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Investigating the mechanical properties of copper matrix composite enhanced with graphene, fabricated by powder metallurgy technique

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Abstract: The powder metallurgy procedure was used to manufacture Cu-matrix hybrid nanocomposites containing different quantities of silicon carbide (SiC) and graphene nanoparticles in this research. The powders were subjected to compression and then exposed sintering into inert gas for a duration of one hour at three distinct temperatures, reaching a maximum of 850 °C. Furthermore, relative, bulk density, porosity, and mechanical properties characteristics of the sintered samples were analyzed. The findings indicate that the use of SiC and graphene ceramics effectively reduced the density and increased the porosity of samples. Moreover, the Cu matrix nanocomposite of the greatest volume percentage of ceramics (CSF8) exhibited considerable enhancements in ultimate strength, microhardness, and elastic modulus.

Keywords: copper matrix nanocomposites; silicon carbide; elastic moduli; powder metallurgy

1. Introduction

Copper (Cu) finds extensive application in high-end sectors such as electronic packages, integrated circuits, and electric switches, owing to its exceptional characteristics including high electrical conductivity, fatigue resistance, workability, and corrosion resistance. However, its low hardness and wear resistance restrict its applicability in these domains. Copper matrix composites (CMCs) have gained significant popularity in recent times for their exceptional wear resistance, high hardness, and high temperature stability, which have all contributed to their extensive use in previous applications (Zhang et al 2020; Moustafa et al 2020). When compared to pure Cu, the CMCs have superior characteristics because of the unique mix of properties of their parts. It is possible to change the features of CMCs by changing the type and amount of support particles used, like silicon carbide (SiC) (Mirsaeed-Ghazi et al 2019; Celebi et al 2011) and carbon nanotubes (Deng et al 2017; Saber et al 2017). transition metal carbides/borides (Mirsaeed et al 2019; Celebi et al 2011).

The SiC particles are an effective reinforcement to strengthen copper and its alloys because they have outstanding characteristics like being very hard, chemically stable, resistant to wear, and resistant to high temperatures (Akramifard et al 2010; Munnur et al 2021). Another reinforcement is graphene, which is one of the most popular reinforcement for improving metal properties due to its ability to improve mechanical properties (Moustafa and Taha 2020). One of the most effective methods to make a material that is good at mechanical properties, wear resistance, and electrical conductivity is to use powder technology. Two or more ceramic phases are added to the metal phase to make hybrid composites that are better in some ways than the individual materials (Youness and Taha 2021; Bezzina et al 2022; Zawrah et al 2022). PM is widely used in mass manufacturing since it is more cost-effective than other methods. The main benefits of the PM method for manufacturing composites over other methods are that the ceramics have a more even distribution in the matrix, the process temperature is lower, and it is affordable to make a lot of them (Abulyazied et al 2021; Katsuyoshi et al 2022). Based upon the aforementioned efforts, the aim of this work is improving the mechanical properties of Cu using the combination of SiC and Gr as reinforcements particles to produce Cu matrix hybrid nanocomposites by the powder metallurgy method. The effect of addition reinforcement on density porosity and mechanical properties was analyzed. We additionally examined how the ceramics volume percent and sintering temperature affected the nanocomposites' microhardness, strength.

2. Experimental:

In order to synthesize Cu-matrix hybrid nanocomposites reinforced with varying percentages of SiC and graphene, the powders of Cu that were obtained were used, with average particle sizes of 100 µm. The powders mixtures were milled for 20 h in a planetary ball mill with rotation speed equals 440 rpm and mass ball-to-powder ratio equal to 15:1. It is worth mentioning that the milling was done in a cycle of 5 h and paused for 2 h. The powder was then pressed around a 30 MPa hardened steel die to make 15 mm diameter discs that were 5 mm thick. This was done at room temperature. The discs were then heated at different rates of 5 ºC/min for an hour at 700, 800, and 850 ºC in an argon atmosphere to make them hard. The liquid displacement method was used to measure the bulk density (BD) and apparent porosity (AP) of each layer of the FGCs sample, and the following formula was used to figure them out (Khalila et al 2018).

$$\mathrm{B.D} = \frac{\mathrm{W_s - W_d}}{\mathrm{W_s - W_i}} \times 100 \tag{1}$$

$$\mathrm{A.P} = \frac{\mathrm{W_d}}{\mathrm{W_s - W_i}} \times \rho_l \tag{2}$$

The density of prepared samples was determined by using the data that Cu has a density of 8.96 g/cm3, SiC has a density of 3.21 g/cm3, and graphene has a density of 2.2 g/cm3. Using bulk density and theoretical density, it is easy to find out the relative density. As mentioned in our recent work (Taha et al 2023), microhardness of the sintered samples was measured Vickers tester according to ASTM: B933-09 with applied load 1.9 N for 10 seconds

$$Hv = 1.854\frac{p}{d^2} \tag{3}$$

where Hv is microhardness, P is applied load (1.9 N) and d is the diagonal of indentation.

