12- 15]. The movement of dislocations is restricted due to the stronger bonding between the constituents [18-20]. The hematite particulate reinforcement was varied from 0% to 12% in increments of 3%, both with and without copper chills. The results indicated that a 9% hematite particulate reinforcement provided optimal hardness after water circulation. However, at higher reinforcement levels, the formation of hematite clusters led to a decline in hardness. Additionally, copper chills proved to be highly effective in enhancing hardness compared to the base metal alloy [21]. The Figure 10 gives the graph for variation of the UTS for different wt. % of hematite particulates and for different cooling conditions for the casting, while figure 11 (a) and figure 11 (b) gives the photographs of the tensile specimens with copper chills, and without water circulation, and without copper chills, and without water circulation respectively.

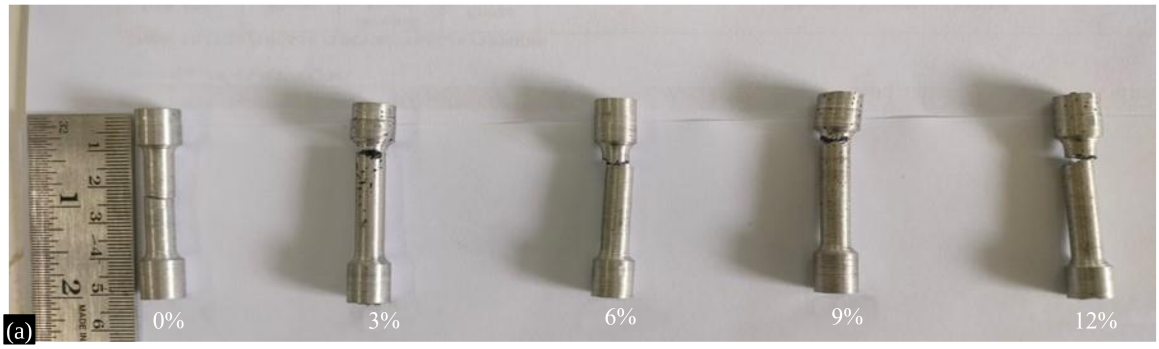

Figure 10. Tensile strength with and without water circulation in copper chills for different wt.% of Hematite.

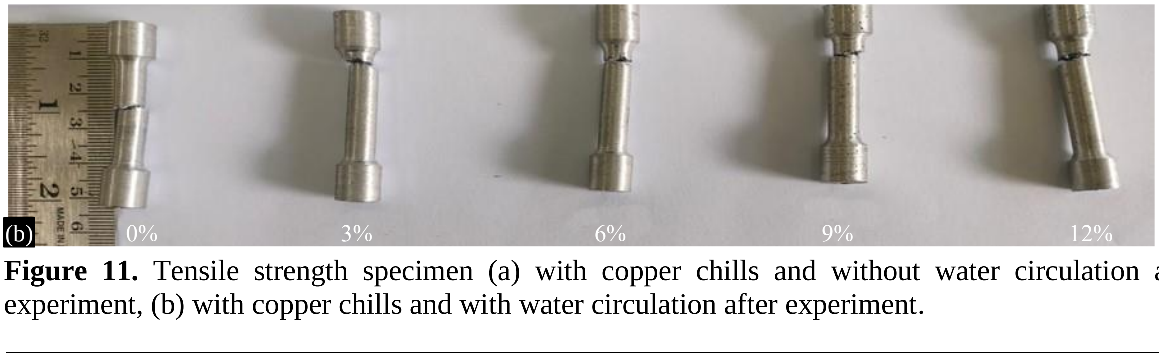

Figure 11. Tensile strength specimen (a) with copper chills and without water circulation after experiment, (b) with copper chills and with water circulation after experiment.

