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Microstructure and Mechanical Properties of Aluminum Alloy Matrix Composite Reinforced with Nano MgO Particles

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Discontinuously reinforced aluminum composites are being recognized as an important class of engineering materials that are making significant progress. The reasons for their success are related to their desirable properties including low density, high hardness, high compressive strength, wear resistance, *etc*. Casting and powder metallurgy are the two major fabrication methods of aluminum matrix composites, though powder metallurgy is more complicated than casting, but it yields to a better interface between reinforcement and matrix alloy, improving mechanical properties of Al-nano MgO composite. Pure atomized aluminum powder with an average particle size of 1 μm and MgO particulate with an average particle size between 60-80 nm were used. Composites containing 1.5, 2.5 and 5.0 % of volume fraction of MgO were prepared by powder metallurgy method. The specimens were pressurized by cold isostatic pressure machine. The consolidation temperatures were 575, 600 and 625 °C. After sintering and preparing the samples, mechanical properties were measured. The results of microstructure, compression and hardness tests showed that addition of MgO particulates to aluminum matrix composites improve the mechanical properties.

Key Words: Aluminum matrix composite, Nano MgO, Powder metallurgy, Mechanical properties, Reinforcement.

INTRODUCTION

Nowadays, demands for developing metal matrix composites for use in high performance applications, have been significantly increased[1]. Aluminum alloy matrix composites attract much attention due to their lightness, high thermal conductivity, moderate melting point, *etc*.[2,3]. Among these composites, metal matrix nano-composites are a new class of nanostructured materials, consisting of nano-scale particles used as reinforcements. It is of interest to use nano-sized ceramic particles to strengthen the metal matrix, while maintaining good ductility, high temperature creep resistance and better fatigue. However, the ductility of the MMCs deteriorates significantly with high ceramic particle concentration[4-8].

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Various kinds of ceramic materials, *e.g.,* SiC, Al_2O_3, ZrO_2 and B_4C, are extensively used to reinforce aluminum alloy matrixes. Superior properties of these materials such as refractoriness, high hardness, high compressive strength, wear resistance, *etc*., make them suitable for use as reinforcement in matrix of composites[9-16]. Nevertheless, low wettability with molten metals and density differences increase their tendency toward agglomeration, which deteriorate mechanical properties[17-19].

Magnesium oxide (MgO) is a refractory material with melting point of about 2780 °C. MgO possesses good properties such as the good thermal shock resistance, high melting point, low thermal conductivity and excellent thermodynamic stability. Its density, Young's modulus and hardness are 3.58 g/cm^3, 320 GPa and 910 HV, respectively[20-22]. There are different methods for the fabrication of aluminum matrix composites that are divided into three major categories: (a) smelting processing, (b) semi-smelting processing and (c) solid state processing; the last one has been divided into two methods: (1) mechanical alloying and (2) powder metallurgy[23,24].

The sintering process in powder metallurgy method including sintering of nano-ceramic particles within metals matrix in comparison with other methods such as casting method, has some important advantages, including better bonding between particles and matrix alloy and being easier to control the matrix structure. But, this method has some problems such as complexity and money consuming[25,26].

In this study, nano MgO particles were used to reinforce A356.1 alloy by powder metallurgy method. The optimum sintering temperature and reinforcement content were also determined by analyzing the microstructure and mechanical properties.

EXPERIMENTAL

Aluminum powder alloy (A356.1 with D_{50} = 1 μm) and nano-sized MgO (with D_{50} = 70 nm) were used for fabrication of composites. Chemical composition of A356.1 is shown in Table-1. After weighing the reinforcement and matrix powders and before preparing the composite samples, powders are required to be mixed with each other completely. In this stage, powders were poured into the mixer and the mixing operation was performed for 0.5 h in alcohol-ethanol environment. After mixing, powders were completely dried by dryers. To evaluate the amount of reinforcement and the effect of sintering temperature on the properties, the composites with 1.5, 2.5 and 5.0 volume per cent of magnesium oxide were prepared. In the next stage, powders were compacted by cold isostatic pressure machine and compressed powders were prepared as cylindrical shapes with 18 mm height and diameter. Applied force for compaction was 200 MPa. Prepared raw composite samples were put into the furnace with argon atmosphere and were sintered at different temperatures (575, 600 and 625 °C) for 1 h. Finally, produced samples in order to provide the standard samples, were cut as cylindrical shape with 1.4 cm of height and 1 cm of diameter.