At room temperature, the nanocomposites that had been prepared were put through compression tests. The stress-strain curve was used to figure out the ultimate strength, compression strength, yield strength, and elongation. The ultimate strength and elongation are the highest numbers of stress and strain on the curve. The point at which a fracture forms was the compression strength. Lastly, the 0.2% offset concept was used to figure out the yield strength.

3. Results and discussion

3.1 Characterization of the sintered nanocomposite

3.1.1 Relative density and apparent porosity

The curves in Fig.1(a-c) show the bulk density, relative density, and apparent porosity of a Cu matrix and its hybrid nanocomposite at different temperatures for sintering. The theoretical densities of the CFS0, CFS1, CFS2, CFS4, and CSF8 samples are 8.960, 8.73, 8.62, 8.50 and 8.31 g/cm3, respectively. As the volume percentages of ceramics go upwards, the bulk and relative densities of these samples go downward, while their apparent porosity goes up, as shown in figure 1c. The decrement in density are due to the densities of SiC (3.21 g/cm3) and graphene (2.2 g/cm3) are much lower than those of the Cu matrix (8.96 g/cm3). Also, there is an enormous variation in the melting temperatures between the Cu matrix and hybrid ceramics, which means that particles don't move around as much during sintering. Also, the SiC particles that make the composite stronger act as a barrier during the diffusion step of the sintering process. This means that there is little diffusion at the interface between the matrix and the reinforcement. This makes the sintered nanocomposites less dense overall and more porous (Ağaoğulları 2019; Prosviryakov 2015). On the other hand, as the sintering temperature rose from 700°C to 850°C, the materials became denser while their outward permeability dropped. People know that the sintering temperature is a key part of the diffusion process and can help explain these things. The diffusion rate goes up as the sintering temperature goes up. This helps the particles contact, the grains grow, and the pore volume goes down (Moustafa and Taha 2021; Rahimian et al 2009; AbuShanab et al 2020).

