Effect of graphene, SiC and graphite addition on hardness, microstructure and electrical conductivity of microwave sintered copper MMCs fabricated by powder metallurgy route

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Abstract. Copper MMCs reinforced with graphene, SiC and graphite flakes with varying mass fractions of 2.5, 5, and 7.5 wt% SiC, 2.5, 5, 7.5, and 10 wt% graphite and 0.2, 0.4, 0.6 and 0.8 wt% graphene particles were fabricated through powder metallurgy route. The powder mixtures were blended and then compacted under a uniaxial pressure of 400MPa for both Cu-SiC and Cu-Gr composites and 600Mpa for Cu-Gn composites. Green compacts were sintered by microwave (MW) sintering process. MW sintering was performed at 950°C in open atmosphere with a heating rate of 25°C/min for all composites. Densification parameter (DP) was determined for all MMCs and a reduction in DP values were observed with an increase in weight percentage of reinforcement particles as a result of increase in porosity. Higher mass fractions of reinforcement particles in the Cu matrix tend to offer a diffusion barrier to copper atoms. Micro-structural analysis was performed using Optical and scanning electron microscope which revealed a homogeneous microstructure of all composites at low mass fractions of Sic, graphite and graphene. In order to detect the presence of any oxides of Cu and other elements, EDS analysis was carried out. Hardness data showed an increasing trend for Cu-SiC and Cu-Gn composites and a declining trend for Cu-Gr composites. Porosity has a significant effect on the electrical conductivity values of the composites.

1. Introduction
Copper MMCs have superior mechanical and thermal properties compared to that of pure copper [1]. Adding dispersed particles into the copper matrix improves the mechanical properties of copper [1,2]. Carbide and oxide phases impart sufficient thermal stability even at elevated temperatures. Cu-SiC metal matrix composites possess the properties of both copper and Silicon Carbide, i.e high thermal conductivity of copper and low coefficient of thermal expansion of SiC [1,3]. This composite is majorly used for heat sinking or heat spreader applications. A Cu-SiC heat spreader offers high thermal conductivity and an adjustable coefficient of thermal expansion (CTE) over a desired range.
Copper–graphite MMCs have excellent thermal and electrical conductivities, and the properties of graphite, i.e. solid lubricating and small thermal expansion coefficient [6]. These composites find wide applications in brushes, and bearing materials due to the excellent mechanical and thermal properties. Copper–graphite MMCs with low weight percentages of graphite is also used in slip rings, switches, relays, connectors, plugs and low voltage DC machines with very high current densities [7]. They are excellent in terms of machining and brazing, also a good candidate for thermal management applications for high power density packaging of advanced semi-conductor devices. These MMCs exhibits superior mechanical, electrical and thermal characteristics. Cu-Gr composites are widely used in bearing materials and brushes because of its excellent thermal and self-lubricating properties [7,8].

It was reported that graphene is the strongest material ever tested [9]. It has been preferred as an excellent reinforcement because of its superior tensile strength (130 GPa), Young’s modulus (1TPa), thermal conductivity (5000W/mK), electrical conductivity, and large specific surface area (SSA-2630m²/g) [10]. Cu-Gn composites are reported to have superior electrical, mechanical and thermal properties as compared to pure copper [11]. Graphene is the building block of graphite, a one atom thick 2D allotrope of carbon with a honeycomb structure. Production of graphene in bulk quantity is an expensive process. Researchers around the globe have been working on graphene based devices like batteries and solid state devices which are predicted to have superior performance and life. Dispersion of graphene in copper phase is challenging due to large difference in relative density of the materials.

