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Enhancement of Mechanical Properties of Al-Cu-Mg Alloy Adding Nano-Sno2 by Using Powder Metallurgy Method

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Abstract

In the present research work, SnO_2 nanoparticle reinforced nanocomposites made from Al–Cu–Mg alloys were prepared by using powder metallurgy. It was observed from the results that the introduction of SnO_2 had significant impacts on the micro structure and possession of the composites. For low amounts of nanoparticle additions, a fairly uniform distribution of nanoparticles within the composite was noticed, whereas for high amounts of nanoparticle additions, there was agglomeration of particles and porosity formation. In addition, the average grain size was decreased as the amount of SnO_2 was increased in the composites. However, although the relative density was decreased, the apparent porosity was increased with increase in the content of SnO_2 in the nanocomposites. On the other hand, the mechanical properties showed marked improvement with an increase in the amount of nanoparticle addition, as a result of which the micro-hardness, compressive strength, and elastic modulus showed progressive increase with increase in the number of nanoparticles to reach a maximum at 8 wt%. Furthermore, the wear resistance was found to be enhanced with the addition of SnO_2 nanoparticles even at higher loads because of increase in hardness and load-bearing capacity.

Keywords: Al-Cu-Mg alloy system, metal oxide composites, tin oxide, sintering, metallurgy technique.

Introduction

The recent past has seen a lot of development and advancement in technology; this, in turn, has resulted in the increased need for engineering materials with better mechanical characteristics, wear resistance, and stability against corrosion, properties that are not adequately offered by conventional metallic materials [1–3]. As such, metal matrix composites (MMCs) mostly Aluminum matrix composites (AMCs) have gained a lot of popularity because they can effectively merge the weight reduction qualities of aluminum with the superior mechanical and tribological properties provided by ceramics [4, 5]. Alloys of Aluminum are extensively used in many significant industries including automotive, aerospace, and military due to their low density, high formability, and exceptional corrosion resistance properties [6, 7]. These corrosion resistant qualities of aluminum alloys are mainly due to the oxide layer formed at their surfaces [9–12]. However, the disadvantages associated with conventional aluminum alloys such as poor strength and structural integrity limits their application in many applications [8, 13–15]. To overcome the drawbacks mentioned above, different types of ceramic reinforcements like SiC, Al_2O_3, and ZrO_2 have been added in an aluminum alloy matrix resulting in substantial improvement in mechanical properties [16]. Different manufacturing methods have been employed to develop composites of ceramics reinforced metals that include powder metallurgy (PM) [17–19], stir casting [22], micro-agitation [20], and compression casting [21]. Of all these methods, powder metallurgy provides some special features, for instance, control over the microstructure of the composite, particle homogeneity, and ability to manufacture nanostructured composites [23–25]. Very recently, tin dioxide nanoparticles have received considerable attention due to their superior hardness, thermal stability, and capacity to effectively arrest the movement of dislocations within the metallic matrix [26, 27]. These unique properties could help in strengthening the aluminum metal matrix composites. However, despite considerable efforts in exploring ceramic metal matrix composites in recent times, very few research works are available that have studied the effect of tin dioxide nanoparticles on aluminum alloys having aluminum copper-magnesium composition prepared by powder metallurgy technique with regard to mechanical, elastic, and wear resistance properties Therefore, it is important that the present research fills this existing gap by synthesizing Al–4.2Cu–1.6Mg nanocomposites containing different wt% of SnO_2 nanoparticles by the use of powder metallurgy method. The current research aims at analyzing the impact of adding SnO_2 nanoparticles to Al–4.2Cu–1.6Mg nanocomposites through characterization of the microstructural properties of the specimen using X-ray diffraction test (XRD) and scanning electron microscopy (SEM), and studying their mechanical, elastic is used to improve the performance of the material.

Experimental details

Material matrix that was used in this research is an alloy of aluminum, copper, and magnesium which is reinforced with nanoparticles of tin dioxide with an average size of less than 80 nm. The reinforcement was done at 0, 2, 4, 6, and 8 wt%, as shown in Table 1 below. The Al–Cu–