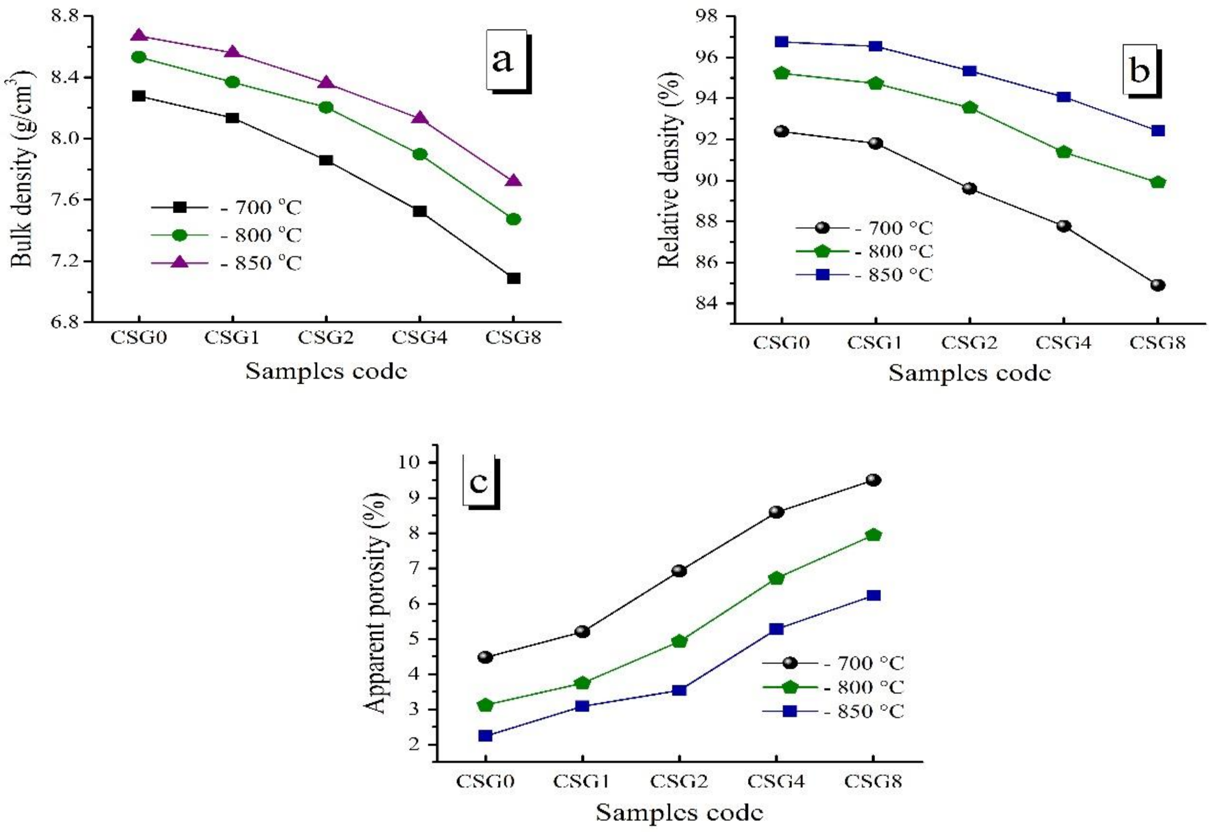

Figure 1: (a) bulk density, (b) relative density and (b) apparent porosity as a function of SiC and Gr for 1 h at different sintering temperatures.

3.1.2 Mechanical properties

3.1.2.1 microhardness

Mechanical characteristics are often influenced by several aspects such as the size, shape, and distribution of the ceramic's particles, as well as the density of the reinforcement and the technique of production (Li et al 2015; Youness and Taha 2022). The Vickers microhardness values of copper (Cu) and a Cu hybrid nanocomposite sintered at temperatures of 700, 800, and 850°C are shown in Figure 2. The figure illustrates a positive correlation between the microhardness values of the samples and both the hybrid ceramic contents and the sintering temperatures. As an example, when the sintering temperature is set at 700 ºC, the microhardness values for CSF0, CSF1, CSF2, CSF4, and CSF8 samples are 272, 300, 400, 490, and 600 MPa, respectively. In addition, raising the sintering temperature to 850 °C results in a subsequent rise in microhardness values for the same samples. Specifically, the microhardness values are 364, 450, 500, 680, and 800 MPa, respectively.

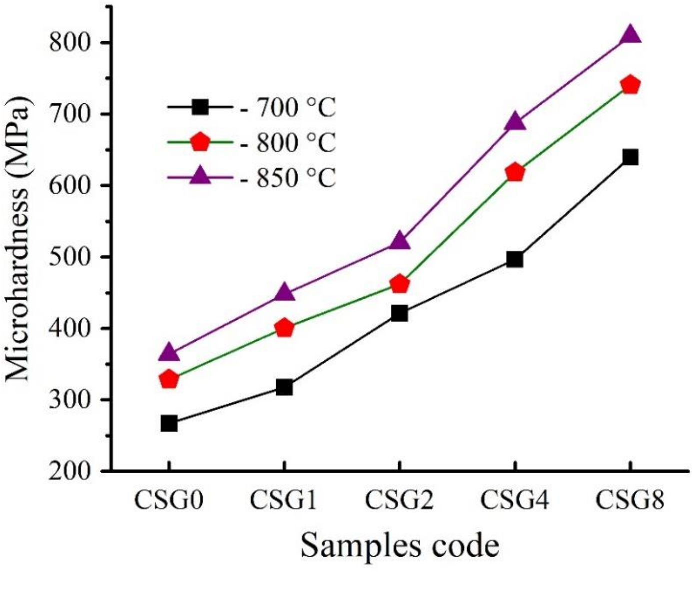

Figure 2. Microhardness of the Cu/SiC/Gr hybrid nanocomposite samples.