Sintering involves heating and reducing the porosity of a green compact. A conventional sintering process uses some external sources and heat energy is transferred by conduction convection and radiation. Generation of heat takes place in the external heating element and it is transferred to the core of the material by conduction heat transfer. Initially the surface of the material is heated and as the temperature rises the heat is transferred to the core, resulting in the development of internal stress and a thermal gradient in the radial direction. In order to achieve thermal equilibrium conventional sintering process requires considerable time. On the other hand microwave sintering process is a distinctive process which enables us to reduce sintering cycle times. Microwave radiations are electromagnetic radiations with frequency ranging from 300 MHz to 300 GHz, with region of wavelengths between 1mm to 1m in Electromagnetic spectrum. Microwave spectrum usually includes 3 bands, Extremely High Frequency (EHF) 30GHz to 300GHz, Super High Frequency (SHF)-3GHz to 30GHz, Ultra High Frequency (UHF) 300MHz to 3GHz. Microwave radiations of frequency of the order of 2.5 GHz are commonly used in commercial microwave furnaces. Unlike a conventional sintering process, microwave heating results in rapid consolidation of the composites by volumetric heating. In this process heat is transferred from the core to the surface of the material which results in low surface temperature of the samples. Thus thermal degradation of the material can be considerably reduced. As compared to conventional sintering process, high heating rates can be enabled in microwave process which reduces the sintering time. Rustum Roy et al. investigated the microwave sintering characteristics of transparent alumina. Sintering was performed at 1750°C for 15 minutes, and it was reported that the samples exhibited full densification and good transparency [12]. Manoj Gupta et al. fabricated Al-SiC nano composites by microwave sintering followed by hot extrusion process. They summarized microwave process as an eco-friendly consolidation method which offers higher heating rates and shorter processing cycle times without compromising on the properties of the material [13].

In this study attempts were made to fabricate copper matrix composites reinforced with varying weight percentage of SiC, graphite and graphene particles through powder metallurgy route. The effect of reinforcements on the microstructural and electrical properties of copper composites was studied.
2. Experimental procedure

2.1 Materials

For the production of composites, gas atomized copper powder with a purity of 99.5% and an average particle size of 100µm (Manufacturer: Sigma Aldrich, USA) has been used. Fine quality graphene powder (Angstrom materials, USA) of average particle size 100nm, SiC powder of 99.9% purity (Manufacturer: Sigma Aldrich, USA) having an average particle size of 20 µm and 99.9% pure graphite flakes of average particle size 50µm (Manufacturer: Angstrom materials, USA) were used as the reinforcement phases. Each composition with a varying percentage of 2.5, 5, and 7.5 wt% SiC particles, 2.5, 5, 7.5, and 10 wt% graphite flakes and 0.2, 0.4, 0.6 and 0.8wt% graphene particles and pure copper powder were mixed in a screw mixer for 30 minutes each. Spheroidal form of copper particles are shown in figure 1a), which is the result of gas atomization process. The morphology of graphene and graphite are flaky in nature and that of SiC is angular as seen in figure 1b), 1d) and 1c). Powder characteristics of as received powders are shown in table 1.

![Figure 1. Powder morphology of as received powders a) Pure copper b) graphene c) SiC and d) graphite](image)

| Table 1. Powder characteristics of as received powders |
|-------------------------------------------------------|
| Characteristics | Copper | Graphite | Graphene | SiC |
| Apparent density (g/cm³) | 4.46 | 0.16 | 0.016 | 1.27 |
| Tapped density (g/cm³) | 5.32 | 0.34 | 0.14 | 0.26 |
| Flow rate in sec/50g | 32 | No flow | No flow | 14 |
| Average particle size (µm) | 100 | 50 | 100nm | 20 |
| Theoretical density (g/cm³) | 8.96 | 2.26 | 2.2 | 3.21 |
| Shape | Spherical | Flaky | Flaky | Angular |
| Purity (%) | >99.5 | 99.99 | 99.99 | 99.99 |
2.2 Fabrication of Cu-SiC, Cu-Gn and Cu-Gr composites

Blended powders were compacted in a closed cylindrical die of 16 mm diameter under a uniaxial pressure of 400MPa for both Cu-SiC and Cu-Gr composites and 600Mpa for Cu-Gn composites. Zinc stearate powder was applied to the die walls and rod in order to facilitate easy ejection. The green compacts thus produced were sintered by microwave sintering process at a temperature of 950° C with a heating rate of 25°C/min and a holding time of 1 hour in all cases. A 6 kW, 2.45GHz multimode cavity commercial furnace was employed for the sintering process. An insulation package with multilayer wall was incorporated to ensure the uniform heating of the samples. Samples were allowed to cool in the furnace itself.

2.3 Metallographic sample preparation

For capturing the optical microimages, metallographic preparations were performed on the samples as per ASTM E407 standard. First the samples were polished by traditional process by employing different grades of emery sheets ranging from 200-2000 grit sizes. Then the samples were polished in a disc polishing machine with diamond paste and Al₂O₃ media. A mirror finish was produced on all the MMC surfaces. Samples were etched with a solution containing 5g Fecl₃, 10ml HCl, 50ml glycerol and 30ml water as per the standard. A controlled etching process was performed where the sample was rubbed against a cotton cloth soaked with the etching media for a time period of 15-60 seconds.

