Original Article

Effect of carbon nanotubes (CNTs) and silicon carbide (SiC) on mechanical properties of pure Al manufactured by powder metallurgy

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A R T I C L E   I N F O

Article history:
Received 20 September 2019
Accepted 9 December 2019
Available online 28 December 2019

Keywords:
CNT
SiC
Aluminum matrix composites
Powder metallurgy

A B S T R A C T

In the present research, the effects of the size and amount of CNT and SiC particles on the mechanical properties of Al matrix composite were investigated. SiC of particle size 10 μm, CNT 10–40 nm, and Al powder of particle size less than 50 μm and purity 99.99% were used. Composites of Al with 3, 6, 9 and 12 wt.% SiC and 0.25, 0.5, 0.75, and 1 wt.% CNT were manufactured by powder metallurgy technique by cold compaction and vacuum sintering. Relative density, hardness, compression and friction coefficient were studied. The results of scanning electron microscope (SEM) and optical microscope observations illustrated that the distribution of the reinforcing particles was uniform. Moreover, increasing the amount of SiC and CNT leads to decreasing the relative density and improving the hardness and compressive strength of Al–SiC and Al–CNT composites.

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1. Introduction

Recently, very advanced materials are spread worldwide to achieve special product requirements. This is because a single material generally cannot achieve the requirements of all engineering fields. For this reason, researchers have done efforts to use composite materials with unique properties. So, in the recent years, there was a tremendous increase in production of metal matrix composites (MMCs) and their applications [1]. In the last decades, many research papers studied aluminum matrix composites (AMCs). The mechanical properties of pure aluminum such as ductility and strength give pure aluminum matrix composite possibility of utilization in advanced applications.

The major barrier to use aluminum in advanced engineering applications is its low wear resistance. So, adding ceramics and carbon nanotubes (CNTs) to aluminum matrix would amend the wear resistance, hardness, strength and corrosion resistance [2,3]. The reinforcement is the principal provider of optimum mechanical and electrical properties in the composite materials. There are many types of reinforcements, such as fibers, flakes, wires, foams, whiskers, particulates, foils, etc. Ceramic particle reinforcement was shown as better than fiber type in terms of mechanical properties and microstructure by optimizing volume fraction and particle size of reinforcement [4]. Carbon nanotubes (CNTs), either multi-
walled (MWCNT) or, single-walled (SWCNT) are extensively used worldwide in recent years as the perfect reinforcements for composites because of their extra high strength (30–100 GPa) and high elastic modulus (around 1 TPa) and also good electrical and thermal properties [5–9]. By consolidating CNT with aluminum metal matrix, it will produce composite with enhanced properties. Combination of CNTs with light metals such as aluminum leads to strong but light composites convenient for the sports industries, the aerospace or automotive industries, where the weight reduction and fuel economy are the first priority [10,11]. To obtain the expected high effectiveness of CNT/Al composites, the composite microstructures and their effects on resultant properties must be studied [12,13]. SiC particles have been generally chosen as the reinforcement phase for many applications [14,15]. This is due to its high hardness, wear resistance, and excellent high temperature properties, as well as its low cost. Furthermore, SiC at high temperatures does not react with the matrix [16]. To produce metal-matrix composites, powder metallurgy is considered as the best technique. The main advantage of powder metallurgy compared to melting techniques is its low processing temperature. Thus, there is no interaction between the matrix and the reinforcement phases [17]. Another advantage of powder metallurgy technique is its ability to manufacture near net shape products with low cost [18,19]. Furthermore, powder metallurgy technique offers the ability to manufacture high melting point advanced superelastic and shape memory alloys like Ti-Ta and Ti-Nb alloys with very good properties [20,21].

Omyma El-Kady and A. Fathy stated that increasing the amount and reducing the particle size of SiC in Al matrix decreases the grain size, reduces the thermal conductivity, and increases the hardness and compressive strength [22]. Sambit Kumar Mohapatra and KalipadaMaity have studied the mechanical and tribological properties of hot extruded aluminum metal matrix by powder metallurgy, and found an improvement in density, compressive strength and microhardness due to the fine distributed graphite particles which act as solid lubricant and decrease wear rate [23]. Jaswinder Singh has studied various aspects concerning the fabrication and wear properties of Al/SiC/Gr hybrid composites. Graphite (Gr) particles significantly enhance the wear properties. The hybrid reinforcements can be successfully incorporated into the Al matrix by powder metallurgy. It was also shown that the presence of SiC particles increases the hardness of the composites. The wear resistance of Al/SiC/Gr composites increases with the addition of Gr [24]. The work done by V. Umasankaret et al. to study the sintered aluminum metal matrix composite reinforced with different weight percentages of SiC particles has highlighted the significance of processing parameters on sintered density, hardness and consequent breaking load [25]. OlehBoshko et al. developed a method for production of a new nanocomposite material comprising iron, copper and multiwalled carbon nanotubes with a high ultimate tensile strength [26]. Shisheng Li et al. revealed the possibility to achieve a uniform distribution of carbon nanotube (CNT) reinforcement in aluminum matrix by novel nano/micro-sized hybrid reinforcements with CNT growing on the surface of SiC particle (SiCp) synthesized by chemical vapor deposition. SiCp (CNT)/Al composite exhibited both improved elastic modulus and tensile strength, mainly because CNT was dispersed uniformly and achieved intimate interfaces with Al matrix with the help of well dispersed SiCp [27].

