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Research Article

Mechanical and Physical Properties Observations for Cu-Gr-SiC Composite Synthesized by Powder Metallurgy

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ABSTRACT

This study examines the mechanical and physical properties of copper-graphite-silicon carbide (Cu-Gr-SiC) metal matrix composites (MMCs), focusing on parameters such as density, micro-hardness, compressive strength, flexural strength, and EDX analysis. Composites were developed using 5 wt.% graphite and varying SiC content (0–15 wt.%), using powder metallurgy techniques. The sintered density decreased from 8.23 g/cc for pure copper to 6.09 g/cc for the composite with 15 wt.%SiC, attributed to the lower densities of the reinforcing phases. Micro-hardness increased from 56 HV to 74.2 HV with rising SiC content, reflecting the hardening and grain refinement effect of SiC. Flexural strength reached a maximum of 200 MPa at 15 wt.%SiC, while compressive strength improved up to 5 wt.% SiC but declined at higher concentrations due to increased brittleness. EDX analysis confirmed uniform dispersion of reinforcements with minimal oxidation. These results support the use of Cu-Gr-SiC MMCs in demanding applications, with an optimal balance between reinforcement and mechanical performance.

1. Introduction

Metal matrix composites (MMCs) have become increasingly important in materials engineering due to their impressive combination of strength, heat resistance, and wear durability. They're widely used in sectors like aerospace, automotive, marine, and electronics—anywhere materials need to be both strong and lightweight [1]. Among these, copper-based MMCs stand out because of copper's high electrical and thermal conductivity, good corrosion resistance, and ductility [2]. However, copper alone doesn't offer enough hardness or wear resistance for heavy-duty applications. That's where reinforcing materials like graphite (Gr) and silicon carbide (SiC) come in—they help create composites with far better performance [3]. Graphite is commonly used thanks to its natural lubricating ability, which helps lower friction and enhance wear resistance [4]. The tradeoff is that graphite is relatively soft, which can reduce the overall hardness and strength of the final composite. On the flip side, silicon carbide is extremely hard and thermally stable, and it provides excellent reinforcement when added to

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a copper matrix [5]. SiC boosts properties like hardness and compressive strength, and it also helps refine the composite's internal structure. When graphite and SiC are combined in a copper matrix, the result is a balanced material that offers both mechanical strength and self-lubrication—ideal for demanding industrial uses [6].

To further improve copper-based composites, recent studies have explored the effects of Cu granules and Cu-coated graphite particles on microstructure and performance. These modifications enhance interfacial bonding, dispersion, and overall composite stability. Notably, a Cu-10Gr composite with 10% Cu granules exhibited superior mechanical and electrical properties compared to conventional counterparts[7]

This study takes a closer look at how different amounts of SiC affect the properties of Cu-Gr-SiC composites. Key mechanical properties like density, micro-hardness, flexural strength, and compressive strength are evaluated. Energy dispersive X-ray (EDX) analysis is also used to explore how the reinforcing particles are distributed within the copper matrix and how well they bond at the microscopic level [8]. SiC addition is expected to promote grain refinement and strengthen the composite through better particle dispersion, leading to improved mechanical reliability.

2. Preparation of Composite Powder

2.1. Copper

Electrolytic copper powder (ECP) with a dendritic particle structure and an average size of 48 μm was utilized in this study. The powder had a high purity level of 99.8%were obtained from Sarda Industrial Enterprises, Jaipur, India. Copper was chosen due to its excellent combination of mechanical strength, fatigue resistance, and outstanding electrical and perform reliably under thermal conductivity, along with its natural resistance to corrosion [9]. These properties make it especially suitable for advanced applications, including self-lubricating systems that must extreme conditions. The detailed chemical composition and physical characteristics of the copper powder are outlined below.