2.4 Characterization

Sintered densities were determined by a method based on Archimedes principle. Micro structural analysis was performed using (Zeiss Axioskop A40, Germany) Optical microscope and (Zeiss EVO MA 10) scanning electron microscope. SEM-EDS analysis was performed to detect the presence of Cu, SiC, graphite, graphene and any presence of oxides of these. Vickers micro hardness test was performed on all the samples using a Vickers micro hardness tester (Matsuzawa MMT-X7 model, Japan) based on optical measurement. A load of 100g was applied and a dwell period of 10s was maintained for testing all samples. Five readings were taken on each of the samples by carefully picking a point which includes both the matrix and the reinforcement homogeneously. Poros present in the samples were carefully avoided to obtain better hardness data. Electrical conductivity of the samples was determined by an instrument which works on the principle of ‘four point collinear probe’. Resistivity of the samples was measured, which is the reciprocal of electrical conductivity. ASTM B193 standard test procedure was followed in the measurement process.

\[ \text{Bulk resistivity} = \frac{1}{2\pi S(V/I)} \]

Where S is space between probes, I is the test current and V is the measured voltage

3. Results and discussion

3.1. Relative density

Relative density plots of the composites sintered at 950°C are shown in figure1. Higher relative density was observed for Cu-Gn composites with a maximum value of 90% as shown in figure 1. Relative density of the Cu-SiC composites varied between 80-86%, Cu-Gr between 76-87% and for Cu-Gn in the range 87-90%. Relative density of pure copper sintered by microwave sintering process was determined as 86%. It was observed that the relative density of the composites decreases with the increase in addition of the reinforcement particles [14]. Lowest relative density was observed for Cu-10wt% Gr MMC. This is due to the solid lubricating nature of graphite which separate the copper grains and inhibits the development of a continuous copper network. The relative density values of Cu-Gn composites were much closer as the weight percentage of graphene particles were below 1%. Density of the graphene (2.21 cm³) is much lower than that of copper (8.89g/cm³). The density of SiC powder was 3.21 g/cm³, 2.26 g/cm³ for graphite flakes and 2.21 g/cm³ for graphene powder. Due to this the relative density of the composites becomes low. Another possible reason may be the presence of porosity in the composites [15]. For lower weight percentage of SiC, Cu-SiC interface was found to be less and hence less copper atom diffusion barrier. Under such conditions copper atoms can easily
diffuse and result in higher densification values of the composite. Similar behavior was predicted for Cu-Gr and Cu-Gn composites [5,15]. The decrease in relative density of composites can be attributed to the formation of oxides which was confirmed by SEM-EDS analysis. Densification parameter was relatively high for all composites with low weight fractions of reinforcements. With the increase in wt% of SiC, porosity observed in Cu-SiC composites were considerably high. Pores present in Cu-Gn composite are a result of large mismatch in relative density of the particles. This has significant effect on properties, and still redeemed by adding graphene with outstanding properties. Agglomeration tendency of graphite was observed in the entire process of mixing, blending and while taking microstructures. Relative density of Cu-Gr composites reduces as a result of the same. Addition of graphite after an optimum value thus impedes the properties of the Cu-Gr MMCs.

![Figure 2. Relative density of Cu-SiC, Cu-Gr and Cu-Gn composites](image)

3.2. Microstructure

Optical micrographs of the Cu-SiC composite sintered by microwave process at 950°C are shown in figure 3. The bright areas represents the copper matrix as shown in microstructure of pure copper in figure 3(a), while the dark spots indicate the uniformly distributed SiC particles in the copper matrix as in figure 3(d). Microstructure of the composite plays a vital role in predicting the mechanical, thermal and electrical behavior of the composites. When the reinforcement is uniformly distributed in the matrix it enhances the mechanical properties of the composite [16]. As the weight percentage of SiC was increases it was observed that the SiC particles get embedded into the copper grains due to the ductile nature of copper [17]. Large grains of copper of the order of 100µm were observed in the micrographs of pure copper, figure 3(a). The distinction between the particle size of the matrix and the SiC particles can be predicted from the micrographs. Compared to Cu-Gr composites, Cu-SiC composites exhibited a homogeneous microstructure even at higher weight fractions of SiC. Hard SiC ceramic phase does not agglomerate easily unlike graphite as observed in Cu-Gr composites. Presence of alumina particles were observed in the microstructures of all composites. Hard alumina particles get embedded into the copper matrix during metallographic sample preparations. A slight variation in color in Cu-SiC composites is observed due to the presence of alumina particles.

