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Exploration of Mechanical Characteristics and Microstructural Analysis of Copper Matrix Composites with Hybrid Reinforcements via Muffle Furnace Sintering

Avinash Sharma[1,*], Rajesh Kumar Porwal[2]

Abstract

Metal Matrix Composites (MMCs) have drawn a lot of interest in the area of innovative materials because of how widely they may be used. Due to their extraordinary qualities, such as high thermal conductivity, higher temperature endurance, improved corrosion resistance, and great weldability, copper matrix composites stand out among them. These qualities make them desirable and promising materials for uses including heat exchangers, automotive parts, and electrical components. In this investigation, Copper Matrix Metal Composites (MMCs) were processed by employing muffle furnace sintering techniques. The study documents enhancements in mechanical properties, specifically compressive strength and hardness, with an increase in the content of reinforcing materials. For this research, six distinct metal matrix composite specimens were fabricated, utilizing pure copper (Cu) as the base material. Each time, the copper was reinforced with silicon carbide (SiC), and graphite was added as a constant additive at a consistent volume fraction (5%). A powder state mixing technique was employed to combine the various constituents. Following the mixing process, the powders were introduced into metallic molds, and the specimens were subsequently sintered using a muffle furnace under an inert gas atmosphere at different temperatures (850°C and 950°C), with varying soaking times. Multiple tests, including hardness assessments, compressive strength measurements, and microstructure analysis, were conducted on the composite specimens. The results indicated that sintering at 850°C resulted in the production of a more effectively fused matrix compared to rapid sintering at 950°C, leading to significantly improved mechanical properties, particularly in terms of compressive strength. This improvement was particularly noticeable at 15% SiC with 5% graphite content when sintered at 850°C.

Keywords: Copper, Graphite, Silicon Carbide, Hardness Test, Microstructure Test, Microwave Sintering, Compressive Test

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INTRODUCTION

In this era of cutting-edge technology, there is an increasing demand for engineering materials with extraordinary properties, including resistance to corrosion, electrical and thermal conductivity, stability, weight reduction, and enhanced strength. These characteristics are essential for a wide range of applications in several industries, including aerospace, medicine, power, automobile, and more. Due to their beneficial qualities, engineering materials are widely used in various applications, making them extremely valuable. Therefore, it is impossible to overestimate their importance in obtaining optimal results [1]. The engineering

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materials known as copper (Cu) and its alloys are often used in various engineering applications. Excellent flexibility, outstanding electrical and thermal conductivity, strong corrosion resistance, and non-magnetic characteristics are just a few benefits that copper demonstrates. Additionally, copper is simple to work with and may be easily linked [2]. Electrical wiring, heating systems, cladding, roofing, water pipes, and fittings are just a few of the many fields in which it is used. However, the comparatively low strength of pure copper may make it unsuitable for several purposes. To create valuable copper in various sectors, it is urgently necessary to improve its qualities [3].

Copper-based metal matrix composites (CuMMCs) were created to meet the demand for enhanced copper characteristics and more versatile application options. These composite materials often mix ceramic and metallic elements with high elastic modulus, compressive strength, and shear strength while remaining stable at high temperatures [4]. CuMMCs have attracted much interest because they may be used to create composite materials with different reinforcing components spread throughout a continuous matrix phase. In copper matrix composites, the copper acts as the matrix phase, producing a network, while the other components, frequently ceramics or non-metallic hard materials, serve as reinforcements. In aerospace, automotive, and shipbuilding industries, composite materials play important roles in today's contemporary industrial sectors and have various benefits over conventional metals [5–7].