The current work aims at studying the effect of the amount of CNT and SiC on the mechanical properties of Al matrix composites synthesized by using powder metallurgy technique. The prepared samples were investigated by the microstructure SEM and optical. The relative density and compression strength of the samples were studied. The idea of performing compression test was taken from the applications of such parts under compressive loads such as upsetting, the extent to which a material can be deformed in special metal working process without the initiation of cracks.

2. Experimental procedure

CNTs were used with average particles sizes of 10–40 nm at 0.25, 0.5, 0.75 and 1 wt.% concentrations, while the particle size of SiC is 10 µm at (3, 6, 9 and 12 wt.% concentrations). The average size of aluminum particles was 425 µm with a purity of 99.99%. The aluminum matrix and reinforcement particles were mixed for 20 min with 10 ml cyclohexane (for each 20 gm of the composite powder) as a control agent and 0.5 wt.% paraffin wax, which was used as a lubricant to facilitate cold compaction. The samples were compacted at 560 MPa using a single-action uniaxial hydraulic press of 20 ton capacity. The green compact samples were sintered in a vacuum furnace at 600 °C for 3 h using the heating rate of 5 °C/min.

The actual densities of the manufactured samples were measured by using the Archimedes’ method (ASTM: B962-13) and compared with theoretical densities to obtain the relative densities. Furthermore, the samples were prepared for microstructure examination and the microstructure evolutions were examined by using optical and scanning electron microscopes and X-ray diffraction. The compression test was performed on the manufactured samples of cylindrical cross-section of 9 mm diameter and 15 mm height by using a Universal test machine; model UH-500 KNA, Schematize at the room temperature and under a speed of 2 mm/min. The wear tests of the sintered specimens were carried out using a pin-on-disc tribometer model TE 79 multi-Axis tribometer. The tested specimens were in the form of a cylinder of 20 × 8 mm. The specimens were loaded against the ring under normal loads of 10 N at sliding speed of 250 rpm for 15 min. The Vickers hardness (HV) was measured as the average of 5 readings along the cross section of polished surface of the specimen using Zwick/Roell hardness tester using the load of 1 kg and the holding time of 15 s. The samples were tested according to Vickers testing as per ISO 6507.

3. Result and discussion

Table 1 represents the calculated relative densities of the manufactured composites at different SiC and CNT concentrations. As can be seen from this table, the relative densities of the manufactured samples decrease with increasing the SiC fractions. It is also observed that the highest SiC percent (i.e. 12%) gives the lowest relative density value. This may be attributed
Table 1 – The calculated relative densities of Al matrix composite at various SiC and CNT concentrations.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Relative density, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>98.5</td>
</tr>
<tr>
<td>Al-3 wt% SiC</td>
<td>97.9</td>
</tr>
<tr>
<td>Al-6 wt% SiC</td>
<td>96.6</td>
</tr>
<tr>
<td>Al-9 wt% SiC</td>
<td>95</td>
</tr>
<tr>
<td>Al-12 wt% SiC</td>
<td>92.2</td>
</tr>
<tr>
<td>Al-0.25 wt% CNT</td>
<td>97</td>
</tr>
<tr>
<td>Al-0.5 wt% CNT</td>
<td>96.7</td>
</tr>
<tr>
<td>Al-0.75 wt% CNT</td>
<td>96.3</td>
</tr>
<tr>
<td>Al-1 wt% CNT</td>
<td>96</td>
</tr>
</tbody>
</table>

The experimental results of the hardness of Al-SiC composites are demonstrated in Fig. 1. As can be seen from the figure, increasing SiC volume fractions leads to the higher hardness values, giving the best value at 12% SiC volume fraction. This may be attributed to the strengthening effect of the hard SiC particles and their higher hardness value. The highest hardness value is 69 HV at 12% SiC; while the lowest one is 53 HV at 3% SiC which is higher than that of pure Al. On the other hand the Vickers hardness values of the Al-CNT composites are depicted in Fig. 2. It is clear that the hardness values increase with increasing the CNT volume fractions. It is noticeable that the increase of hardness of Al composites by CNT reinforcement is less than that of reinforcement by SiC.