Table 1. Chemical composition of copper matrix

Element	As	Sb	Mn	Pb	Fe	Sn	Cu
Content %	0.0002	0.005	0.005	0.05	0.005	0.005	Remaining

2.2. Reinforcement Particles

A composite was fabricated through solid-state mixing, using silicon carbide (SiC) and graphite (Gr) particles as reinforcement agents were obtained from Luoyang Tongrun Info Technology Co., Ltd., Henan, China.

These materials and their compositional percentages were selected for their complementary properties, which collectively enhance the overall performance of the composite. SiC, with an average particle size of 35 μm and a density of 3.12 g/cm^3, is well-known for its exceptional hardness, thermal stability, and wear resistance—qualities that contribute to increased strength and long-term durability of the composite material [10]. Its inclusion boosts the material's load-bearing capacity and resistance to deformation under mechanical stress, making it ideal for structural applications that demand high reliability.

In contrast, graphite particles—measuring around 50 μm in size with a density between 2.02 and 2.32 g/cm^3—were added primarily for their excellent self-lubricating properties [11]. Graphite helps reduce friction and wear during operation, making it particularly valuable in tribological settings. Its natural flake-like structure shears easily and forms a lubricating film on contact surfaces, minimizing surface damage over time. By combining SiC and graphite, the resulting composite achieves a desirable balance of mechanical strength and wear resistance.

Scanning Electron Microscope (SEM) analysis of the reinforcement particles highlights their distinct morphologies, as illustrated in Figure 1. SiC particles display a dense, angular, and primarily cubic shape, while graphite exhibits a layered, flake-like appearance. These structural differences influence how the particles disperse and interact within the copper matrix. A uniform distribution of both types of particles is essential to ensure effective reinforcement without clumping, thereby improving the composite's mechanical integrity and functional performance.

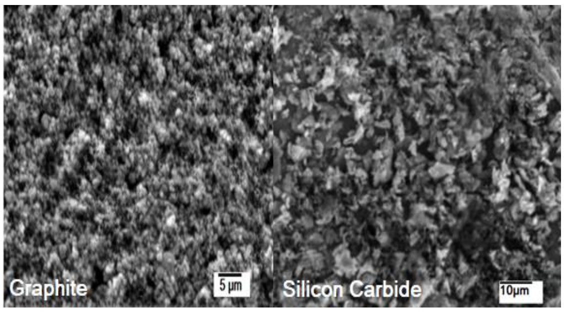

Fig. 1. SEM image of Graphite and SiC

2.3. Ball Milling / Blending

Copper-based composites were developed using the powder metallurgy technique, incorporating varying weight percentages of silicon carbide (SiC) (0, 5, 10, and 15 wt.%) and graphite (Gr) (5 and 10 wt.%) as reinforcements. The goal of the blending process was to ensure a uniform distribution of the reinforcement particles within the copper matrix—an essential factor for achieving optimal mechanical and tribologicalproperties. Dry ball milling was used as the mechanical mixing method, carried out over a six-hour period at a controlled speed of 50 rpm. Stainless steel balls, each 10 mm in diameter, served as the grinding media, with a consistent ball-to-powder weight ratio of 10:1 maintained to promote thorough mixing while minimizing cold welding or excessive particle fragmentation [12].

After milling, the blended powder was pre-heated at 100°C to eliminate any moisture or volatile compounds that might compromise the integrity of the composite during compaction and sintering. This drying step was important to prevent porosity and ensure strong bonding in the final material. The dried powder was then compacted using a hydraulic press under an applied pressure of 850 MPa. A die and punch assembly was used to form cylindrical green compacts. To reduce friction between the powder and the die walls, and to allow smooth ejection of the compacted parts, the inner surfaces of the die cavity were coated with 1 wt.% zinc stearate. This lubricant not only eased the compaction process but also helped improve the surface finish and dimensional accuracy of the green compacts.