TABLE-1
CHEMICAL COMPOSITION OF Al-356 ALLOY

Element	Al	Si	Fe	Cu	Mg	Mn	Zn	Ti	Ni
Mass (%)	91.73	7.23	0.32	0.18	0.38	0.02	0.05	0.01	0.05

Specimens fabricated in nine various conditions were prepared for subsequent microstructural and mechanical analyses. The bulk density of the samples was determined by the Archimedes method. The composites were subjected to XRD analysis (Philips, PW-1800 model). The microstructural studies were done by scanning electron microscope (SEM, Oxford CAMSCAN-MV2300), equipped with X-ray mapping system.

The compressive strength test was conducted in air at room temperature (Instron Universal Testing Machine-1195 machine) according to ASTM-E9. At least five specimens were tested for each sintering conditions. After grinding of samples, for determining the hardness of specimens, they were polished down to 1 µm by the Brinell method. Hardness tests were made with a load of 306.56N and a punch diameter of 2.5 mm. Data of hardness were determined using at least ten indentations on two polished specimens.

RESULTS AND DISCUSSION

Density measurements: The effects of the sintering temperature and volume per cent of Nano MgO on the density of the Al-nano MgO composites produced by cold isostatic pressure (CIP) method are shown in Fig. 1. As it can be seen, the highest density value in three temperatures belongs to the samples containing 1.5 and 2.5 volume per cent of nano MgO. According to mixture law, by increasing the volume fraction of MgO particles in aluminum, density of samples should be increased because the density of magnesium oxide is higher than aluminum. But with increasing the volume fraction of refractory MgO particles, sintering and wettability of MgO by molten Al alloy become less; furthermore, particles agglomeration were expected and any of these factors and the incidence of created porosities will result in reduction of density.

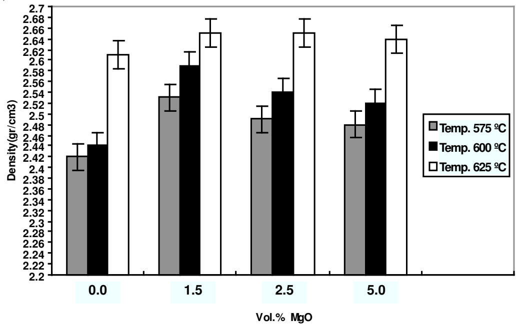

Fig. 1. Density results of the Al alloy and the composite specimens containing 1.5, 2.5 and 5.0 vol % MgO sintered at 575, 600 and 625 °C

This phenomenon can be attributed on prevented effect of MgO particles on samples compaction during sintering. Because of the melting point of magnesium oxide, MgO in sintering temperature is quite rigid and its strong lattice formation prevents samples compaction.

As it can be seen, samples density increased with increasing of sintering temperature. With increasing the sintering temperature, increased permeability of atoms; therefore, will increase the ability of sintering leading to increased density of samples. Also, increasing the temperature causes increasing of particles wettability which helps to reduce the porosities rate. The results show that increasing the sintering temperature has an effective role in increasing the density of samples.

XRD and microstructural analyses: The phases identified by XRD analysis were similar for all composites. Although, their peak intensity was different but magnesium oxide (MgO), silicon (Si) and aluminum (Al) were just detected. Fig. 2 shows the XRD pattern of composite, containing 2.5 vol % MgO, fabricated at 600 °C. Microstructures of composites with the content of 2.5 and 5.0 vol % MgO, sintered at 625 °C are shown in Figs. 3 and 4, respectively. Dark Al matrix and bright particles of MgO can be clearly observed. The phases are indicated by arrows on images. It should be noted that nano-sized MgO are well embedded in the matrix of aluminum and just a partial agglomeration in composites with high content of MgO can be detected. The agglomeration occurred in composite containing 5 vol % MgO that is illustrated in Figs. 4 and 5.