Graphite particles have a natural tendency to form agglomerates as observed from the optical micrographs of Cu-Gr composites. Presence of graphite agglomerate in the copper matrix cannot be avoided completely due to the inherent nature of graphite as shown in figure 4(c). Graphite particles due to its light nature sometimes floated on the surface which could be observed while taking the micrographs [7,8]. The mixing of copper and graphite powder was a challenge due to large difference in relative density values. For low mass fractions of graphite upto 5 wt%, homogeneous microstructure
of Cu-Gr was observed. Many researchers have reported that by adding 5-7 wt% of graphite into copper matrix, the mechanical and thermal properties of Cu-Gr MMCs can be enhanced to a greater extent [18].

Microimages of the Cu-Gn composites exhibited a homogeneous distribution of graphene particles within the copper matrix. In the micrographs the dark area indicates the uniformly distributed graphene particles as seen in figure 5(a). As the weight percentage of graphene increased a tendency to form agglomerates was observed as shown in figure 5(c) and (d). Some of the graphene particles were embedded in the copper matrix while the rest of the particles were observed in the grain boundary of the copper matrix, figure 4(a). Embedded particles do not have a re-arranging ability. With the increase in addition of more graphene the number of particles present in grain boundary of copper increases and leads to agglomeration [9]. High specific surface area and low density of graphene poses great challenge while mixing the powders. Homogeneity can be maintained by increasing the mixing time and by controlling the size of Cu grains.

Figures 6-8 shows the SEM micrographs of the composites. From the SEM micrograph of Cu-SiC composite it was observed that the SiC particles were present in the grain boundaries of the copper grains. Dark areas indicate the SiC particles as illustrated in figure 6(d). Clustering behavior of Sic particles were observed in the SEM micrographs, which was not evident in optical images as seen in figure 6(d). Uniform distribution was much higher for composites containing lower weight percentage of SiC particles. Apart from the Cu-SiC, interface no other phases were seen in the micrographs of Cu-SiC composites. In the micrographs of Cu-Gr composites, agglomerates of graphite were observed due to the inherent nature of graphite to form clusters as shown in figure 7 (a) and (b). Dark areas indicate the graphite agglomerates in the micrographs. The variation observed in the hardness value can be justified by the SEM micrograph. Presence of any interfacial products were not observed from the microstructure which confirms that no reactions takes place between copper and graphite during the sintering process [7,8]. Apart from the Cu-Gr interface no other phases were observed in the micrographs. Graphite induces into the matrix due to its soft nature which was evident from the micrographs [18]. Due to the low solubility of carbon in copper only mechanical bonding between two phases occurred.

![Figure 3. Optical micrographs of Cu-SiC MMCs sintered by microwave process](image-url)
Figure 4. Optical micrographs of Cu-Gr MMCs sintered by microwave process

Figure 5. Optical micrographs of Cu-Gn MMCs sintered by microwave process
Figure 6. SEM micrographs of Cu-SiC MMCs sintered by microwave process

Figure 7. SEM micrographs of Cu-Gr MMCs sintered by microwave process
Figure 8. SEM micrographs of Cu-Gn MMCs sintered by microwave process

For the Cu-Gn composite a continuous distribution of graphene particles in copper matrix was observed for all the compositions as shown in Figure 8. Porosity was observed for the higher weight percentage addition of graphene as shown in Figure 8(c). Due to the smaller grain size, graphene particles were observed in the grain boundaries of the copper matrix and no other phases were observed except the Cu-Gn interface. Presence of pores is due to expansion of the composites in open atmosphere. A reducing atmosphere can be provided inside the furnace to avoid oxidation and expansion of the composites. A slight change in density was observed due to the presence of atmosphere in furnace.