Compression Test Results

The presented data and figures illustrate the results of compression tests conducted on specimens containing copper chills, with and without the circulation of water, across various concentrations of hematite. Tables 4 and 5 outline the compression strengths recorded under different conditions, with a focus on the percentage of enhancement compared to a base case. Figures 12 and 13 offer before-and-after images of the test specimens, presenting tangible evidence of the experimental outcomes. Additionally, Figure 14 graphically depicts the compression strengths obtained with and without water circulation for different hematite concentrations, providing a comparative analysis of the effects of water circulation on compression strength across the range of hematite percentages tested. These findings collectively shed light on the performance of copper chills under different circumstances, informing potential applications and optimization strategies.

Table 4. Compression test results for specimens cast with copper chills and without water circulation

% of Hematite	Compression strength without water (MPa)	Percentage of Enhancement
0%	610	-
3%	680	10
6%	718	15
9%	745	18
12%	710	14%

Table 5. Compression test results for specimens cast with copper chills and with water circulation.

% of Hematite	Compression strength with water (MPa)	Percentage of enhancement
0%	680	-
3%	770	11.68%
6%	830	18%
9%	890	23.59%
12%	870	21.8%

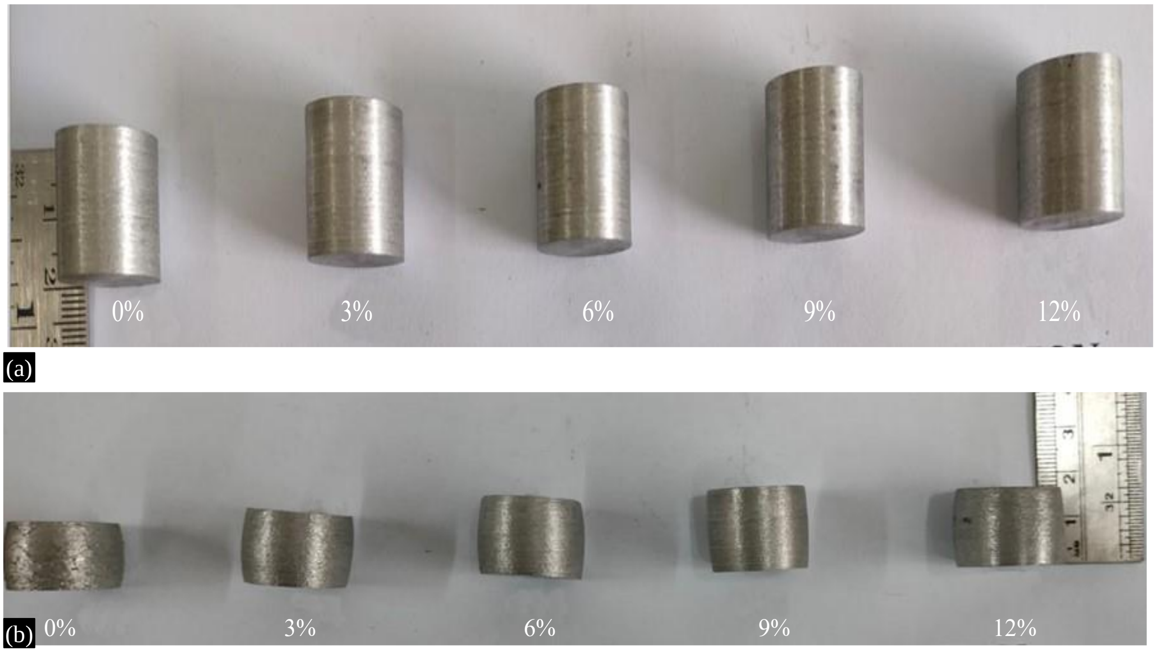

Figure 12. Compression test specimen with copper chills and with water circulation after experiment.(a) before Experiment (b) After Experiment.