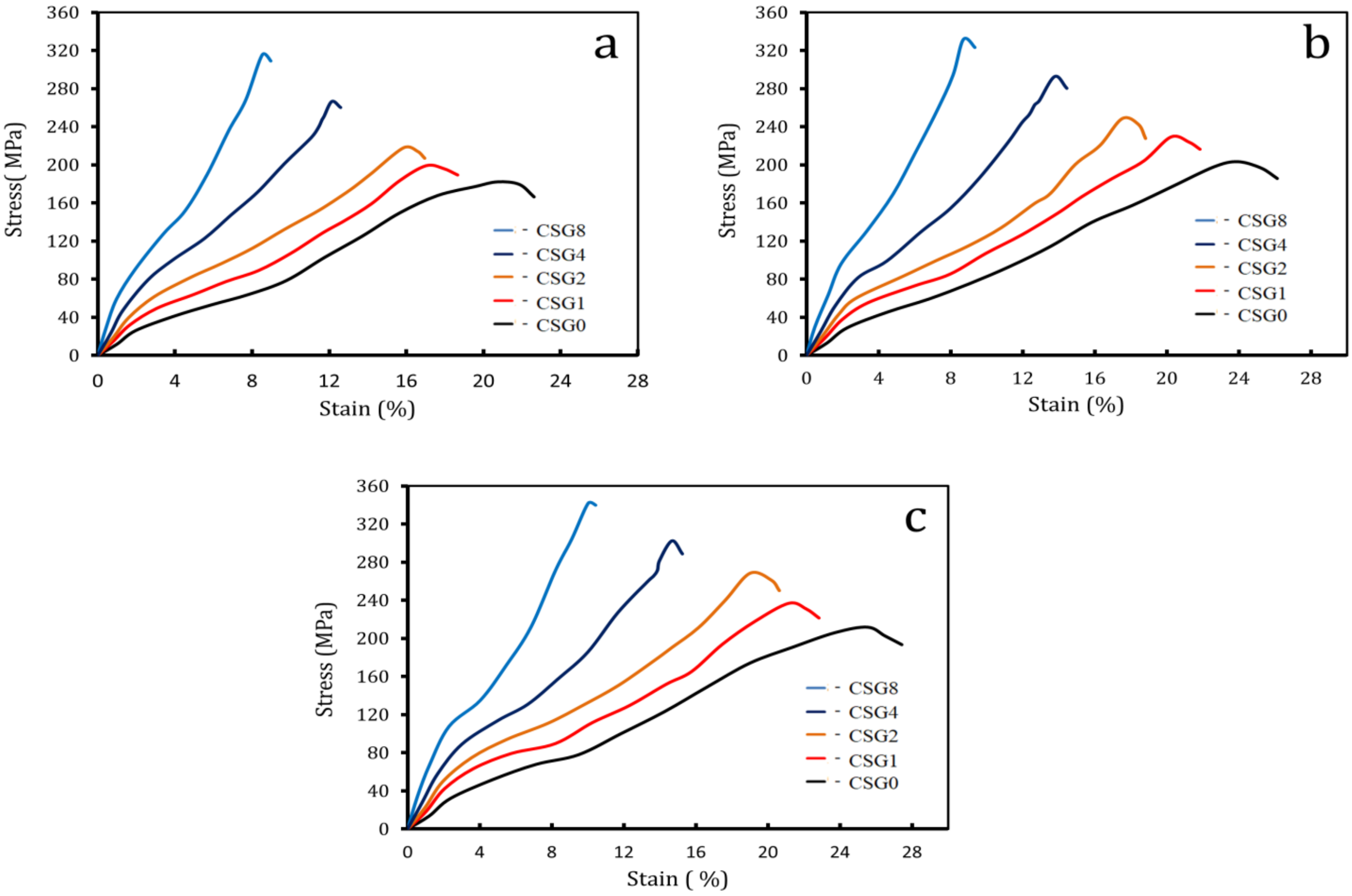

Figure 3. Compressive curves of the samples sintered at (a) 700 °C, (b) 800 °C and (c) 850 °C

Figures 3(a-c) illustrate the compressive stress-strain curves of sintered Cu matrix nanocomposites. The values of ultimate strength, yield strength, compressive strength, and elongation were estimated using the obtained curves; these values are illustrated in Figures 4 (a-d). It is evident that as microhardness decreases, ultimate strength, yield strength, and compressive strength exhibit the same pattern. According to the data presented in the figures, the compressive, ultimate, and yield strengths of samples sintered at 850 °C increase by 340, 342, and 60 MPa, respectively.

