Evaluation of microstructure, thermal and mechanical properties of Cu/SiC nanocomposites fabricated by mechanical alloying

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Abstract

In this work, nano-sized silicon carbide (SiC; 0, 1, 2, 4 and 8 wt.%) reinforced copper (Cu) matrix nanocomposites were manufactured, pressed and sintered at 775 and 875 °C in argon atmosphere. Both X-ray diffraction (XRD) and scanning electron microscope (SEM) were carried out to characterize microstructural evolution. The density, thermal expansion, mechanical and electrical properties were studied. XRD analyses showed that by increasing SiC contents, the microstrain and dislocation density increased, while crystal size decreased. It was found that the coefficient of thermal expansion (CTE) values of nanocomposites samples were lower than that of Cu matrix. The improvement of CTE with increasing sintering temperature may be due to the densification in their microstructure. Moreover, the mechanical properties of these nanocomposites showed noticeable enhancement by the addition of SiC and sintering temperatures where microhardness and apparent strengthening efficiency of nanocomposites contain 8 wt.% SiC and sintered at 875 °C were 958.7 MPa and 1.07 1/vol%, respectively. Electrical conductivity of these samples slightly decreased with the addition of SiC contents and increased with sintering temperature. Based upon the aforementioned results, we can conclude that the prepared Cu-
SiC nanocomposites possess good electrical conductivity, high thermal stability and excellent mechanical properties.

Keywords: Cu matrix nanocomposites; SiC; CTE; Elastic moduli; Electrical conductivity; Mechanical alloying.

1. Introduction

Owing to good chemical stability and excellent thermal and electrical conductivities, great efforts have been paid towards copper (Cu) and its alloys to be broadly used in different engineering applications. Unfortunately, their mechanical properties are low, particularly at high temperatures, and consequently, their applications are limited. Therefore, fabricating copper (Cu)-matrix composites by producing secondary phases in Cu and its alloys is considered as the optimum solution to face this problem [1,2]. In this regard, many researchers found that the enhancement in the mechanical properties of Cu such as hardness, compressive strength, Young's modulus, etc. is strongly correlated to the reinforcement type, its particles sizes and their distribution [3-5]. Sorkhe et al. [3] have fabricated Cu-TiO$_2$ composites with various percentages of TiO$_2$ (0, 1, 3, 5, 7 wt.%) through mechanical alloying method to investigate the density, mechanical and electrical properties of these composites. They found that the microhardness of nanocomposites was increased to about 100 Hv, while the electrical conductivity decreased about 110% by increasing the amount of TiO$_2$ up to 7 wt.%. Taha and Zawrah [4] have invested the effect of different ZrO$_2$ contents up to 12 wt.% on mechanical and electrical conductivity on Cu matrix. They found remarkable improvement in the strength of Cu matrix with noticeable effect on its electrical conductivity. Akbarpour et al. [5] investigated the influence effect of various sized silicon carbide particles on morphology, strength and wear behavior of the
Cu matrix. The result showed that the produced nanocomposite is characterized by higher wear resistance and improved strength compared to the microcomposite. Based on this effort, using of nano-SiC is considered as one of the best choices to be added to Cu because of its superior mechanical properties, perfect thermal conductivity, low density, low coefficient of thermal expansion (CTE) and good electrical conductivity [6,7]. It is worth to note that there is a handful of researchers worked on the improvement of mechanical properties of aluminum (Al) [6], magnesium (Mg) [8] and copper (Cu) [5] by SiC. However, this work is hindered by the lack of proper distribution of SiC into the matrix of composite systems [7-9]. Amazingly, most composites based on metal suffer from mismatch in CTE of two joining materials which consequently, contributes to producing stress as well as strain at the joining interface. It is substantial to stress that these consequences are considered as series ones due to that they negatively affect the properties of the composites [10]. Notably, several studies discussed the effect of different ceramic types, i.e. SiC [10], lead titanate (PbTiO₃) [11], tungsten carbide (WC) [12] on thermal properties of Cu matrix. Generally, there are two routes for synthesizing reinforced nanocomposites based on Cu. One synthesizing route deals with using chemical reactions/phase transformations with the aim of producing in-situ formation of reinforcement particles in Cu-based nanocomposites [13]. On the opposite side, the second one is based on using mechanical alloying/or selective fracturing of secondary particles through mechanical approach to disperse the reinforcement into the matrix [14,15]. Since mechanical alloying is a suitable and cost-effective process, it is broadly utilized to prepare many nanocomposites [16,17]. It is important to note that the latter route is basically relied upon several factors, included time, speed, ball-to-powder ratio (BPR), atmosphere, temperature and the reinforcement type [18,19]. Based on the
abovementioned considerations, the major objective of this article is to produce Cu matrix nanocomposites with different weight percentages of nano-sized SiC up to 8wt. % and sintered at 875 °C to obtain nanocomposites having better densification behavior. Moreover, mechanical properties including microhardness, and group of elastic moduli and apparent strengthening efficiency of these nanocomposites will be extensively studied. Furthermore, microstructure, thermal expansion, physical and electrical properties will be studied also in details.