Mg alloy was prepared using mechanical alloying through the use of highly pure elemental metal powders of aluminum (99.99%), copper (99.99%), and magnesium (99.98%). The alloying was done by planetary ball mill operating with 130 rpm for 24 hours. Later on, the powder mixture was milled again for another 24 hours at 500 rpm. During milling, two hour milling process and two hours resting process were applied alternately in order to avoid overheating due to milling operation. The microstructural characteristics of the mechanical alloyed powder including morphological structures and phase compositions were analyzed using SEM and XRD analyses. The average size of the powder crystallites was determined based on the broadened peak using Scherrer formula, and the particle size distribution was also determined using diffractometer [6]. Finally, after milling operation, the powder mixture was compressed and sintered at 550°C for one hour in argon atmosphere. Densities of the manufactured samples were determined through the ruling of mixtures, founded on the densities of SnO_2 and Al-Cu-Mg alloy which are 5.68 g/cm³ and 2.7 g/cm³, respectively. However, bulk densities and porosities of the sintered specimen were specific by means of Archimedes technique. Microstructural features of the sintered specimen were further scanned through scanning electron microscope (SEM, Philips XL30). Micro-Vickers hardness test was performed on the specimens utilizing Shimadzu-HMV hardness tester (Japan), as per ASTM B933-09 standards cited in Ref. [26]. Compression tests were further conducted on the sintered nanocomposites following appropriate ASTM standards. Compressive properties such as compressive strengths, output strength, and strains were estimated of the stress-strain graphs. Maximum stress point in the graph was taken into consideration as ultimate compressive strength, whereas the corresponding strain indicated fracture strain. The wear exam was performed on a pin-on-disc tribometer. Before the tests, all specimens were ground into equal sizes and polished using abrasive silicon carbide papers in the range of 600 to 4000. The mass of the specimen was measured by a digital scale with an accuracy of 0.0001 g. The wear performance was studied at four various tonnages. The wear rate can be traced back to mass loss is determined according to the following formulas [28]:

$$Net\ weight = weight\ befor\ wear - weight\ after\ wear \quad (1)$$

$$Wear\ rate = net\ weight/time \quad (2)$$

Table 1. The composition of the prepared Ai-Cu-Mg alloy.

Sample	The dping mixture	
	Al-Cu-Mg alloy	SnO_2 (wt%)
AS0	100	0
AS2	98	2
AS4	96	4
AS6	94	6

AS8	92	8

Results and Analysis

The XRD patterns of the nanocomposite powders AS0, AS2, AS4, AS6, and AS8 after 20 hours of ball milling are shown in Fig. 1. According to the standard cards, the main phases present in the matrix alloy can be determined as Al, Al_2Cu, and $MgCuAl_2$ phases. The XRD spectrum of the sample AS0 proves that the desired Al–Cu–Mg alloy has been successfully produced as a result of the dissolution of Cu in the aluminum matrix and intermetallic phase precipitation. Besides, SnO_2 nanoparticles exhibited unique diffraction peaks in the reinforced alloys depending on the amount of SnO_2. As shown in Figure 2, increase in the amount of SnO_2 content led to broadening of the diffraction peak width along with decrease in the peak intensity due to decrease in crystallite size. This could be explained by the formation of refined grains due to the introduction of SnO_2 nanoparticles in the milling step. The calculated average crystallite sizes of the AS0, AS2, AS4, AS6, and AS8 samples were 32.25, 31.35, 29.43, 24.99, and 19.53 nm, respectively. The obtained results a good agreement with the observations made by Özay et al. (2018) [29].