Fig. 2. Ball Mill

2.4. Sintering

The green compacts—comprising copper reinforced with 5 wt.% graphite and varying concentrations of silicon carbide (SiC) at 0%, 5%, 10%, and 15%—were sintered to enhance mechanical bonding and overall structural integrity. The sintering process was conducted at a controlled temperature of 820°C for 60 minutes. To protect both the copper matrix and the reinforcing particles from oxidation during the high-temperature cycle, sintering was performed in a dissociated nitrogen atmosphere. This gas mixture, primarily composed of nitrogen and hydrogen, created a reducing environment that prevented oxide formation on metal surfaces, thereby preserving key material properties [13].

During sintering, the supplied thermal energy facilitated atomic diffusion across particle boundaries, leading to improved densification and stronger interparticle connections. Graphite, beyond acting as a solid lubricant, contributed to thermal stability throughout the heating process. Meanwhile, the addition of SiC introduced mechanical rigidity, helping maintain dimensional accuracy during the sintering and holding stages [14].

Once the sintering cycle was complete, the furnace was allowed to cool slowly with the specimens left inside. This gradual, uniform cooling prevented thermal stress buildup and reduced the risk of micro-cracks, which are common in brittle or multi-phase materials exposed to rapid cooling. After reaching ambient temperature, the sintered samples were machined to standard test dimensions—35 mm in height and 8 mm in diameter—tailored for tribological evaluations such as wear and friction testing [15].

To provide a baseline for comparison, copper samples with no graphite or SiC reinforcements were also processed under identical compaction and sintering conditions. These control specimens enabled a clear assessment of how the individual and combined reinforcements influenced the mechanical and tribological behavior of the composites. Comparing the reinforced and unreinforced samples offered valuable insights into the performance enhancements achieved through the addition of graphite and SiC [16].

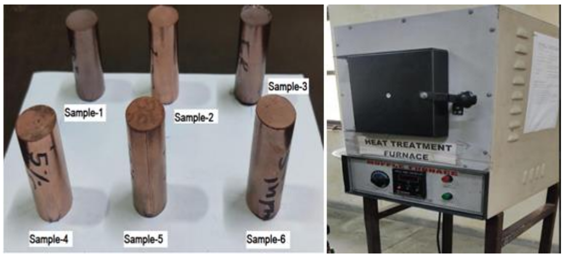

Fig. 3. (a) Green compact samples, (b)Muffle Furnace

3. Results and Discussion

3.1. Density and Micro Hardness

The mechanical and physical properties of the developed copper-based composites—including micro-hardness, relative density, and sintered density—are summarized in Table 2.

The influence of silicon carbide (SiC) addition on sintered density is illustrated in Figure 5. As observed, increasing the weight percentage of SiC significantly affects the overall physical and mechanical behavior of the copper matrix. Specifically, the sintered density decreases with higher SiC content, which can be attributed to the incorporation of lower-density reinforcement materials such as SiC and graphite into the comparatively denser copper matrix.

Additionally, the effect of SiC on the hardness of the composite is demonstrated in Figure 4. The inclusion of SiC leads to a noticeable increase in micro-hardness, owing to its inherently high hardness and the ability to promote a refined and uniform microstructure. To evaluate this property, Vickers microhardness testing was performed on sintered composite specimens. The samples were initially machined to 5 mm thickness and 10 mm diameter, then cold-mounted in a 25 mm die. They were further machined to 25 mm diameter and 20 mm height, followed by surface preparation using 1000-grit paper and polishing. Hardness measurements were conducted using an LM248AT tester under a 0.30 kg load with a 15 s dwell time.

Several factors contribute to this enhancement in hardness:

i). The intrinsic hardness of SiC particles acting as reinforcement,

ii). The effective dispersion of SiC within the copper matrix, providing a strengthening phase,

iii). The uniform distribution of SiC, which suppresses grain growth and promotes microstructural refinement.

Together, these effects underscore the dual role of SiC in enhancing both the strength and structural uniformity of the composite.