2. Materials and experimental procedures

In order to produce copper (Cu) matrix nanocomposites powders with various silicon carbide (SiC) contents, i.e. 0, 1, 2, 4 and 8 wt.% using mechanical alloying method, pure Cu and SiC (99.9% purity; particle sizes 200 μm and 55 nm) were used as starting materials. It is worth to mention that planetary ball mill with Al₂O₃ containers and balls was employed using the following conditions, i.e. the milling time, speed and the BPR were 20 h, 550 rpm and 20:1, respectively. Transmission electron microscopy (TEM) were used to investigate the microstructure of as-received Cu and nano-SiC particles as shown in Fig.1. The figure appear that the mean particle sizes of Cu is about 203 nm and particles exhibit high agglomeration, while that of SiC particles is about 39 nm with low agglomeration.

The phase compositions of milled powders were investigated by X-ray diffraction analysis. The crystalline size (i.e. D), lattice strain (ε) and dislocation density (δ) were determined from the X-ray line broadening (B) for the principle (hkl) planes, i.e. (1 1 1), (2 0 0), (2 2 0) and (3 1 1) at 2θ = 43.317, 50.499, 74.126 and 89.938, respectively using the equations mentioned in Refs. [20,21]:
\[ D = \frac{0.9\lambda}{B\cos\theta} \] ........................ (1)

\[ \varepsilon = \frac{B}{4\tan\theta} \] ........................ (2)

\[ \delta = \frac{1}{D^2} \] ........................ (3)

Fig. 1. TEM micrographs of as-received Cu and SiC particles.

where \( \lambda = 1.54059 \) Å (Cu–Ni radiation) and \( \theta \) is the angle in radian.

Subsequently, the resultant powders have been cold pressed to pellets and sintered at 775 and 875 °C for 1 h in argon with heating rate= 5°C/min.

Using Archimedes method (ASTM: B962-13), physical properties of the
fired samples was measured. Moreover, theoretical density of the samples calculates employed to mixture rule and consequently we can calculate relative density. Microstructures of the powder and sintered samples were examined by scanning electron microscopy (SEM; Quanta FEG25). Thermal expansion measurements of the sintered nanocomposites samples were studied from 50 to 600 °C in air. The microhardness of the produced nanocomposites was evaluated by Vickers tester (Vickers hardness machine-model: Shimadzu corporation hardness tester) [22].

By using pulse-echo technique, longitudinal ($V_L$) and shear ultrasonic velocities ($V_S$) were measured.

On the opposite side, constants of Lame's (i.e. $\lambda$ and $\mu$) were calculated according to the formula present in Refs. [23,24]:

\[
\lambda = \rho (V_L^2 - 2V_S^2) \quad \text{.................. (4)}
\]

\[
\mu = \rho V_S^2 \quad \text{.................. (5)}
\]

The elastic modulus ($L$), Young's modulus ($E$), shear modulus ($G$), bulk modulus ($B$) and Poisson's ratio ($\nu$) of the nanocomposites were calculated by equations [24,25]:

\[
L = \lambda + 2\mu \quad \text{.................. (6)}
\]

\[
G = \mu \quad \text{.................. (7)}
\]

\[
E = \mu \frac{3\lambda + 2\mu}{\lambda + \mu} \quad \text{.................. (8)}
\]

\[
K = \lambda + \frac{2}{3}\mu \quad \text{.................. (9)}
\]

\[
\nu = \frac{\lambda}{2(\lambda + \mu)} \quad \text{.................. (10)}
\]

Based on ASTM standard E9, the compressive test of the specimens were studied. Furthermore, the yield strength, ultimate strength elongation and apparent strengthening efficiency were calculated from stress-strain curve. The electrical conductivity ($\sigma$) of the nanocomposites was measured using Keithley 6517B system according to the formula found in Ref. [2]:


All prepared and characterization steps are represented, in schematic form, in Fig.2.