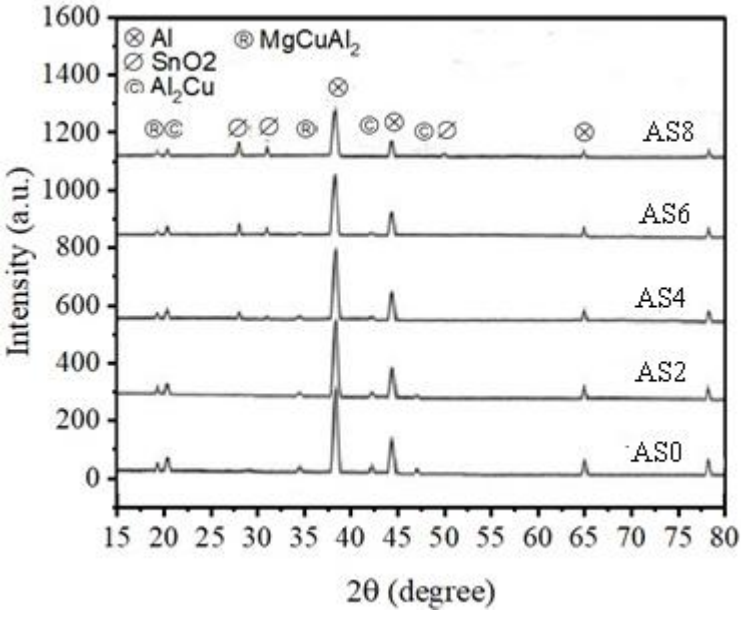


Figure1 XRD diagrams of Al-Cu-Mg: SnO_2 alloy

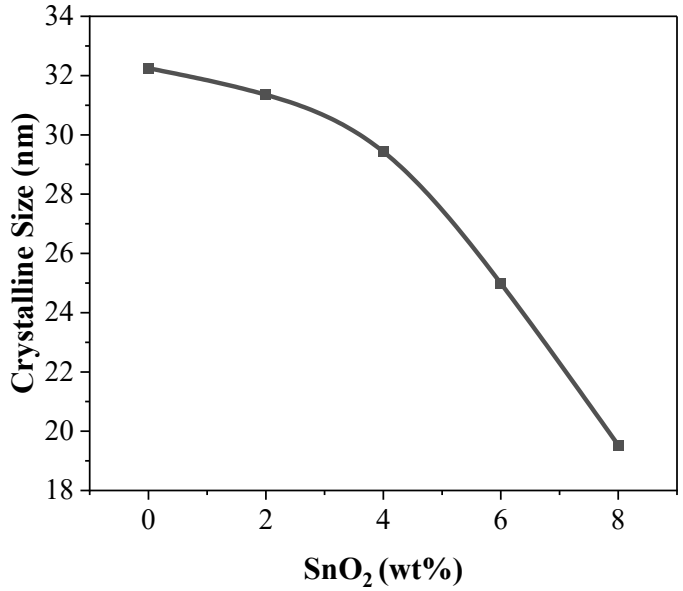


Figure 2. The crystalline size of SnO_2 particle doping Al-Cu-Mg powders.

Compacting the composite nanopowder mixture is a key process step in the production of bulk material after powder synthesis since it greatly affects the porosity and the microstructure of the sintered composites [30]. Figure 3 showed the relative intensity and apparent porosity of the sintered samples treated at 550 °C for 1 hour, whereas Table 2 shows the values of their respective standard deviations. Based on theoretical calculations, the densities of AS0, AS2, AS4, AS6, and AS8 samples were expected to be 2.66, 2.69, 2.72, 2.78, and 2.91 g/cm^3, respectively. Following sintering at 550 °C, the relative densities of the AS0 and AS8 samples turned out to be 97.57% and 92.12%, respectively. Thus, there was an evident decrease in the amount of densification with the increase of the SnO_2 content. This can be explained by the high hardness and the elevated melting temperature of SnO_2 (~1630 °C) making the atomic diffusion and thus the process of bonding of particles more difficult [31]. At the same time, the increased sintering temperature of 550 °C resulted in improvement of particle bonding and better contact between adjacent powder particles [32]. Besides, the increase in apparent porosity was caused by the lower diffusion rates of SnO_2 particles and their propensity for agglomeration at higher reinforcement content.