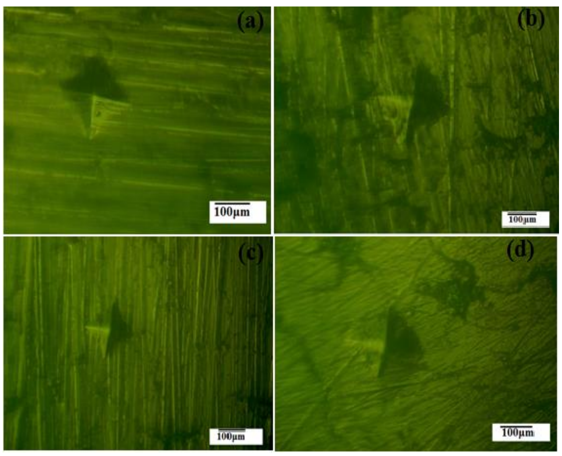

Fig. 4. MicrohardnessimagesforvariousSiC reinforcement (a) 0%,SiC, (b) 5%SiC, (c) 10%SiC (d)15%SiC

Table 2. sintered density, relative density, micro hardness

Sample No	Conventionally sintered composites (wt %)	Sintered density (g/cc)	Relative density (%)	Micro Hardness (HV)
1	Unreinforced Cu	8.23	91.26%	56
2	Cu-Gr (5%)	7.20	92.90%	52.6
3	Cu-Gr (5%)-SiC (5%)	6.82	94.59%	64.6
4	Cu-Gr (5%)-SiC (10 %)	6.48	96.43%	71.5
5	Cu-Gr (5%)-SiC (15 %)	6.09	96.67%	74.2

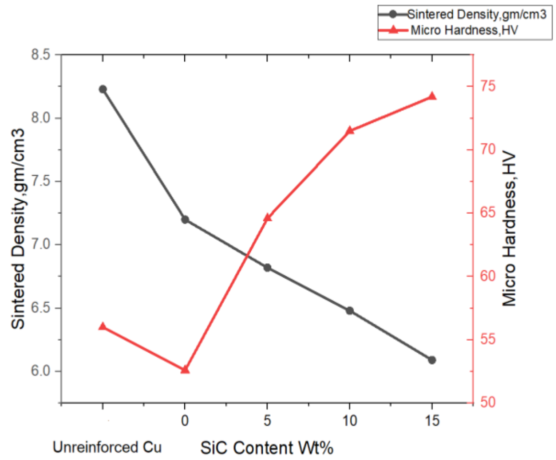

Fig. 5. Sintered density and micro hardness

3.2. *Energy Dispersive X-ray Examination of Composites*

The microstructural and elemental characterization of the composite was carried out to evaluate particle dispersion and phase composition. The microstructural analysis of the composite was performed using an FEI NOVA NANO SEM 450, which is integrated with an energy-dispersive X-ray (EDX) detector for elemental and compositional evaluation. This analysis helped to identify the distribution and morphology of graphite and copper particles within the matrix. Imaging was carried out in backscattered electron (BSE) mode at an accelerating voltage of 20 kV. Additionally, the optical structure of the copper granules was captured using a NIKON ECLIPSE 80i optical microscope equipped with digital image acquisition capabilities[17].

The EDX analysis of sintered Cu-10 weight percent Gr-X weight percent SiC (X = 0–15) composites treated at 900°C is shown in Figure

6. The effective integration of SiC particles into the Cu matrix is confirmed by the existence of significant peaks in the EDX spectrum that correspond to Cu, C, and Si. Furthermore, the incorporation of graphite as a solid lubricant is validated by the observed carbon content [18]. The EDX peak values of Cu showed a low-intensity oxygen peak with a small oxygen impact, indicating the creation of Cu oxide as a result of the interaction between Cu and air oxygen at high temperature. Additionally, the EDX spectra show that there were no chemical interactions between SiC, graphite, and copper. Cu is represented by the powerful peak, whereas Gr and SiC are represented by the lesser peaks.