![Schematic diagram of the production and characterization of nanocomposites.](image)

Fig. 2. Schematic diagram of the production and characterization of nanocomposites.

3. Results and discussion

3.1. Properties of nanocomposites powders

3.1.1. X-ray diffraction

Fig.3 displays the XRD of Cu/SiC nanocomposites powders having different SiC contents (i.e. 0, 1, 2, 4 and 8 wt.%) after 20 h of milling. By careful analyses of the obtained XRD patterns according to (JCPDS 85-1362 and 89-2225) standard cards, it is clearly seen that these patterns are mainly composed of Cu and SiC phases (primary phases of the starting
mixture) having in mind that Cu and SiC powders exhibit cubic and rhombohedral crystal structure, respectively. Importantly, absence of the characteristic SiC peaks in nanocomposites having 1 and 2 wt.% of SiC can be attributed to their low weight percentages of SiC and accordingly, they lie below the detection limit of XRD device. After milling process, a significant broadening with noticed decrease in peaks' intensities of Cu matrix takes place while the peaks' intensities of SiC increase with the increasing of weight percentages of nano-SiC particles [26].

![XRD of nanocomposite powders with different SiC contents](image)

**Fig. 3.** XRD of nanocomposite powders with different SiC contents; 0, 1, 2, 4 and 8 wt. % SiC.

In order to characterize microstructure of the prepared nanopowders, the Cu matrix crystallite size, dislocation density and microstrain of Cu-SiC nanocomposite powders, after 20 h of milling, are calculated using the broadening of their diffraction peaks. Therefore, the effect of SiC contents on crystallite size, dislocation density and microstrain of Cu-SiC nanocomposites powders are illustrated in Fig. 4. It is obviously noticed that with increased SiC weight percentages, the crystal size decreases while
the dislocation density and microstrain increase due to severe plastic deformation and grain size refinement occur, during mechanical alloying process, due to the added nano-SiC particles [6,27]. The crystal sizes of Cu- 0, 1, 2, 4 and 8 wt.% SiC milled powders are 21.03, 20.69, 19.95, 18.1 and 14.33 nm, respectively while the microstrain of the same samples are 0.3333, 0.3383, 0.3522, 0.3857 and 0.4915 %, respectively.

3.1.1. SEM analyses

Generally, the existence of metal (ductile) particles along with ceramics (brittle) ones forms a ductile-brittle system which consequently, leads to several changes during milling process. Firstly, the ductile particles suffer from deformation, while brittle ones suffer from fragmentation. Based on
Fig. 5. SEM images of the milled powders a) Cu, b) Cu-1 wt.% of SiC, c) Cu-2 wt.% of SiC, d) Cu-4 wt.% of SiC and e) Cu-8 wt.% of SiC specimens.

This behavior of particles, brittle particles tend to stay between ductile ones at the instant of the ball collision [5,19,28]. Accordingly, a real composite is formed. In this sense, the morphology of Cu matrix and Cu SiC nanocomposites powders was investigated using SEM as shown in Fig. 5. It can be seen that with increases in nano-SiC reinforced particles, a finer nanocomposite powder is obtained with homogenous distribution for SiC particles in Cu matrix which is substantial for improving mechanical,
electrical and thermal properties. Surprisingly, SEM images are insufficient to ensure uniform distribution of SiC particles into Cu ones due to the incorporation of SiC particles into grain boundaries of Cu. Therefore, chemical element distribution maps of samples-containing 4 wt.% and 8 wt.% SiC is presented in Fig.6 (a,b).