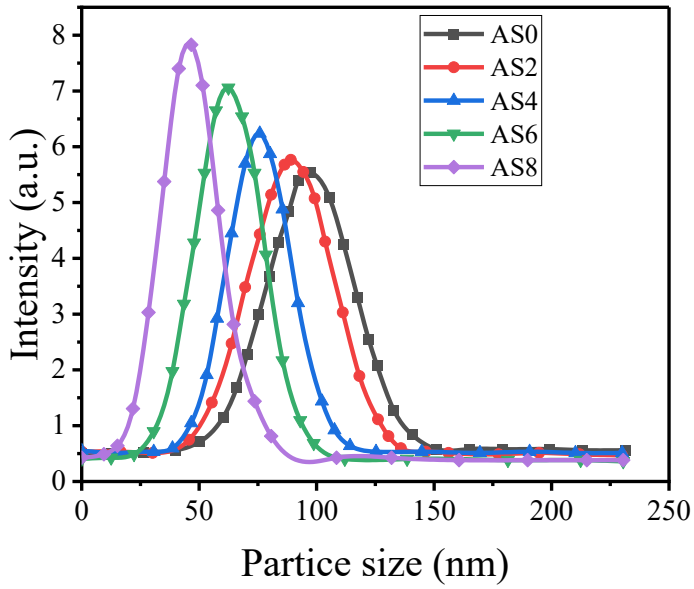


Figure 3. The distribution of particle size obtained vs intensity

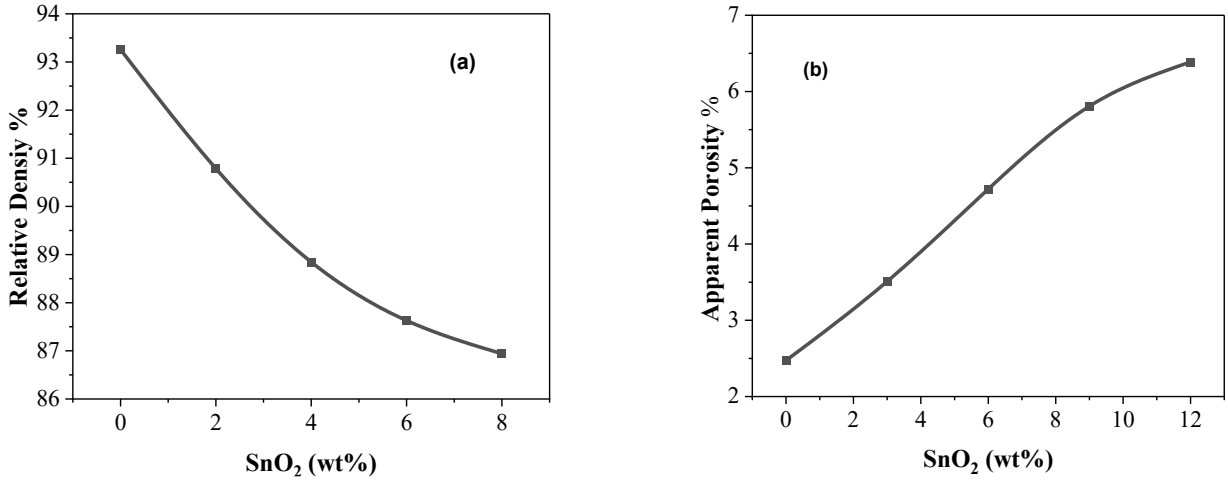


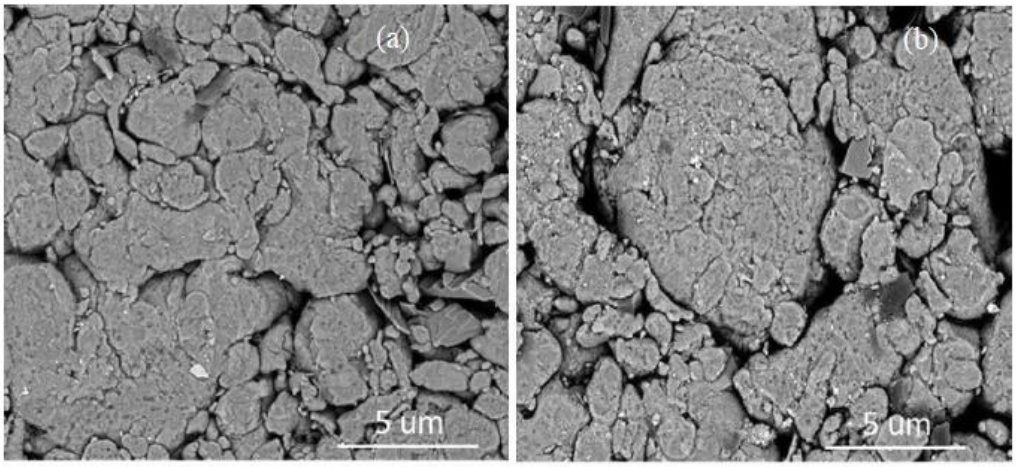
Figure 4. (**a**) Relative density vs weight f percentage of SnO_2 and (**b**) apparent porosity of the sintered samples.

Table 2. The standard deviation of relative density and apparent porosity for all samples tested.

Samples	Stander deviation	
	Relative density (%)	Apparent porosity (%)
AS0	0.244	0.61
AS2	0.222	0.70
AS4	0.218	0.88