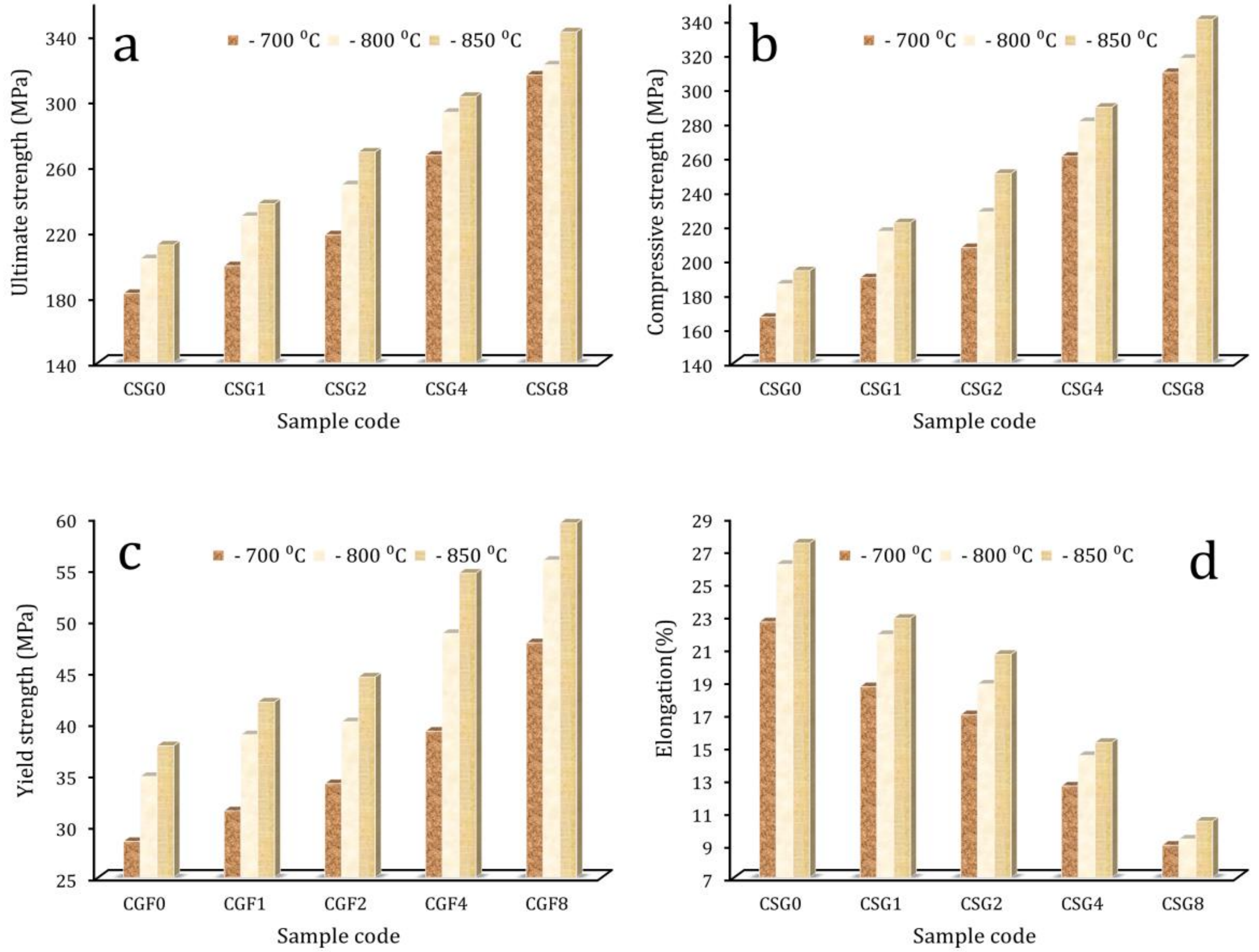

Figure 4. (a) Ultimate strengths, (b) compressive strengths, (c) yield strengths, and (d) elongations of Cu and Cu- hybrid nanocomposites.

The enhanced in mechanical properties observed may be attributed to the inclusion of SiC and Gr reinforced particles, which possess a greater hardness than the Cu matrix as a result of their effective dispersion. These particles impede dislocation movement within the Cu, leading to increased resistance to indentation and a reduction in the number of Cu matrix grains(Li et al 2015; Youness and Taha 2022; Akbarpoura 2019). Conversely, sintering temperature influences the microhardness and strength of the samples in a positive way. Elevated temperatures promote atomic diffusion, resulting in an expansion of the contact area between particles. This expansion subsequently enhances the density of composites while simultaneously diminishing their porosity.

4. Conclusion

- The powder metallurgy method was used to effectively manufacture a hybrid nanocomposite Cu matrix strengthened with SiC and Gr.
- The bulk and relative density went down as the amount of reinforcements went up, while the actual porosity went up. Increasing the sintering temperature made both of these properties better.
- The microhardness and ultimate strength of the sample with 16 vol.% additives were found to be 2 and 1.5 times higher than those of the Cu matrix sample, respectively.

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