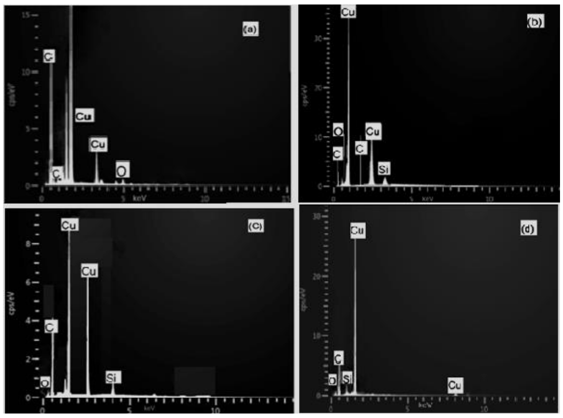

Fig. 6. EDX analyses of MWS composite samples: a) Cu/10Gr, b)Cu/10Gr/5SiC, c) Cu/10Gr/10SiC, d) Cu/10Gr/15SiC at 900 °c

3.3. Flexural Strength Study

The updated flexural stress vs. deflection graph illustrates how silicon carbide (SiC) reinforcement affects the flexural characteristics of Cu-Gr composites and is consistent with the anticipated material behaviour. The test was performed by using a 100kN INSTRON8501, and specimens were prepared as per the ASTM B 312. The findings show that flexural strength is greatly increased by increasing the SiC concentration. Cu-Gr (5%)-SiC (15%) had the greatest peak flexural stress of around 200 MPa among the compositions evaluated, followed by Cu-Gr (5%)-SiC (10%) at about 170 MPa, and Cu-Gr (5%)-SiC (5%) at about 50 MPa. This pattern demonstrates that a larger SiC concentration increases the composite's load-bearing capacity, which in turn enhances its resistance to bending stresses.

The elastic deformation phase is represented by the first linear increase in flexural stress seen by the stress-deflection curves. Each composition achieves a peak as tension rises, and then the stress progressively decreases, signifying the beginning of a fracture or material breakdown. The Cu-Gr (5%)-SiC (15%) composite exhibits the highest flexural strength and deformation resistance, whereas the Cu-Gr (5%)-SiC (10%) composite performs similarly but somewhat worse, and the shape of the curve changes due to particle agglomeration and non-uniform stress distribution. Conversely, Cu-Gr (5%)-SiC (5%) has the lowest flexural strength and collapses at a significantly lower stress level, indicating that its ability to support loads is compromised by inadequate reinforcing. These results demonstrate that Cu-Gr composites' mechanical qualities are enhanced by an increase in SiC concentration, which makes them more appropriate for uses requiring strong bending resistance and structural endurance.