AS6	0.182	1.03
AS8	0.145	1.05

The scanning electron microscope micrographs for the compacted nanocomposite powders AS0, AS4, and AS8 after 20 h of milling followed by compaction under 50 MPa pressure are shown in Figures 5(a) to (c). From the detailed observation of the micrographs, it can be concluded that the dispersion of SnO2 nanoparticles in the Al-Cu-Mg matrix is one of the opener factors that impact the microstructure and mechanical behavior of the synthesized nanocomposites. From the microstructure point of view, SnO_2 nanoparticles have mainly been concentrated around grain boundaries of the aluminum metal. As the amount of reinforcement decreases to a level below 4 wt% (AS4), the nanoparticles are evenly dispersed in the aluminum matrix. But at an increase in the SnO_2 concentration to a level of 8 wt%, the degree of agglomeration of particles has become significant, leading to uneven dispersion of nanoparticles. Moreover, the increase in the porosity of the specimens was seen to be gradual as the SnO_2 percentage increased. This is also supported by the decrease in relative density that was discussed earlier. The effect of porosity on the specimens with high amounts of reinforcements did not hinder effective inter-particle bonding. Sintering had played a major role in promoting inter-particle bonding, as well as matrix-reinforcement interaction. Moreover, the increase in necks formation between neighboring particles shows the improvement in diffusion bonding between the Al-Cu-Mg matrix and SnO_2 nanoparticles, where there is no visible interfacial crack in the specimens. The results obtained are consistent with the previous study done by Lai et al., (2021).



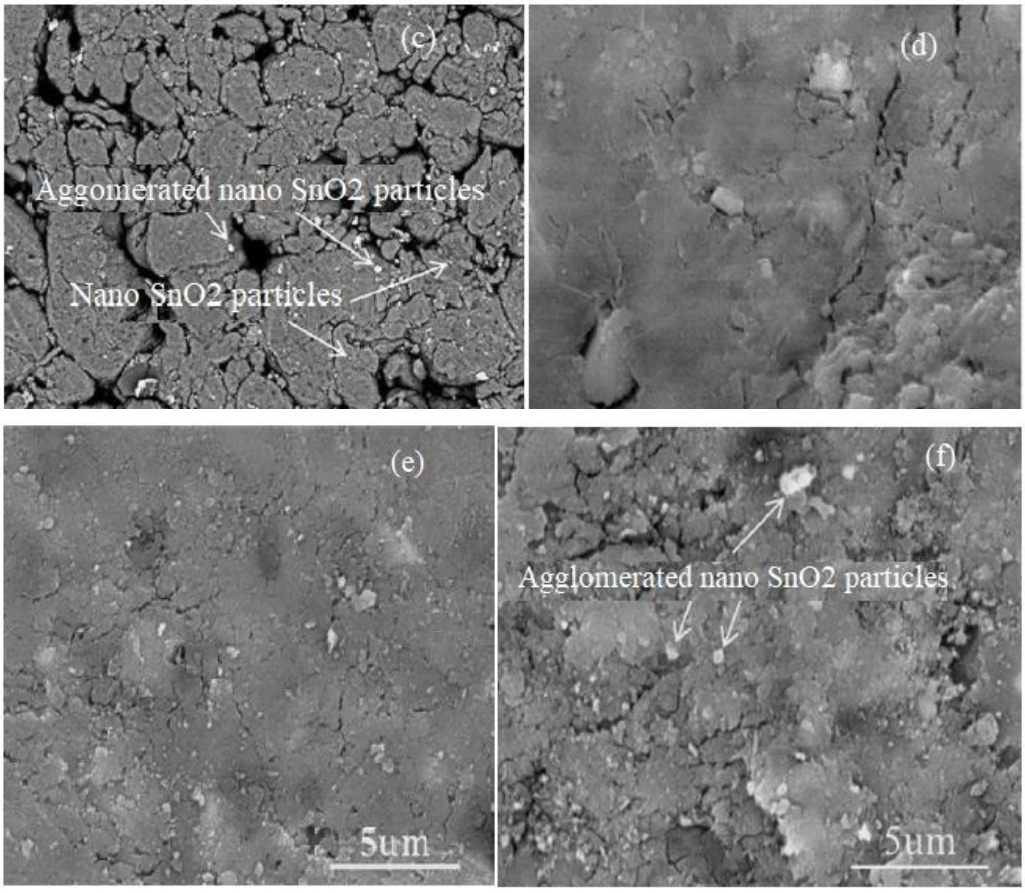


Figure 5 The SEM images of (a) AS0, (b) AS4 and (c) AS8 compacted specimen, (**d**) AS0, (**e**) AS4 and (**f**) AS8 specimen sintered at 550 °C