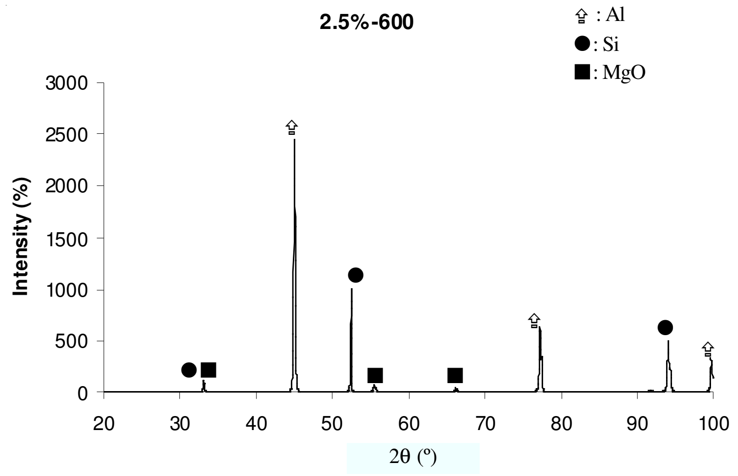

Fig. 2. XRD pattern of composite containing 2.5 vol % MgO sintered at 600 °C

Figs. 5 and 6 represent microstructure of composite containing 5 vol % MgO, sintered at 575 and 600 °C, respectively. Fig. 6 shows the corresponding X-ray mapping of the sample sintered at 600 °C. X-ray maps confirmed the presence of MgO and their well distribution in matrix of composites. Similar microstructures were also observed for composites, fabricated in various sintering temperatures

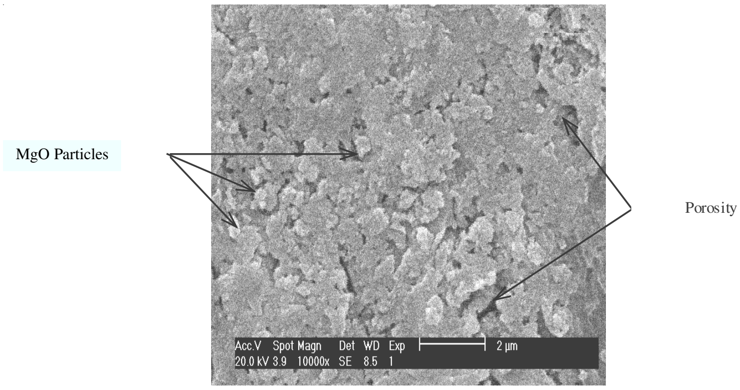

Fig. 3. SEM image of composite containing 2.5 vol % MgO sintered at 625 °C

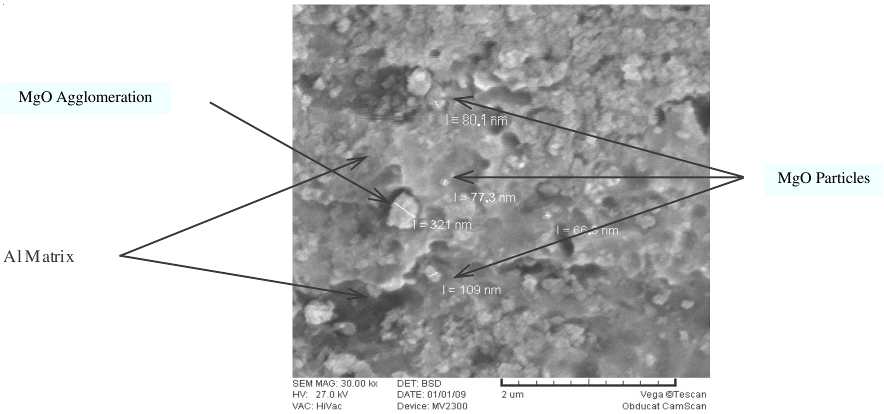

Fig. 4. SEM image of composite containing 5 vol % MgO sintered at 625 °C

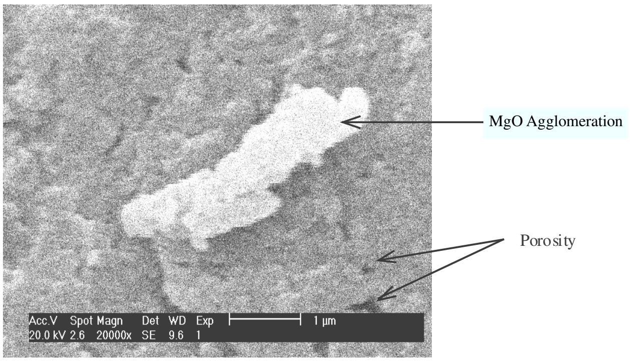

Fig. 5. SEM image of composite containing 5 vol % MgO sintered at 575 °C

and volume fraction of MgO. The only minor difference was related to the content of porosity. The above-mentioned results, obtained from XRD and microstructural analyses, confirm feasibility of powder metallurgy method to produce such a kind of