The manufactured samples of Al with the reinforcement particles were subjected to compression test to study the effect of SiC and CNT volume fractions on the ultimate and yield compressive strength of the composites. Fig. 3 shows the stress-strain curves of Al-SiC composite samples. As can be observed from the figure, the higher SiC volume fraction values (i.e. 9% & 12%) have lower percentage strain than those at lower values (i.e. 3% & 6%). On the other hand the Al-CNT composite compressive stress-strain curves are represented in
Fig. 4. It is noticed that the CNT volume fractions have small effect on the compression strength values. However, increasing CNT volume fractions resulted in observable softening, which may be due to the void formation effect of CNT.

Fig. 5 demonstrates the friction coefficients of Al-SiC composite samples at different SiC volume fractions. As can be observed from the figure shown, the friction coefficients of the manufactured samples are improved by increasing the SiC volume fractions. They are all lower than that of pure Al sample. On the other hand, the Al-CNT composites friction coefficients are presented in Fig. 6. The Al-composite samples containing CNT have shown very similar values among each other, implying that the used CNT percentage levels have very similar effects on the friction coefficient of the composite. However, all the samples of Al-composites have shown much improved coefficient of friction compared to that of pure Al sample.

Figs. 7 and 8 demonstrate the optical micrographs of Al-SiC and Al-CNT composites. As can be observed from the presented figures, the higher the SiC volume fraction, the highly particles distribution through the aluminum matrix occurs. A slight grain refinement effect can also be observed from Fig. 7. On the other hand, Fig. 8 shows that the introduction of CNT into the microstructure of Al-composites have shown successive and consistent grain refinement until the CNT percentage reaches 0.75 wt.%. After that, and at the percentage of 1 wt.%, the CNTs are considerably agglomerated, which eliminates their effects on the structure, which eventually results

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Fig. 6 – Friction coefficient of Al-CNT composite.

Fig. 7 – Optical micrographs of Al-SiC composites.
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in the formation of coarse grains similar to those of pure Al sample.

The manufactured composite samples of aluminum matrix have been analyzed to check the percentage of the elements inside the composite structure. Fig. 9 depicts the EDS analysis of Al-3% SiC and Al-1% CNT composites at two points. As can be observed from this figure at point 2, the analysis gives a mixture of 26%Al-34%Si-36%C-4%O. This analysis reflects the good mixing of Al matrix and SiC particles; while the existence of oxygen may be due to the oxidation of aluminum during the sample preparation as Al can be easily oxidized. Moreover, at point 1 the analysis produces fully 100% aluminum. On the other hand the EDS analysis of Al-1%CNT is represented in Fig. 9-b. It is observed that the CNT are homogenously distributed through Al matrix as can noticed from point 4 analysis. It is also noticeable that the pure aluminum is found in the analysis of point 3.

The XRD analysis of Al-12%SiC and Al-1% CNT has been evaluated to check the phase structure formed during the powder metallurgy process. As demonstrated in Fig. 10, there are no phases formed during the sintering process other than the original pure Al and SiC particles. It is also worth mentioning that the percentage of CNTs are very low (1 wt.% maximum) to be observed in the XRD pattern of Al-CNT composite sample.
4. Conclusions

The pure Al samples, Al-SiC, and Al-CNT composites were manufactured by powder metallurgy technique. The below conclusions may be drawn from the presented results;

- Both CNTs and SiC particles could be homogeneously distributed in the structure of the Al-composites by the use of wet-mixing.
- The XRD analysis did not show any further structure formed during powder metallurgy process which refers that there is no solid state reaction happened between Al and CNT or SiC.
- The density values for the prepared Al-SiC composite indicated that the densification decreases by increasing SiC and CNT contents.
- Both the hardness and the compressive strength for samples increases compared to pure Al by increasing CNT & SiC percent.
- The coefficient of friction has been improved for the composite by about 26% by using either of SiC or CNTs compared to the pure sample.
- The use of SiC particles as reinforcement for Al is a better choice compared to CNTs based on the mechanical properties of the composites, especially hardness.

Conflicts of interest

The authors declare no conflicts of interest.

REFERENCES