In the present study, non-destructive ultrasonic testing (NDT) technique was applied for measuring the longitudinal (VL) and shear (VS) ultrasonic velocities of the sintered nanocomposites at different SnO_2 concentrations processed at 550 °C, as shown in Figure 6. As can be observed, there is an appreciable enhancement in ultrasonic velocities with the increment in the SnO_2 reinforcement from 0 to 8 wt% in the sintered nanocomposites. In particular, longitudinal ultrasonic velocity (VL) increased from 5886.5 to 7510.3 m s^{-1}, whereas shear ultrasonic velocity (VS) increased from 3205.7 to 4027.3 m s^{-1} The elasticity features of the developed nanocomposites are shown in Figure 7. The elastic modulus showed the same pattern as was found for the velocity of ultrasound waves, thereby indicating a significant relationship between the propagation process and the stiffness of the materials being used [35]. In the case of the AS0 composite, the elastic modulus and the value of Poisson's ratio were equal to 89.7 GPa and 0.2896, respectively; however, upon adding 8 wt% SnO_2, these values were raised to 150.6 GPa and 0.2983, respectively. The positive changes in both the velocities of ultrasound waves and elastic modulus can be explained by the hardness of SnO_2 nanoparticles added into the aluminum-copper-magnesium composite, resulting in the increase of the resistance of the composite to elastic deformation. These results are consistent with the increases of microhardness and compressive strength; thus, they indicate the reinforcing action

of SnO_2 particles on the composite matrix. Similar findings have been obtained by Khan et al. (2024) [36].