A single metal matrix phase combines two or more reinforcing phases to create hybrid metal matrix composites (HMMCs). HMMCs usually have distinctive characteristics that are difficult to obtain with a single reinforcing step. Studies have been carried out to improve the mechanical and structural qualities of HMMCs utilizing different matrix phases [8]. For instance, copper-based metal matrix composites were processed using powder metallurgy and a variety of reinforcements, including silicon carbide (SiC) particles and fibers. A microstructural examination using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) showed that the reinforcements were distributed randomly inside the matrix and that the reinforcement and matrix had excellent bonding. The reinforced fiber and SiC volume fraction in these composites enhanced their hardness. [9, 10]. Another strategy involves using SiC and Al_2O_3 particulates as reinforcements to create hybrid copper matrix composites using the stir-casting process. As the reinforcement content rose, mechanical characterization improved ultimate tensile strength, yield strength, Young's modulus, shear modulus, and hardness. With more significant reinforcement additions, Poisson's ratio and density also starts decreasing. Due to the addition of graphite, these composites also displayed better machinability, wear resistance, and thermal and electrical conductivity [11]. Additionally, studies have examined the physical, mechanical, and wear resistance characteristics of copper matrix composites produced using stir casting with reinforcements made of steel machining chips. The results showed that adding steel machining chips as reinforcement significantly reduced the porosity levels in the composites and enhanced their hardness, tensile strength, and wear resistance. Furthermore, alumina (Al_2O_3) reinforcement-based copper matrix composites made by powder metallurgy demonstrated increased hardness with higher alumina content, a slight decline in compressive strength, decreased density with increased alumina content, and increased porosity [12]. Graphite and silicon carbide were used as the reinforcing materials for this investigation. It is well known that silicon carbide has good abrasion resistance and is used at high temperatures when it forms a protective silicon oxide covering. Its excellent thermal conductivity and minimal thermal expansion offer thermal shock resistance. A crystalline form of carbon called graphite improves the machinability of composite materials. To increase the suitability of the composites for a wider range of engineering applications, this research aims to examine the effects of adding silicon carbide and graphite particulates to copper alloy regarding their morphology and mechanical properties [13–15]

MATERIALS AND METHODS

Materials

Using powder metallurgy (P/M), graphite, silicon carbide, and copper composites were created. A mixture of electrolytic copper powder with an average grain size of 40 μm, silicon carbide powder

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with an average size of 30 µm, and graphite powder with an average size of 50 µm was used in the procedure. Different volume fractions of silicon carbide (5%, 10%, 15%) and graphite (5%, 10%) were manually combined with the copper powder in a pestle and mortar to guarantee a uniform distribution. Table 1 provides specifics about the specimens' makeup. The powders were thoroughly blended in the pestle and mortar for about an hour. The combined powders were then preheated in a muffle furnace at 130°C to remove any volatile components.

Composite Fabrication

This experiment employed a split-type die consisting of two parts joined together using a clamp mechanism. The green compact, formed during the process, could be released from the split dies by disengaging the clamp and opening the two-part mold cavity. The green agreement would Occasionally fracture along a vertical plane while removed from the split mold. The setup of the compression machine and die is shown in Figure 1. Using this die, six different compositions of specimens were produced, as outlined in Table 1. The preheated powders were subjected to uniaxial compaction in a CTM (Compression Testing Machine). This process resulted in forming cylindrical specimens with dimensions of 20 mm in diameter and 50 mm in height, with pressure ranging from approximately 500 MPa to 1000 MPa, corresponding to the plunger diameter of the die.

Sintering and Characterizations

The process that turns the weak mechanical links in the green compact into strong metallic bonds is known as sintering. A unique setup using a typical inert gas muffle furnace was created to aid this procedure as shown in Figure 2. A temperature range of 600 to 1000°C was used for sintering several sets of specimens, varying from one to two hours. The "green compact" models were put in the furnace, and the temperature was raised at a pace of 10 to 20 degrees Celsius per minute. The tuning controller manually regulates the furnace's heating rate. The temperature stays higher after reaching it for the required amount of time. After sintering, specimens were furnace cooled at a 40°C/min.

Table 1. Composition of specimens in %

Specimen	Copper %	Graphite %	SiC%
Specimen-1	90	5	5
Specimen-2	85	5	10
Specimen-3	80	5	15

Figure 1. Die and compression set-up.

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Figure 2. Green compact and furnace set-up.