3.2. Properties of sintered nanocomposites samples

3.2.1. Physical properties
To obtain Cu-SiC nanocomposites with high densification behavior, their powders were compacted and sintered. During sintering process, the necks at the boundaries between the particles grow which consequently, gives the sintered nanocomposites the desired densification. Theoretical, bulk and relative densities and apparent porosity of nanocomposites samples sintered for 1h at 775 and 875 °C with various SiC wt.% and sintered for 1 h at 775 and 875 °C are tabulated in table 1. It is obvious from the table that the relative densities of the specimens remarkably reduced with the increase in weight percentages of SiC reinforced particles. On the contrary, apparent porosity increases by such factor. With increasing of sintering temperature from 775 to 875 °C, the relative densities of the specimens increase while apparent porosity decreases. The major reason behind this behavior is the presence of SiC which possesses lower compressibility compared to that of Cu matrix along with large difference in the melting temperature between them (Cu ≈1080 and SiC ≈ 2730 °C) which in turn, leads to weak bonding between them and subsequently, limits diffusion. Furthermore, the SiC reinforcement particles act as barrier during the diffusion step of sintering process [29,30]. Similarly, increased amounts of ceramic particles (i.e. ZrO₂, SiC and TiC particles … etc.) into the Cu matrix reduce the relative density of the sintered nanocomposites [4-6,31]. Generally, the added ceramics to metals matrix are responsible for low diffusion, at the interfaces between matrix and reinforcement; therefore, the densification of the sintered nanocomposites decreases [29,32]. This measurable improvement in the densities, i.e. reduced porosity with increasing of sintering temperature to 875 °C may be due to increasing of diffusion rate which contributes to
increasing the contacts between particles, grain growth and decreasing the pore volume [33,34]. Hence, the higher relative densities (lower porosity) are achieved at higher sintering temperature. This can be more clarified by noticing eqn. (11) which shows that the sintering temperature plays an essential role in the diffusion process [35]:

\[ D = D_0 e^{-\frac{Q}{RT}} \] ...................................... (11)

where \( D, D_0, Q, R \) and \( T \) are the diffusion coefficient, constant, activation energy, Boltzmann's constant and temperature, respectively.

### 3.2.2. Microstructure

<table>
<thead>
<tr>
<th>SiC content (wt. %)</th>
<th>Sintering temperature (°C)</th>
<th>Theoretical density (g/cm³)</th>
<th>Bulk density (g/cm³)</th>
<th>Relative density (%)</th>
<th>Apparent porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.96</td>
<td>8.49</td>
<td>94.7</td>
<td>3.78</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8.80</td>
<td>8.28</td>
<td>94.1</td>
<td>4.52</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>775</td>
<td>8.65</td>
<td>8.06</td>
<td>93.2</td>
<td>5.11</td>
</tr>
<tr>
<td>4</td>
<td>8.36</td>
<td>7.65</td>
<td>91.5</td>
<td>7.66</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>7.84</td>
<td>7.01</td>
<td>89.4</td>
<td>9.11</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>8.96</td>
<td>8.73</td>
<td>97.4</td>
<td>2.11</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8.80</td>
<td>8.55</td>
<td>97.1</td>
<td>2.51</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>875</td>
<td>8.65</td>
<td>8.32</td>
<td>96.2</td>
<td>3.37</td>
</tr>
<tr>
<td>4</td>
<td>8.36</td>
<td>7.95</td>
<td>95.1</td>
<td>4.99</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>7.84</td>
<td>7.34</td>
<td>93.61</td>
<td>6.94</td>
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</tr>
</tbody>
</table>
SEM micrographs of nanocomposites specimens having 2 and 8 wt.% of SiC sintered at 775 and 875 °C are shown in Figs. (7 and 8). It is clearly observed that increase in nano-SiC particles is attributed to the observable change in microstructure of the nanocomposites which leads to an increase in porosity and considerable weakness in the contact between Cu particles. It is interesting to see from Fig. 7 that bonding between SiC and Cu is weak due to insufficient sintering temperature. However, by increasing sintering temperature to 875 °C, suitable bonding strength is reached between SiC and Cu as seen from Fig. 8.

![SEM micrographs of the sintered a) Cu-2 wt.% and b) Cu-8 wt.% of SiC specimens at 775 °C.](image-url)
It is important to stress that this sintering temperature is responsible for better densification behavior as shown by noticed grain growth along with decrease the pores [36].