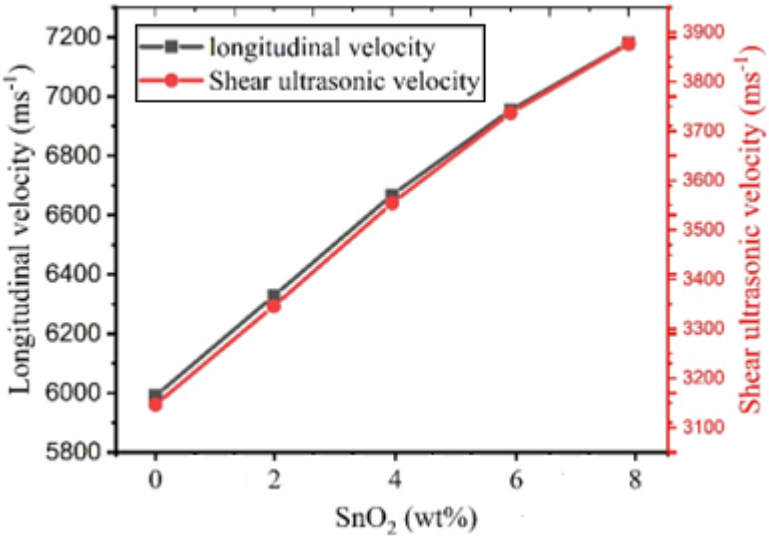


Figure 6. Ultrasonic velocities of (Al-Cu-Mg): SnO_2 samples

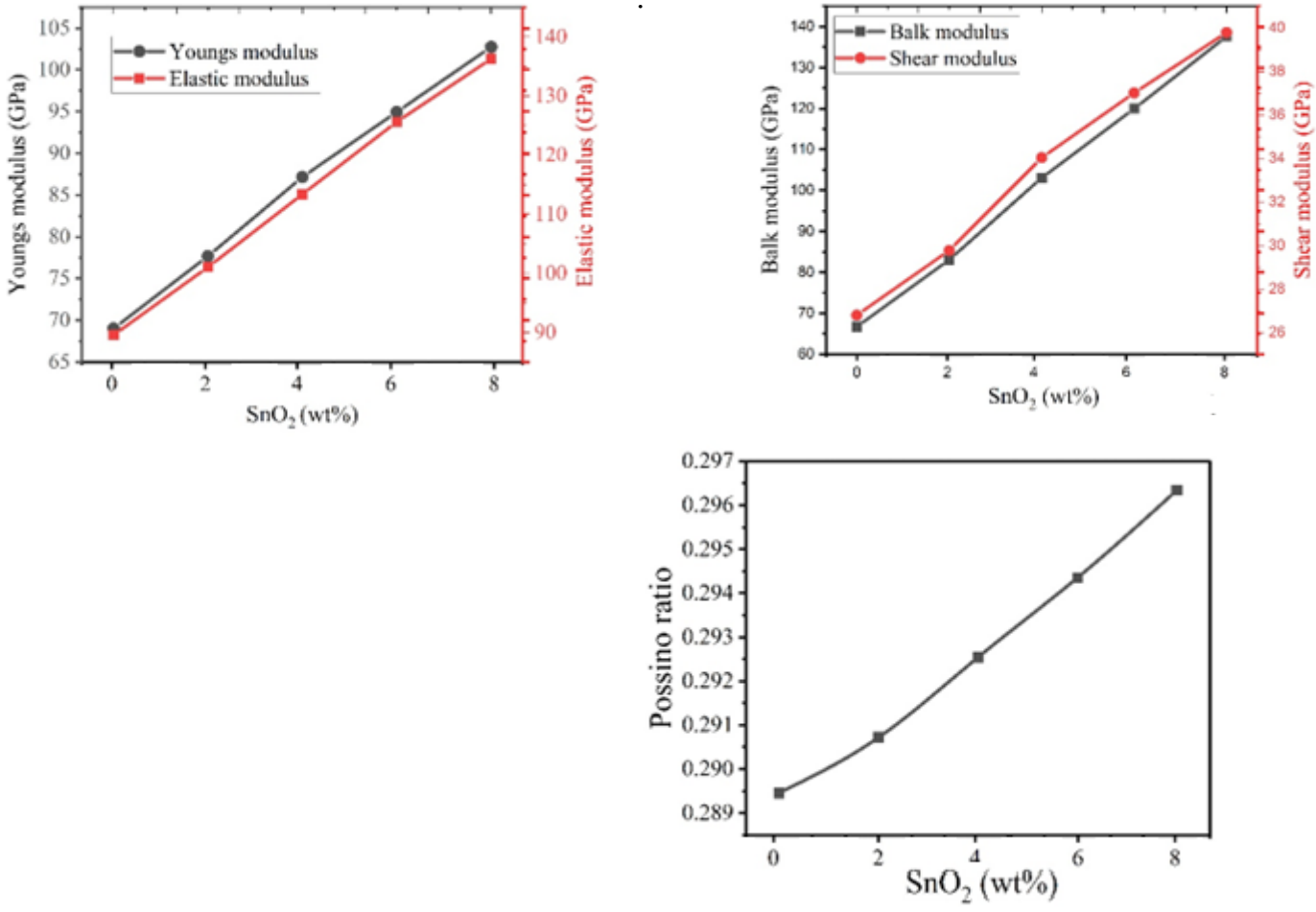


Figure 7. The group of elastic moduli of (Al-Cu-Mg): SnO_2 samples

Middle microhardness (HV) of Al–Cu–Mg alloy and its nanocomposites containing SnO_2 particles sintered at 550 °C is shown in Figure 8. There is a noticeable increase in microhardness of the Al–Cu–Mg alloy when SnO_2 content is increased. Microhardness value raised from 431.13 MPa for the unmodified alloy (AS0) to 1124.6 MPa in the composite with 8 wt% SnO_2. There are several reasons for such a considerable increase in microhardness. First, SnO_2 nanoparticles have a higher hardness compared to the matrix material. Second, it can be observed that reinforcement particles have quite an even distribution in the matrix. The grain refinement effect caused by adding nanoparticles also plays an important role here. Furthermore, reduction of crystal grain size leads to a restriction of dislocations' movement in composite samples [36].