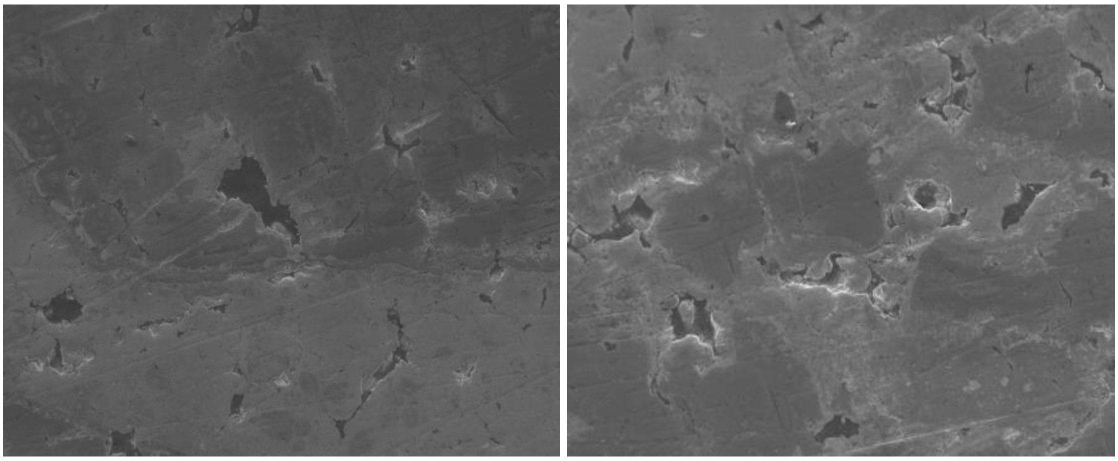

Figure 3. At 850℃ Magnification: 200X.

RESULTS AND DISCUSSION

Investigation of Microstructure Result

Results at 850°C with a 5% SiC concentration are shown in Figure 3. Two sets of microstructure pictures were obtained, showing totally fused areas during sintering and a negligibly small quantity of free copper that was still unfused. Along with small, equiaxed copper grains, the copper matrix also contains black, tightly packed free graphite particles and grey Sic particles.

Figure 4 shows microstructure visuals that were captured at the same temperature (850°C), but with 10% SiC. These pictures depict fully fused portions during sintering along with some free copper that has not yet fused. Similar to Figure 3, the matrix includes tiny equiaxed copper grains, tightly aggregated black free graphite particles, and grey SiC particles.

Figure 5 displays two sets of microstructure pictures taken at 950°C and -5% SiC. These photos show totally fused areas during sintering with very little free copper that hasn't been fused. Along with small, equiaxed copper grains, the matrix also contains black, agglomerated free graphite particles and grey Sic particles. Larger and finer SiC particles are disseminated in the matrix as the SiC concentration rises.

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Figure-6 microstructure pictures taken at 950°C and -10% SiC. These photos show totally fused regions during sintering with little free copper that isn't fused. Once more, the matrix reveals the presence of highly agglomerated free graphite particles and grey Sic particles.

Two sets of microstructure visuals are shown in Figure 7 at 950°C and -15% SiC, showing totally fused areas during sintering and barely any unfused free copper. Grey Sic particles and darkly agglomerated free graphite particles may be seen in the matrix, together with small, equiaxed copper grains. All save the largest copper granules have fused.

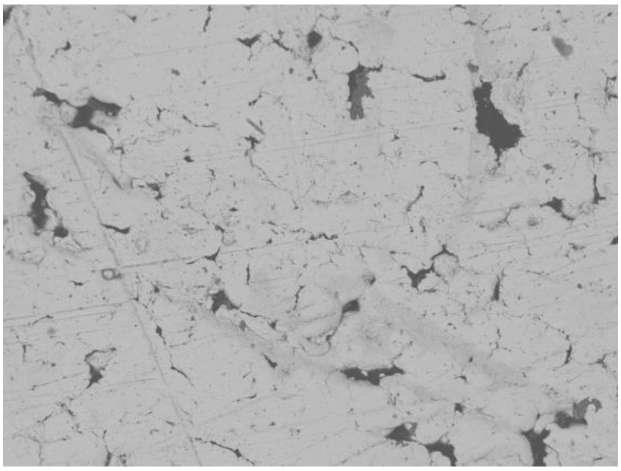

Figure 4. At 850℃ Magnification: 200X.

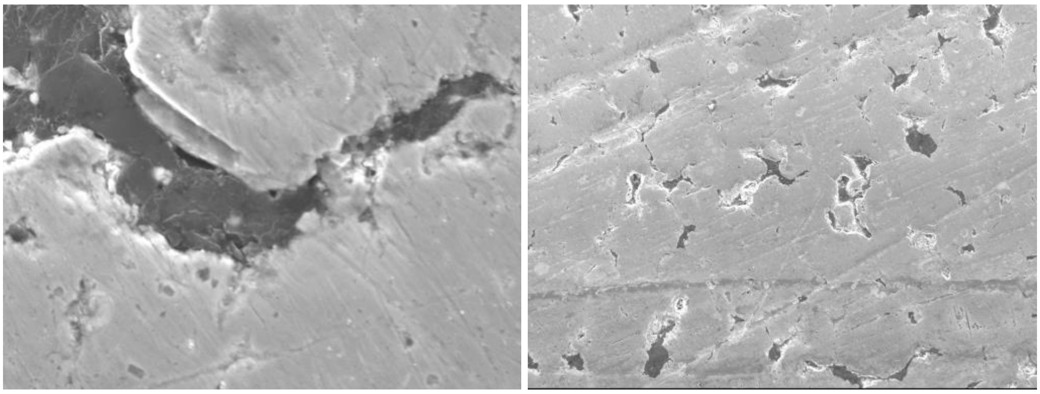

Figure 5. At 950℃ Magnification: 200X.