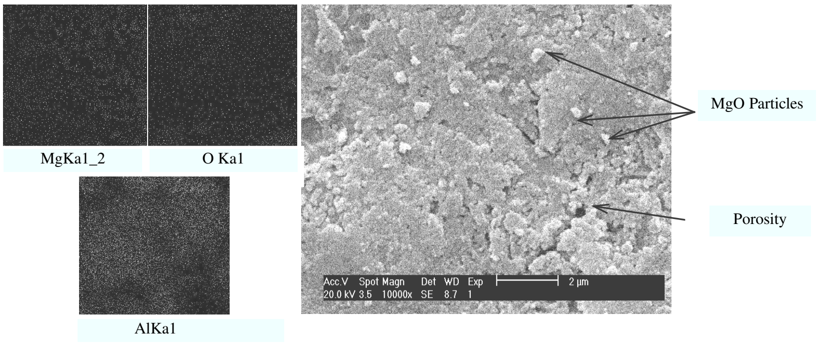

Fig. 6. SEM image of composite containing 5 vol % MgO sintered at 600 °C as well as corresponding X-ray maps

composite with well distribution of reinforcement. Lack of undesirable phases, which results from undesirable reactions, is another prominent result of this study.

Mechanical properties

Hardness test: The effects of the sintering temperature and volume per cent of nano MgO on the harness of the Al-nano MgO composites produced by cold isostatic pressure method are shown in Fig. 7. The hardness values obtained from experiment show that increasing the volume fraction of magnesium oxide nano particles in the composite, the value of hardness in most produced composites increased. Considering that the hardness of magnesium oxide is much more than that of aluminum and the hardness of composites increase with increasing volume per cent of MgO particles, not far from the expected. This matter in case of the mixture law in composites is understandable. Thus, the properties of a composite effect, accept the volume percentage of each material in the composite.

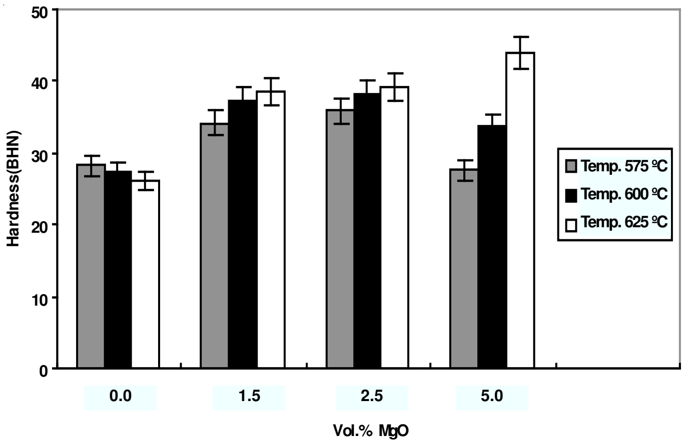

Fig. 7. Hardness of the Al alloy and the composite specimens containing 1.5, 2.5 and 5.0 vol % MgO sintered at 575, 600 and 625 °C

As it can be seen in Fig. 7, with increasing amount of MgO particles up to 2.5 and 5.0 volume per cent, as expected, hardness also increased. Sample Al-5 vol % MgO produced at 625 °C has highest hardness between the other samples because a higher temperature could do the better sintering on this composite and optimum condition between two variable factor as temperature and volume per cent of nano MgO is achieved. In samples of pure aluminum can be seen that with increasing sintering temperature, hardness of the samples have decreased. This phenomenon of grain growth due to increase of temperature is justified because the grain size has a great effect on all mechanical properties of materials and with grain growth, hardness and strength properties, reduced. But the presence of MgO particles in matrix alloy as the obstacle in the way the grain boundary and prevent the grain growth. Therefore, the effect of temperature on the increase of grain growth will largely neutral.

As the density was also described, with increasing sintering temperature, atoms diffusion and consequently influence of sintering intensity will increase. Thus, the properties of samples, including density and hardness become increased. Increased density improves many properties of the samples such as hardness. Porosity reduction is the most important reasons in increase of hardness due to increasing sintering temperature. Because the porosity is the most important defects known as empty areas of the material that strongly decrease the properties of composites. Therefore, increasing the sintering temperature increased density, reduced porosity and consequently will increase the hardness. Other factor is improving the interface and bonding between nano MgO particles and Al matrix alloy due to increasing of wettability in higher sintering temperature.