SEM-EDS analysis was performed to analyze the presence, morphology and distribution of Cu, SiC, graphite, Graphene and any oxides of these in the composite, shown in figure 9-12. As the green compacts were sintered at 950°C oxides of copper might have formed which was confirmed by the EDS analysis, and the presence of oxygen was detected [5,12,19]. Presence of chlorine and aluminium was detected in EDS analysis of pure copper and Cu-SiC composites. During etching and polishing processes of the composites, etching media and alumina particles get entrapped into minute pores present in MMCs [1]. EDS analysis only confirmed the presence of Si and C which in turn can be predicted as SiC present in the composite. It was reported that at high temperatures SiC decomposes into Si and C. But presence of any carbides of copper was not detected. Copper is not a carbide former and presence of any such phases is thus ruled out at present. Oxygen detected in the Cu-SiC by EDS analysis can be supported by figure 9 [15]. Due to the ductile nature of copper alumina particles get embedded into the matrix, which was difficult to remove and was detected in the EDS analysis. Presence of oxygen detected might be from alumina media used for etching.
Table 2. SEM-EDS analysis of Cu-7.5SiC composite sintered by microwave sintering process at 950°C

| Element | Weight% | Atomic% |
|---------|---------|---------|
| C K     | 5.20    | 17.99   |
| O K     | 9.66    | 25.10   |
| Si K    | 0.34    | 0.50    |
| Cl K    | 1.71    | 2.01    |
| Cu L    | 83.10   | 54.39   |

Totals 100.00 100.00

Table 3. SEM-EDS analysis of Cu-10Gr composite sintered by microwave sintering process at 950°C

| Element | Weight% | Atomic% |
|---------|---------|---------|
| C K     | 28.28   | 64.07   |
| O K     | 4.10    | 6.97    |
| Cu L    | 67.63   | 28.96   |

Totals 100.00 100.00

Table 4. SEM-EDS analysis of Cu-0.8Gn composite sintered by microwave sintering process at 950°C

| Element | Weight% | Atomic% |
|---------|---------|---------|
| C K     | 4.68    | 17.26   |
| O K     | 7.90    | 21.86   |
| Cu L    | 87.41   | 60.88   |

Totals 100.00 100.00

Figure 9. Field under consideration for SEM-EDS analysis of Cu-7.5SiC MMC

Figure 10. Field under consideration for SEM-EDS analysis of Cu-10Gr MMC

Figure 11. Field under consideration for SEM-EDS analysis of Cu-0.8Gn MMC
3.3. Hardness

Figure 12 shows the hardness values of the composites sintered by microwave process at 950°C. Indenter of the hardness tester was carefully placed on the composites so as to pick a point which constitutes both the matrix and reinforcement for getting accurate hardness values. It was observed that the hardness value increases with the increase in content of the reinforcement particles except for Cu-Gr composite which was observed low for the range in the study. SiC particles are excellent barriers to the dislocation movement in the copper matrix. Increasing the SiC content, strongly impeded the plastic flow, resulting the hardness of Cu–SiC composite to increase as shown in the figure 12 [1,20]. Higher hardness value was observed for Cu-Gn composite for the entire range due to the superior mechanical properties of graphene despite the presence of pores [21]. Areas with pores were carefully avoided while selecting points. It was reported that graphene has a tensile strength of 130Gpa and youngs modulus of 1Tpa [10]. Highest hardness value of 82 ± 2.4HV 100 was observed for Cu-0.8Gn. Due to the soft nature of graphite the hardness values of the Cu-Gr composites were observed to be the lowest. As the weight percentage of graphite increased, hardness values were found to be significantly low. The hardness results showed an increasing trend in the beginning and started to decline with more addition of graphite. Presence of adequate mechanical mixed layer (MML) is reported to have significant effect in the tribological and mechanical properties of graphite. Cu-5Gr shows better hardness values compared to other compositions of Cu-Gr. This can be attributed to homogeneous microstructure of the composite. Lowest hardness value of 35.3±2.2 HV 100 was observed for Cu-10Gr. Presence of large pores was detected in these composites. It was observed that a very small weight percentage of graphene particles added to the matrix could improve the hardness values to a bigger extend [9,10]. Dispersion strengthening is the main strengthening mechanism which was responsible for the improvement in the hardness values of the composites [8]. The hardness results mainly projected the mechanical properties of the reinforcement particles where a high hardness value was observed for Cu-SiC and Cu-Gn composites. Lower values of Cu-Gr composites were observed due to the soft nature of graphite, SiC being hard and graphene with superior mechanical properties contributed to improvement in hardness values.