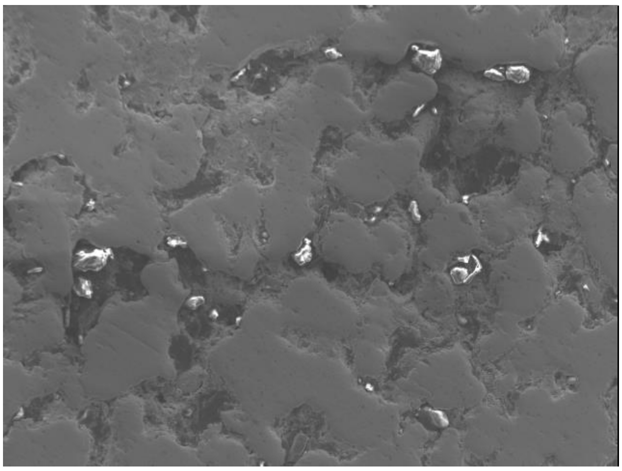

Figure 6. At 950℃ Magnification: 400X.

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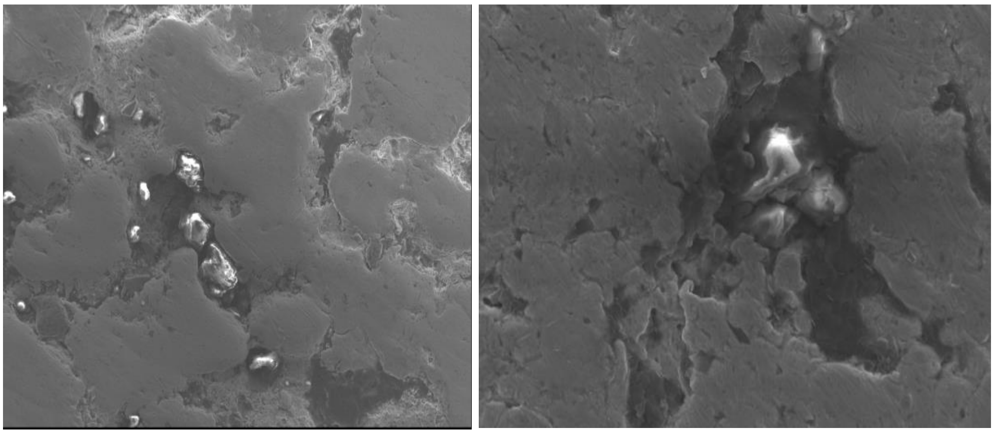

Figure 7. At 950°C Magnification: 400X.

Investigation of Hardness Test Results

The examination into hardness shows an upward tendency as the silicon carbide percentage rises. In comparison to lower temperatures with a soaking period, there is a reduction in hardness when the temperature is maintained. This effect can be explained by the enhanced diffusion bonding that occurs when the materials are sintering at lower temperatures for a longer period of time. The Vickers' Hardness Number (VHN) increases with the increasing fraction of SiC at a sintering temperature of 850°C. Aside from slight variations at 950°C, the Vickers's Hardness Number also shows (Figure 8) an increase with the rise in sintering temperature, which may be caused by the presence of impurities or an uneven distribution of SiC's heat inside as shown in Table 2.

Investigation Compressive Test Results

Utilizing a computerized compression testing device the compressive strength of each mixture was evaluated. The study of displacement for numerical comparisons as well as the computation and comparison of breaking loads were made possible by this. The reinforcement shown in Table 3 for MMC with a composition including 15% SiC and a constant 5% of graphite was sintered at 850°C for

Table 2. Hardness values with constant graphide

	Sic-5% Gr-5%	Sic-10% Gr-5%	Sic-15% Gr-5%
850°C	38.2	44.32	56.18
950°C	35.1	32.18	52.13