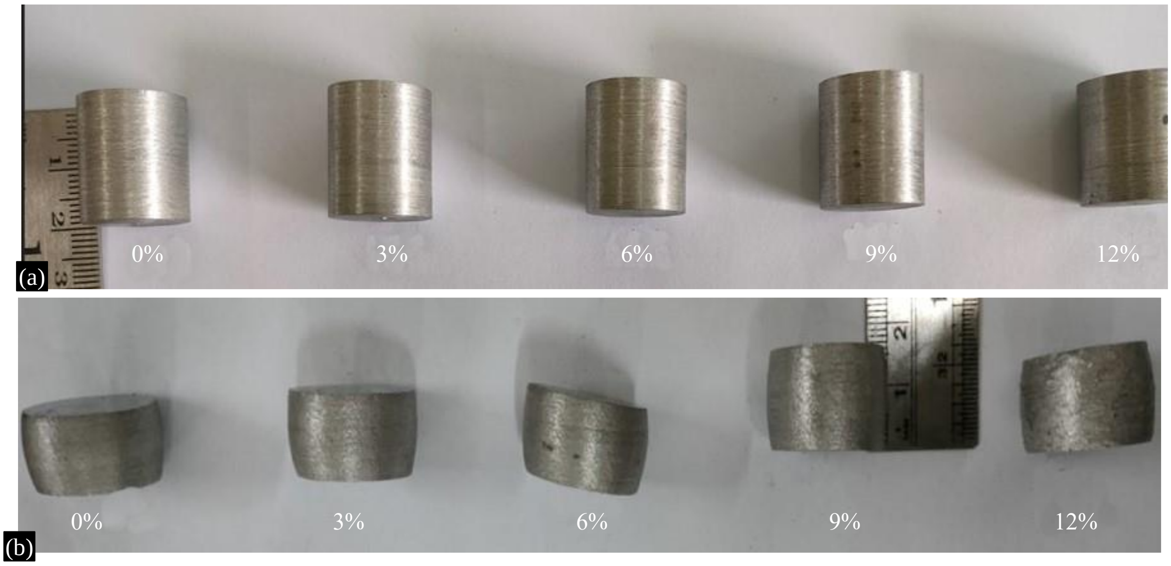

Figure 13. Compression test specimen with copper chills and with-out water circulation after experiment.(a) before experiment (b) after experiment.

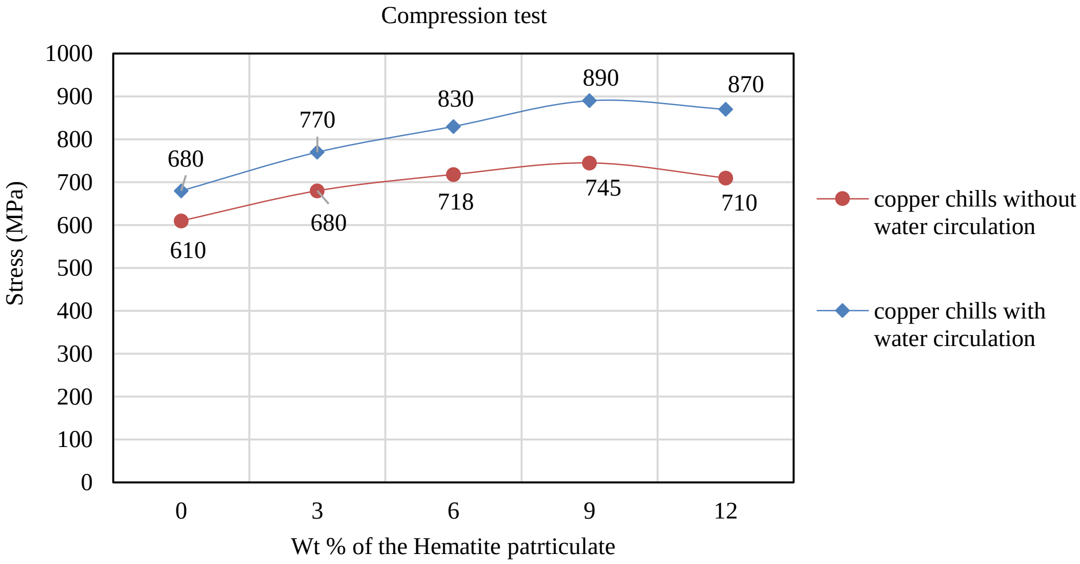

Figure 14. Compression strength with and without water circulation in copper chills for different wt. % of Hematite.