![SEM micrographs of the sintered specimens](image)

**Fig. 8.** SEM micrographs of the sintered a) Cu-2 wt.% and b) Cu-8 wt.% of SiC specimens at 875 °C

### 3.2.3. Thermal expansion

Fig. 9 illustrates the value of thermal expansion versus temperature of Cu-SiC nanocomposites with various weight percentages of nano-SiC particles. Generally, the value of relative expansion ($\Delta L/L$) of nanocomposites with various SiC contents increases as the temperature increases significantly. Furthermore, it reduces with increasing SiC weight percentages. The results of CTE of samples for different sintering
temperatures are shown in Fig.10. It is noticeable from figure that CTE values reduce with increased SiC contents while they increase with increasing of sintering temperature. The theoretical value of CTE for Cu-0, 1, 2, 4 and 8 wt.% SiC nanocomposites samples calculated using the simple rule of mixtures are 17, 16.64, 16.28, 15.61 and 14.40 10^{-6}/°C, respectively. The CTE of un-reinforced Cu sintered at 875 °C was measured to be 15.67×10^{-6}/°C and with addition of 1, 2, 4 and 8 wt.% SiC to Cu matrix reduce CTE values to 14.81×10^{-6}, 14.07×10^{-6}, 12.9×10^{-6} and 11.1×10^{-6}/°C, respectively. Interestingly, the theoretical values of CTE of the sintered samples are larger than experimental ones due to the existence of high bonding between Cu matrix and SiC particles which means the excellent interfacial bonding also imposes effective constraint on the expansion of the Cu matrix [10,37]. Generally, the lowered CTEs of the Cu matrix by adding SiC particles should be attributed to the lower CTE of SiC (3.7×10^{-6} °C) than that of Cu (17×10^{-6} °C) matrix which comes from the interfacial bonding between SiC nanoparticles and Cu matrix. Furthermore, for nanocomposite samples, residual stresses (compression and tensile stresses) resulted from thermal mismatch between the Cu matrix and SiC particles have a strong role to play in determining the behavior of thermal expansion [36]. On the contrary, increasing of thermal expansion of nanocomposites behavior with increased sintering temperature from 775 to 875 °C is compatible with the results of relative density and apparent porosity, those discussed former, due to the development of microstructure and densification [38].

Furthermore, this thermal mismatch generates residual stress field in the Cu matrix and SiC reinforcement where the pores undergo a compression stress which causes the shrinkage of the pore volume. Subsequently, the thermal expansion and CTE value of the composite decreases with the increases of porosity and vice versa [10].
Fig. 9. Variations of the thermal expansion of nanocomposites sintered for 1h at (a) 775 °C and (a) 875 °C.
An efficiency factor (i.e. R) is supposed to assess the influence of SiC contents and sintering temperatures on CTE of Cu matrix nanocomposites according to eqn. (12) [39]:

\[
R = \frac{\alpha_c - \alpha_m}{V} \quad \text{…………….. (12)}
\]

where \(\alpha_c\) and \(\alpha_m\) are CTE values of the nanocomposite and Cu, respectively, and \(V\) is the SiC volume percentage. The relationship between \(R\) and SiC contents are represented in Fig. 11. As obviously noticed from the figure, \(R\) value changes with increasing of SiC contents, while increases with temperatures.
3.2.4. Mechanical properties

Fig. 12 shows microhardness values of Cu-SiC nanocomposites samples. The microhardness of samples is higher than that of the unreinforced Cu sample processed in the same sintering temperature. Furthermore, microhardness increases with increase in SiC weight percentages and sintering temperature. The standard hardness value of both Cu and SiC ranges from 343 to 369 Mpa and 23.5 to 25.5 GPa, respectively. The microhardness value of Cu matrix increases and reaching 808.9 MPa for the composite sample containing 8 wt. % SiC sintered at 770 °C. With increasing sintering temperature up to 870 °C, the microhardness further increases to 958.7 MPa for the composite sample. The longitudinal and shear ultrasonic velocities of (i.e. $V_L$ and $V_S$) and the group of elastic moduli of sintered samples are listed in table 2, while $V_L$ and $V_S$ are represented in Fig.13. It is interesting to see that $V_L$ and $V_S$ increase by weight percentages of SiC and sintering temperature. The results in Table 1 indicate that with increase in SiC contents from 0 to 8 wt. %, the $V_L$
Fig. 12. Microhardness of Cu-SiC nanocomposites specimens
Table 2 Young's modulus (E), elastic modulus (L), bulk modulus (K), shear modulus (G) and Poisson's ratio (ν) of nanocomposites samples sintered for 1h at 775 and 875 °C in argon.