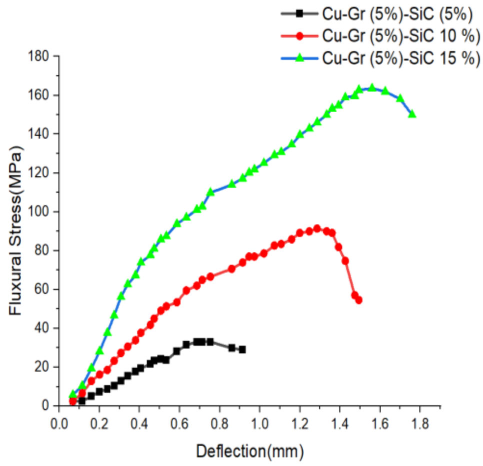

Fig. 7. Variation of flexural strength with strain of Cu-graphite-SiC MMC

3.4. Compressive Strength Study

Figure 8 illustrates the variation of compressive strength with strain for copper and Cu-Gr-SiC composites with varying SiC content. For the compression test, specimens were prepared in accordance with ASTM standard E9-89. Testing was carried out using an INSTRON 8501 Universal Testing Machine (UTM) at room temperature. From the figure, it is observed that the addition of graphite reduces the strength of the composite due to the soft nature of graphite. However, up to 5 vol.% graphite, compressive strength improves due to positive dispersion strengthening, beyond which the strength declines due to the brittle nature developed from graphite agglomeration. Similarly, the graph shows that the compressive strength of the composite increases with the addition of SiC up to 5 wt.%, attributed to enhanced interfacial bonding and dispersion strengthening. However, further SiC addition results in strength reduction due to the inherent brittleness of SiC particles.

In the Cu-graphite-SiC composite, as shown in the figure, an increase in compressive strength is observed with SiC addition for a fixed graphite content. Among the composites, the curve with squares represents copper, exhibiting the highest compressive strength with no yielding, as expected from its ductile nature. The circle curve represents Cu-Gr (5%)-SiC (5%), which shows slightly reduced compressive strength compared to Cu but maintains a stable trend, indicating moderate reinforcement. The downward triangle curve corresponds to Cu-Gr (5%)-SiC (10%), which follows a similar trend but exhibits higher strength at greater strain levels, confirming improved mechanical properties due to SiC reinforcement. However, the upward triangle curve, representing Cu-Gr (5%)-SiC (15%), demonstrates a significant drop in strength due to reinforcement exceeding the optimal limit, which may lead to particle clustering, agglomeration, and poor dispersion in the copper matrix. This causes stress concentration zones, resulting in early microcrack formation and premature yielding. These findings highlight that while moderate SiC content enhances strength, excessive reinforcement introduces brittleness, affecting the composite's mechanical performance.

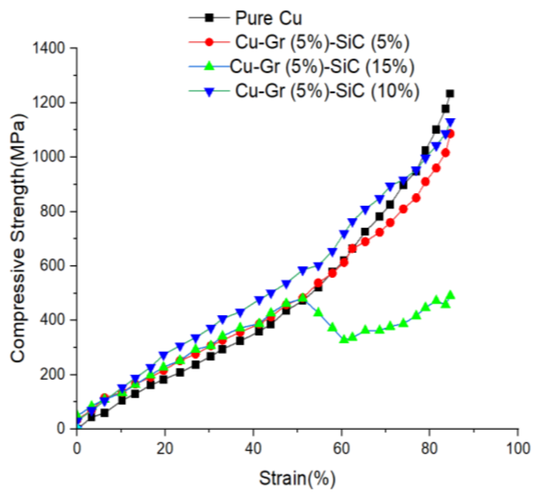

Fig. 8. Variation of compressive strength with strain of Cu-graphite-SiC MMC

4. Conclusions

This study comprehensively examined the characterization of Cu-Gr-SiC metal matrix composites, focusing on density, hardness, strength, and EDX spectroscopy. Numerous inferences may be drawn from these observations.

- The sintered density of the composites decreased with increasing SiC and graphite content due to their lower inherent densities compared to copper.
- Hardness of the composites increased significantly with higher SiC content, mainly due to the high intrinsic hardness of SiC and its grain refinement effect.
- Flexural strength improved with increasing SiC, with the Cu-Gr (5%)-SiC (15%) composite showing the highest peak flexural stress of approximately 200 MPa.
- Compressive strength increased up to 5 wt.%SiC but decreased at higher concentrations because of the brittleness introduced by excessive ceramic reinforcement.
- EDX analysis confirmed the successful and uniform incorporation of SiC and graphite into the copper matrix, with minimal oxidation and no harmful chemical reactions.
- Overall, the Cu-Gr-SiC composites demonstrated enhanced mechanical properties suitable for high-load, wear-resistant, and self-lubricating applications such as sliding contact electrical brushes, etc. However, excessive SiC content may reduce impact resistance due to increased brittleness.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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