An increase in the volume fraction of particulate-reinforced hematite has led to the appearance of cracks and deboning in the fractured composites, resulting in brittle fracture.[17].

Fatigue Test Results

Torsional fatigue testing (high cycle fatigue) through S-N curve method was used as it is applicable to components subjected to cyclic torsional loads mostly encountered in automobile engines. The figure 15, and 16 gives the details about the number of cycles to failure under fatigue loading for a stress ratio (R) of 0.1. The fatigue life (Nf), is typically influenced by factors such as stress levels, material composition, and experimental conditions such as the stress ratio. Fatigue testing is essential to evaluate the durability of materials under repeated stress cycles until failure. The fatigue life, or the number of cycles until failure, is a key measure for assessing how materials will perform under real-world cyclic loading conditions, such as in vehicle or aerospace parts. The stress ratio (R) plays a crucial role in fatigue tests, with R=0.1 indicating that the material remains predominantly under tensile stress, minimizing the occurrence of compressive stress which could otherwise help in mitigating fatigue damage. This scenario tends to reduce fatigue life because the material is continually stressed without the relief cycles provided by compressive stresses. Regarding the effects of material composition and enhancements, introducing elements like hematite to composites can influence fatigue life. Hematite can increase the composite’s overall stiffness and strength, which might extend its fatigue life under lower stress conditions. However, the increased stiffness might also contribute to brittleness, potentially lowering fatigue life under higher stress levels. Additionally, employing a copper chill during casting can improve the composite's microstructure, enhancing fatigue resistance. This improvement is likely due to copper’s superior thermal conductivity, which promotes faster and more uniform cooling, leading to a more consistent grain structure that is beneficial under cyclic stresses. In analyzing fatigue test data, it's important to observe how different variables such as material compositions or the use of copper chill affect fatigue life. For instance, if data indicates that composites with 9% hematite achieve longer fatigue lives consistently under various stress conditions, this suggests an optimal balance between increased stiffness and the resultant brittleness. Furthermore, if the presence of copper chill consistently shows a positive impact on fatigue life compared to tests without it, it can be deduced that the microstructural benefits conferred by the copper chill play a significant role in enhancing the material's fatigue resistance. These insights are invaluable for engineers and materials scientists aiming to design durable materials tailored to specific operational stresses and environmental conditions. To provide more granular insights or precise numerical results, detailed data from the fatigue tests, including the exact number of cycles endured under each tested condition, would be necessary.

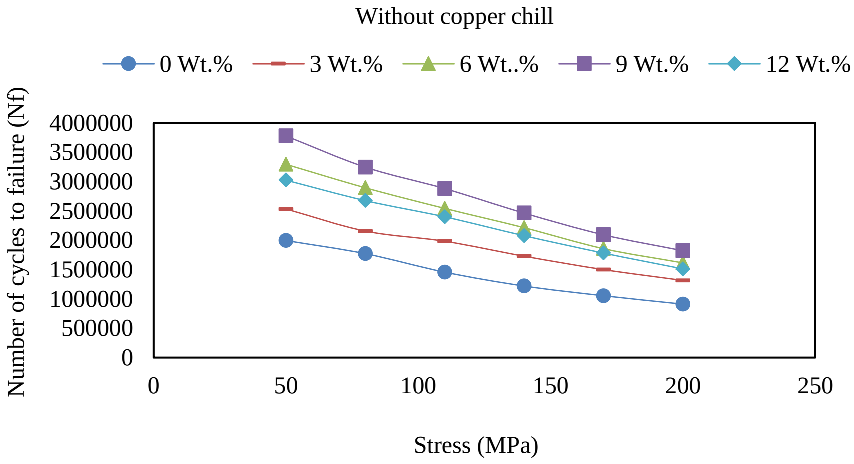

Figure 15. Stress (S)-Number of cycles (N) for composite specimens without copper chill.