Compression test: The effects of the sintering temperature and volume per cent of nano MgO on the compressive strengths of the Al-nano MgO composites produced by cold isostatic pressure method are shown in Fig. 8. With increasing volume per cent of magnesium oxide reinforcement particles, the value of the compressive strength compared with unreinforced matrix alloy, initially increased and then decreased at all three sintering temperatures. The reason for this increasing seems to be due to increased work-hardening. This could be related to effects of elastic properties of ceramic particles and inhibition of plastic deformation of matrix by them; ceramic particles can only deform elastically while aluminum matrix can deform plastically. So if the boundary is assumed to be strong, ceramic particles inhibit plastic deformation of the matrix and this leads to stronger work-hardening. The difference between coefficients of thermal expansion of ceramic and matrix metal may cause stress concentrations, thus high density of dislocations; the strength of the aluminum matrix increases accordingly. These confirm the obvious effect of MgO particles on strengthening of composites. With increasing volume fraction of magnesium oxide particles in the constant particle size, the distance between particles decreases and causes in increasing of dislocation density and their pile-ups behind the MgO particles. Therefore, higher stress need to move dislocation, which also has the effect on strength increasing. It should be noted that the strength increased due to increasing amount of reinforcement particles. This will continue until the porosities because increasing of reinforcement particles does not cause significant reducing of samples properties. In addition, the porosity cause discontinuity in the samples, act as stress concentration locations and cause severe decreases in samples properties. On the other hand, with increasing amount of reinforcement particles, homogeneity in distribution of magnesium oxide particles in the matrix decreased and in some areas as they form the cluster assembly. Therefore, the effect of MgO particles by direct contact with each other and lack of the strong mechanical bonding between them, decreases compressive strength. Increasing temperature causes better wettability of MgO particles by aluminum, but increasing temperature can increase the internal stresses in composite that in higher percentages of MgO particles, even causes cracks in the samples.

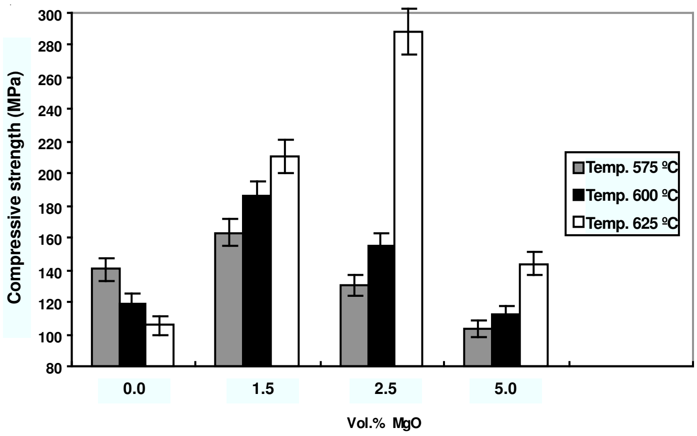

Fig. 8. Compressive strength of the Al alloy and the composite specimens containing 1.5, 2.5 and 5.0 vol % MgO sintered at 575, 600 and 625 °C

Composite sample Al-2.5 vol % MgO sintered at 625 °C is the optimum condition and has maximum failure strength. Samples containing 1.5 vol % MgO shows the increasing of compressive strength compared with the non-composite samples. Samples containing 2.5 vol % MgO sintered at 575 and 600 °C, because of being less temperature and being more amount of nano MgO particles, there is not good incorporation between the particles and matrix alloy that causes the reduction in compressive strength.

Process of strength reduction in composite samples with 5 vol % of MgO particles has been observed. Certainly decreasing the compressive strength, with increased volume of MgO particles more than 5 % in aluminum, will occurs with more intensity. Sintering temperature is an important factor on the results of the experiments in powder metallurgy method. Fig. 8 shows that with increasing sintering temperature in composite samples containing equal volume percentages of magnesium oxide, compressive strength is increased because with increasing sintering temperature, amount of wettability and penetration rate of particles increase.

Conclusion

A356.1 aluminum alloy reinforced with nano-sized MgO was successfully fabricated *via* powder metallurgy method. SEM micrographs indicate that reinforcement particles were homogeneously distributed in the matrix of composites. However, partial agglomeration was observed in composites with high content of MgO. Therefore, powder metallurgy was found as a suitable method for fabrication of this kind of composites. Mechanical properties such as hardness and compressive strength improved. Composites containing 2.5 and 5.0 vol % MgO fabricated at 625 °C showed maximum compressive strength and hardness, respectively, in comparison with other specimens and they can be selected as optimum samples. However, composite containing 2.5 vol % MgO would be more reliable, since it has maximum density. Furthermore, mechanical properties of composites, generally decreased by increasing the large content of MgO.

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