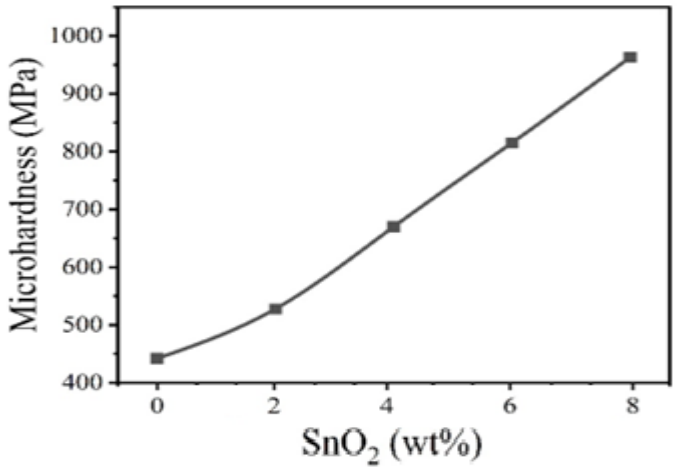


Figure 8. Microhardness of (AL-Cu-Mg): SnO_2 samples

Figure 9 shows the wear rates of the nanocomposite samples AS0, AS2, AS4, AS6, and AS8 under applied loads of 10, 20, and 40 N, respectively. Furthermore, Table 5 gives the standard deviations for the wear rate measurements. It is evident that the wear resistance of the prepared composite samples was better at a higher SnO_2 content, while the wear rate of the composite samples increased with applied load [37,38]. The wear resistance improvement of the reinforced samples could be explained by their improved hardness and ability to withstand loads due to the presence of SnO_2 nanoparticles in the Al-Cu-Mg matrix. furthermore, the raise in applied load led to an raise in friction and resulted in higher wear rates. The wear rates of the unreinforced sample AS0 under applied loads of 10, 20, and 40 N were found to be 0.01, 0.0084, and 0.0126 g/s, respectively. These results clearly demonstrate the improvement in the tribological behavior of the Al-Cu-Mg alloy with reinforcement with SnO_2 nanoparticles.

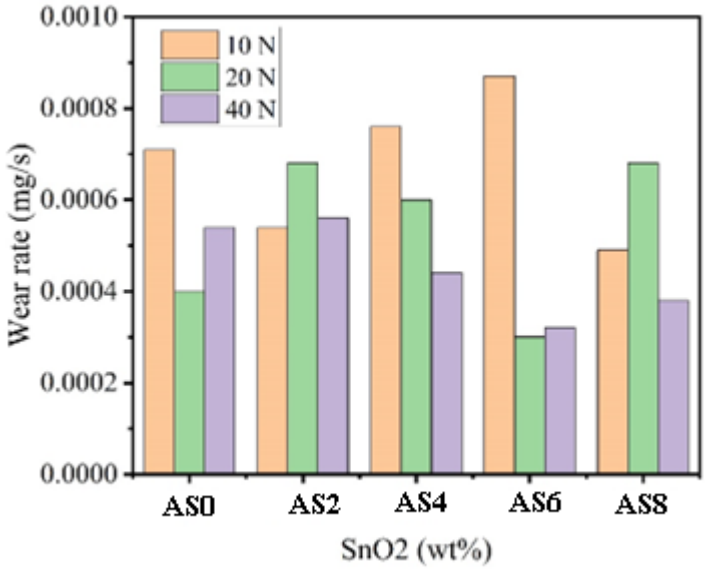


Figure 9. Wear rate of heat treated (Al-Cu-Mg): SnO_2 alloys at (10, 20, 40) N.

Table 3. The standard deviation for the wear rate for (Al-Cu-Mg): SnO_2 alloys.

Samples	Stander deviation		
	Load at 10 N	Load at 20 N	Load at 40 N
AS0	0.00071	0.0004	0.00054
AS2	0.00054	0.00068	0.00056
AS4	0.00076	0.0006	0.00044
AS6	0.00087	0.0003	0.00032
AS8	0.00049	0.00068	0.00038

Conclusions

Nanocomposites with SnO_2 particles incorporated into Al–Cu–Mg alloys were produced through powder metallurgy in the current study. From the outcomes achieved, the presence of tin oxide nanoparticles in the produced nanocomposites appeared fairly uniform although some agglomeration occurred with higher reinforcements. In this regard, an increase in the amount of tin oxide nanoparticles in the material caused a significant reduction in the particle sizes from 90.8 nm at 2 wt% down to 45.9 nm at 8 wt%. Besides the above, the increase in the SnO_2 amounts led to increased apparent porosities as well as reductions in the relative densities. However, the mechanical and elastic properties of the material improved significantly with an increase in the content of tin oxide nanoparticles. Specifically, bulk modulus and elastic modulus went up by about 71% and 69%, respectively, with the increase

in SnO_2 to 8 wt%. Microhardness, ultimate tensile strength, and yield strength also saw a remarkable improvement, with AS8 having values 1.9 and 2.2 times the values of AS0. Regarding the tribological characteristics of the materials, the wear rate decreased with the increase in SnO_2 content but increased with the applied load. Although there was a minor decline in the densification of the composite, remarkable enhancement in the mechanical and elastic properties was noted when more SnO_2 was used as reinforcement material. The elastic modulus was increased from 89.7 GPa in AS0 to 150.6 GPa in AS8, and the microhardness was increased from 431.13 MPa to 1124.6 MPa. This is probably due to the hardness of SnO_2, grain refinement strengthening, and limitation of dislocations in the aluminum-copper-magnesium matrix. In addition, the wear resistance of the produced nanocomposite significantly improved as more SnO_2 was added. On the other hand, the wear rate increased when the applied load was increased. In summary, the use of SnO_2 nanoparticles is an active method to progress the characteristics of Al–Cu–Mg alloy nanocomposites fabricated through powder metallurgy.

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