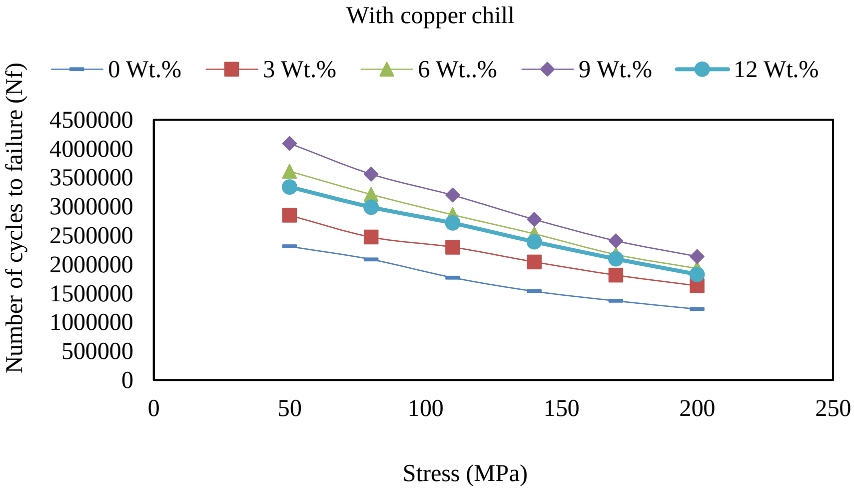

Figure 16. Stress (S)-Number of cycles (N) for composite specimens with copper chill.

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CONCLUSIONS

Based on the comprehensive data from tensile and compression testing under different conditions, here are the detailed conclusions drawn from the study.

1. Tensile tests show a consistent increase in both yield strength (YS) and ultimate tensile strength (UTS) with the incorporation of hematite. For example, with copper chills and without water circulation, YS increased from 227 MPa (0% hematite) to 287 MPa (9% hematite), and UTS increased from 258 MPa to 359 MPa in the same range. This represents a 21% and 28% enhancement in YS and UTS, respectively.
2. Both YS and UTS peak at 9% hematite under all tested conditions, indicating an optimal hematite content for maximizing mechanical strength. For instance, with copper chills and water circulation, the UTS at 9% hematite reached 320 MPa, a 25.6% increase compared to the baseline without hematite (238 MPa).
3. Beyond 9% hematite, the tensile and compression strengths tend to decrease, likely due to the formation of voids and particle cracking. For example, with copper chills and without water circulation, the UTS declines from 359 MPa (9% hematite) to 317 MPa (12% hematite).
4. Water circulation during the casting process significantly enhances the mechanical properties. With copper chills and water circulation, the compression strength increases more dramatically across hematite concentrations, peaking at 890 MPa at 9% hematite, a 23.59% enhancement compared to the baseline without hematite (680 MPa).
5. Fatigue tests show that composites with 9% hematite also exhibit the best fatigue resistance, with a significant increase in the number of cycles to failure compared to lower hematite levels.
6. Fatigue life is similarly extended under these conditions, indicating improved material resilience under cyclic loading.
7. Utilizing copper chills and water circulation significantly refines the microstructure, which not only increases strength but also enhances fatigue resistance, evident from the prolonged fatigue life in testing.
8. The combination of copper chills and water circulation results in composites that exhibit superior mechanical properties and increased fatigue life, making these techniques preferable for producing high-performance composites for demanding applications.

These conclusions highlight the effectiveness of specific hematite concentrations and processing techniques in optimizing the mechanical and fatigue properties of composites.

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