<table>
<thead>
<tr>
<th>SiC content (wt.)</th>
<th>Sintering temp. (°C)</th>
<th>E (GPa)</th>
<th>L (GPa)</th>
<th>K (GPa)</th>
<th>G (GPa)</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>104.3</td>
<td>154.5</td>
<td>39.2</td>
<td>39.2</td>
<td>0.3299</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>109.8</td>
<td>162.7</td>
<td>41.3</td>
<td>41.3</td>
<td>0.3301</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>113.1</td>
<td>167.8</td>
<td>42.5</td>
<td>42.5</td>
<td>0.3304</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>137.5</td>
<td>204.9</td>
<td>51.6</td>
<td>51.6</td>
<td>0.3316</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>172.9</td>
<td>261.9</td>
<td>64.7</td>
<td>64.7</td>
<td>0.3360</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>114.1</td>
<td>171.2</td>
<td>128.3</td>
<td>42.8</td>
<td>0.3332</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>121.4</td>
<td>182.4</td>
<td>136.9</td>
<td>45.5</td>
<td>0.3337</td>
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</tr>
<tr>
<td>2</td>
<td>128.5</td>
<td>193.2</td>
<td>145.3</td>
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<tr>
<td>4</td>
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<td>179.0</td>
<td>58.9</td>
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</tr>
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<td>8</td>
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<td>309.9</td>
<td>234.5</td>
<td>75.5</td>
<td>0.3391</td>
<td></td>
</tr>
</tbody>
</table>

The value of the samples sintered at 750 and 850 °C ranges from 7502 to 11,035 ms⁻¹ and 8247 to 10,369 ms⁻¹, respectively and the $V_s$ value for the same
samples ranges from 4751 to 6776 ms\(^{-1}\) and 5138 to 6384 ms\(^{-1}\), respectively. As indicated by this table, the elastic moduli exhibit the same trend for ultrasonic velocities.

![Graphs showing longitudinal and shear ultrasonic velocities of Cu-SiC nanocomposite at different sintering temperatures.](image)

**Fig. 13.** Longitudinal and shear ultrasonic velocities of Cu-SiC nanocomposite at different sintering temperature.

The present results of elastic modulus of nanocomposites sample contains 8 wt.% SiC sintered at 775 and 875 °C (261.9-309.9 Gpa, respectively) is
higher than that of un-reinforced Cu matrix (154.5-171.1 GPa, respectively) sintered at the same temperature.

Fig. 14 displays compressive stress-strain curves at room temperature (i.e. 30 °C) relevant for Cu-SiC nanocomposites with different SiC contents and sintered at 775 and 875 °C. The results represented by ultimate strength, yield strength and elongation are listed in Fig. 15. As can be inferred from the figure, strengths of Cu matrix reveals significant improvement with the addition of different content of nano-SiC particles and with increased sintering temperature. On the other hand, the addition of SiC particles is responsible for considerable decreasing in ductility of Cu matrix while it increases with increased sintering temperature. The elongation is reduced from ≈ 29.7 for Cu matrix to ≈ 19.2% for Cu sample-contains 8 wt.% of SiC nanocomposite sample sintered at 775 °C while at sintered temperature 875 °C, the elongation is reduced from 33.7 to 21% for the same sample. Apparent strengthening efficiency (i.e. \( R_a \)) of nanocomposites samples as function of SiC contents is presented in Fig. 16. It is noted, the improvement of \( R_a \) as a result of increasing both SiC contents and sintering temperature. The \( R_a \) value can be calculated as [40]:

\[
R_a = \frac{\sigma_c - \sigma_m}{V_{\sigma_m}} 
\]

............... (13)

where \( \sigma_c \) and \( \sigma_m \) are the yield strength of nanocomposite and Cu matrix \( V \) is the volume fraction of reinforcement particle. Based upon the above results, one can conclude that adding various weight percentages of nano-SiC to Cu matrix remarkably improves the mechanical properties involving Vickers microhardness, the group of elastic moduli, ultimate strength, yield strength and strengthening efficiency. This improvement

![Graph showing stress-strain curves for Cu-SiC composites](image)
Fig. 14. Compressive curve of nanocomposites sintered at a) 775 °C and b) 875 °C.

may be a result of the addition of very hard SiC particles to the ductile Cu matrix, uniform distribution of nano-SiC particles and refinement of grains [41].