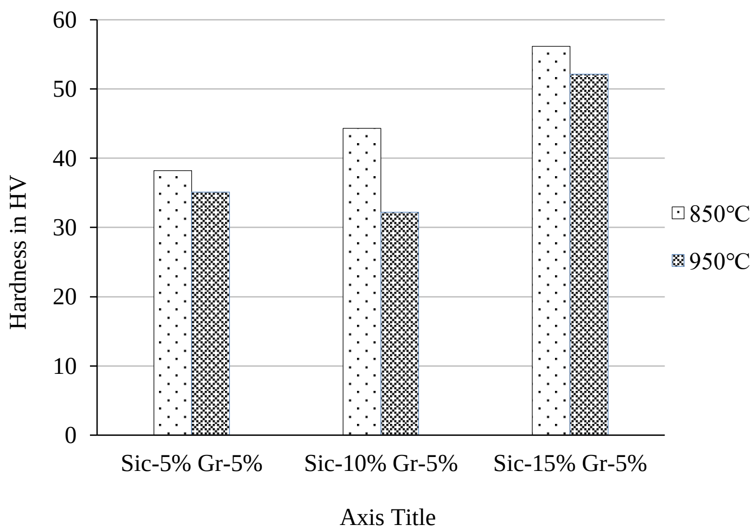

Figure 8. Hardness test Result.

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a soaking period to provide the greatest compressive strength. When sintering occurred at 950 degrees without a soaking interval, the compressive strength at 850 degrees with the soaking time showed greater strength. This pattern could be seen in Figure 9 as obtained in results, where the compressive strength performed better at 850 degrees with soaking time than it did at 950 degrees.

Table 3. Compression values with constant graphite

	Sic-5% Gr-5%	Sic-10% Gr-5%	Sic-15% Gr-5%
850°C	5.62	6.35	5.91
950°C	4.35	5.12	3.21

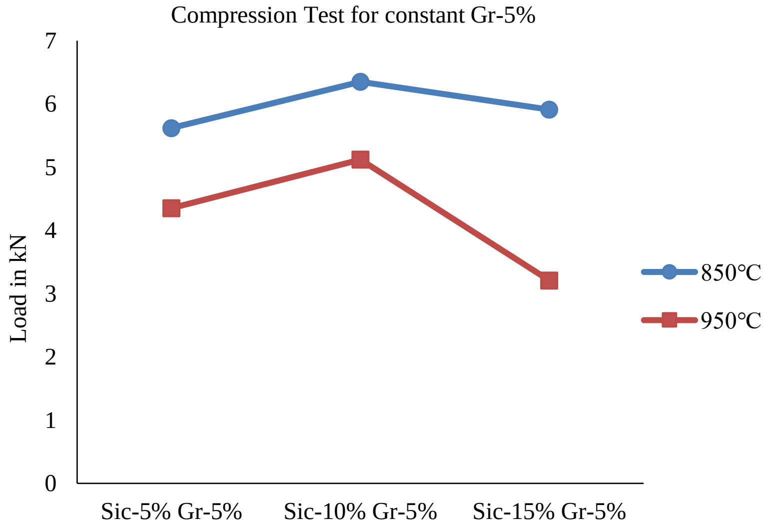

Figure 9. Compression Test

CONCLUSIONS

In summary, the present investigation yielded the following key conclusions:

- *Successful Fabrication:* The Copper-Silicon carbide-graphite composites were effectively fabricated using the muffle furnace sintering process.
- *Vickers's Hardness Number (VHN):* The Vickers's Hardness Number demonstrated an increase with the rising SiC composition at a sintering temperature of 850°C. However, some deviations were observed, indicating a slight decrease in hardness with an increase in SiC percentage at the same sintering temperature. This deviation could primarily be attributed to the presence of unwanted impurities.
- *Sintering Temperature Effect:* The Vicker's Hardness Number also exhibited an increase with the elevation of sintering temperature for a specific SiC composition (5% graphite). Minor exceptions were noted at 950°C, possibly due to impurities or non-uniform heat distribution of SiC within the copper matrix.
- *Microstructure Analysis:* It is found that there is uniform distribution of graphite and SiC reinforcement in the copper matrix. Notably, sintering at 850°C produced a more effectively fused matrix compared to rapid sintering at 950°C.
- *Compressive Strength:* The maximum compressive strength was attained with a composition comprising 15 vol. % SiC and a constant 5 vol% of graphite in a reinforced MMC, sintered at 850°C with soaking time. This finding highlighted that the compressive strength achieved at 850°C with soaking time surpassed that obtained at 950 degrees without a soaking period.

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