Figure 12. The variation of Vickers micro-hardness for the composites sintered by microwave sintering processes at 950°C
3.4. Electrical conductivity

Electrical conductivity of all sintered composites are shown in table 5. Pure copper exhibited excellent electrical conductivity. Annealed copper has an electrical conductivity of 59 MS/m (100%) which is set as the standard. 6% IACS variation from that of annealed copper is due to presence of porosity and slight variations in purity of composites by the encapsulation of oxides. Cu-0.2Gn MMC with highest relative density value exhibited the highest electrical conductivity of 95% IACS. Due to presence of porosity in the composites conductivity values started to decline with more addition of graphene. Lowest electrical conductivity reported for Cu-Gn MMC was 86% IACS for Cu-0.8Gn composite. For most of the application which demands for high hardness and significantly high conductivity values Cu-0.8Gn composites can be employed. A tradeoff between electrical conductivity and hardness is preferred for use in brushes, slip rings etc. Presence of a conductive network is inevitable in attaining high electrical conductivity values. With the addition of ceramic SiC particles where there is a great mismatch between the conductivity values, a drastic decline in electrical conductivity of Cu-SiC composites was observed. Addition of 2.5wt% SiC results in a significant reduction in conductivity of copper. A maximum of 80% IACS and a minimum of 54% IACS was observed for Cu-2.5SiC and Cu-7.5SiC composites. Adding more SiC into copper increases hardness but reduces electrical conductivity to a greater extent. Almost 75% reduction in conductivity was observed for Cu-7.5SiC composite as compared to pure copper sample. Conductive network of copper is hindered by the addition of large fraction of less conductive SiC particles. Cu-2.5Gr composite exhibited an electrical conductivity value of 88% IACS. Graphite is a good conductor of electricity, so addition of small weight percentages does not bring much change in the observed values. Relative density values decline with addition of large weight percentages and which in turn reduces the conductivity values of MMCs. Lowest value among the Cu-Gr composites was observed for Cu-10Gr MMC with an electrical conductivity of 55% IACS. It was observed that an optimum addition of graphite (2.5-5 wt%) enhances the properties without large variations in electrical conductivity values.

Table 5. Variation of electrical conductivity of Cu-SiC, Cu-Gr and Cu-Gn MMCs sintered by microwave process at 950°C

| Composition | Electrical conductivity (%IACS) | Composition | Electrical conductivity (%IACS) | Composition | Electrical conductivity (%IACS) |
|-------------|---------------------------------|-------------|---------------------------------|-------------|---------------------------------|
| Pure Copper | 94                              | Cu-2.5Gr    | 88                              | Cu-0.2Gn    | 95                              |
| Cu-2.5SiC   | 80                              | Cu-5Gr      | 81                              | Cu-0.4Gn    | 92                              |
| Cu-5SiC     | 65                              | Cu-7.5Gr    | 60                              | Cu-0.6Gn    | 89                              |
| Cu-7.5SiC   | 54                              | Cu-10Gr     | 55                              | Cu-0.8Gn    | 86                              |
4. Conclusion
Microwave sintering process was employed to successfully fabricate copper matrix composites with a varying addition of SiC, graphite and graphene. The effect on hardness, microstructure and electrical conductivity of these MMCs were investigated.

- Microwave sintering resulted in better consolidation of the composites.
- Relative density of Cu-Gn composites exhibited better values as compared to its counter parts. Densification response of all composites found to reduce with an increase in addition of the reinforcement particles.
- Optical and SEM micrographs revealed the uniform distribution of the reinforcement particles in the copper matrix for Cu-SiC, Cu-Gn and Cu-Gr composites for low weight percentages of reinforcement particles.
- No other second phases were observed in the micrographs except the copper reinforcement interface
- SEM-EDS analysis revealed the presence of oxygen in all the composites due to oxidation of copper at sintering temperature.
- From Vickers micro hardness results it was observed that a higher content of SiC and graphene could improve the hardness of the composite drastically. Due to the soft nature of graphite, hardness values of Cu-Gr MMCs were seen to decline with addition graphite.
- A maximum hardness value of 82 ± 2.4HV_{100} was observed for Cu-0.8Gn composite. Lowest value observed was 35.3±2.2 HV_{100} for Cu-10Gr composite.
- For obtaining superior electrical properties, an optimum quantity of graphene and graphite is preferred. For higher hardness combined with tailorable electrical conductivity of Cu-SiC composites, 2.5-5 wt% SiC is suggested.

Scope for future work
- Thermal conductivity and wear behavior of the composites can be studied.
- Coefficient of thermal expansion (CTE) of the composites can be investigated.

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