Additionally, the addition of SiC particles to Cu matrix contributes to transferring the applied load from Cu matrix to SiC which consequently, increases the resistance to plastic deformation of the sintered nanocomposite samples due to the variation in CTE values of Cu.
Fig. 15. a) Ultimate strength, b) yield strength and c) elongation of Cu-SiC nanocomposites samples.
matrix and SiC reinforcement particles. Accordingly, the generated thermal mismatch increases dislocation density in the vicinity of SiC thereby increasing the strength of nanocomposite samples (Section 3.2.1). The thermal stresses work to enhance microhardness of the nanocomposites and flow stresses in the sample, making the plastic deformation more difficult [59]. Furthermore, the grain boundaries increase due to grain refinement that takes place after milling process [60]. The interaction between reinforcement and dislocations is a major reason for the strength of composite materials. This mechanism is so-called "Orowan mechanism" which described that the passage of dislocations via particles causes placing of residual dislocation loops around each particle. Indeed, these particles act to enhance the strength of material through prohibiting the migration of dislocations [44].

On the other hand, the decrease in ductility of nanocomposite samples exhibits considerable increases due to the successive addition of SiC particles. The main reason behind this reduction in ductility due to the presence of SiC is the weak bonds between SiC and Cu matrix which act
as stress concentrators and forming micro cracks, propagation and fracture of nanocomposite samples during the compression tests [45]. In general, the enhancement in mechanical properties with increasing of sintering temperature from 775 to 875 °C is closely correlated to the densification of the studied sample. The increasing of sintering temperature causes decrease in the inter-atomic spacing which consequently, increases the propagation of ultrasonic waves in nanocomposites samples and therefore, increases elastic moduli and acceleration of diffusion process [46].

3.3. Electrical properties

The dependence of conductivity of the sintered nanocomposites on SiC contents, at two different sintering temperatures, is illustrated in Fig. 17. It is noted that, the electrical conductivity reduced with the increase in SiC particles contents, while it increased with increased sintering temperatures. It is known that the conductivity of metals is highly dependent upon the movement of electrons into the structure. However, the addition of SiC particles contributes to distorting this structure and hindering the movement of Cu electrons and accordingly, the conductivity reduces [47]. After milling process, the grain boundaries increased, as a result of grain refinement, which act to prohibit the electron path. In addition, the dislocations as well as the porosity increased, as a result of adding ceramic particles, leading to electrons scattering phenomenon [3,48]. When increasing sintering temperature increases, the conductivity of nanocomposite samples is increased as a result of reduced the porosity. Similar results were reported by Islak [49], Ayyappadas et al. [50] and Taha et al. [4]. Moreover, Moustafa and Taha [2] have reported that electrical conductivity directly proportional to the sintering temperature for Cu matrix composites.
4. Conclusions

Cu-matrix nanocomposites containing various nano-SiC percentages, i.e. 0, 1, 2, 4 and 8 wt% have been prepared successfully by mechanical alloying cold-pressed and sintered for 1 h at 775 and 875 °C, in argon atmosphere. The following remarks were concluded:

- CTE, R and electrical conductivity values reduced with increased weight percentages of SiC particles indicating high dimensional stability. On the other hand, they considerably increased with increased sintering temperatures.

- The values of microhardness and Young's modulus for Cu-8 wt% SiC sample sintered at 775 °C in argon atmosphere for 1 h were 812 MPa and 1028 GPa, respectively. With increasing of sintering temperature up to 875°C, for the same samples, the measured values of microhardness and Young's modulus were 812 MPa and 1028 GPa, respectively.
Under compression testing, the ultimate and yield strength values of nanocomposites sintered at 875 °C increased from 66 and 313 MPa for pure Cu to about 119 and 392 MPa with the addition of 8 wt.% SiC, respectively, which are ~ 80% and ~ 25% greater than those of pure Cu.

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