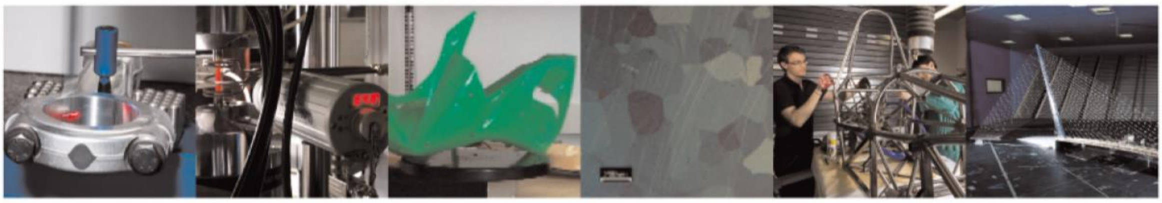

Effect of Al2O3 Nanoparticles as Reinforcement on the Wear Properties of A356/Al2O3 Nanocomposites Produced by Powder Metallurgy

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Effect of Al_2O_3 nanoparticles as reinforcement on the wear properties of A356/Al_2O_3 nanocomposites produced by powder metallurgy

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ABSTRACT

In this study, microstructure and wear properties of A356 aluminium matrix nanocomposites reinforced with nano-Al_2O_3 *particles were investigated. Powder metallurgy method was used for the production of 1 wt.% and 2 wt.% nano-*Al_2O_3 *particle reinforced nanocomposites. After 1 hour of mechanical milling of A356 and nano-* Al_2O_3*powders, green compacts were obtained by cold pressing. Green compacts were sintered at 550°C and vacuum environment (*10^{-6} *mbar) for 1 hour. Samples were characterized by density, hardness measurements, scanning electron microscopy investigations and wear tests. As the reinforcement ratio increased, there was a decrease in the densities of the nanocomposites, as well as an increase in the porosity. The highest hardness and the lowest weight loss values were obtained in 1wt.%* Al_2O_3 *reinforced nanocomposites. A decrease in hardness was measured at 2 wt.%* Al_2O_3 *reinforced nanocomposites.*

INTRODUCTION

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Aluminium matrix composites (AMCs) are produced by adding particles with different properties into the Al alloy by various methods in order to be used in applications requiring functional properties. In particle-reinforced aluminium composites, Al alloy is generally defined as the matrix and additional particles are defined as the reinforcement phase. It is possible to produce composites with different properties by reflecting the specific properties of the matrix and reinforcement materials to the composite material. AMCs reinforced with SiC, Al_2O_3 (alumina), B_4C, TiB_2, ZrO_2, SiO_2 and graphite particles are frequently used in automotive and aerospace applications due to their superior mechanical and physical properties [1]. AMCs are also reinforced with other synthetic, recycling and natural reinforcement materials such as tetragonal zirconia polycrystalline [2], Si_3N_4 [3], fly ash, rice husk ash [4-6]. With the powder metallurgy method, particle reinforced AMCs are produced at lower temperatures than liquid production methods (such as infiltration and Stir casting). In addition, as the reinforcement particles can be distributed more homogeneously in the matrix, the desired properties are obtained more efficiently [7]. Carbide, boride and oxides are often used as reinforcement materials in particle reinforced composites [8-12]. The improvement in the mechanical properties of AMCs is directly related to the type, size and reinforcement ratio of the reinforcement particles. [13]. When the reinforcement particles used in the production of AMCs are nano-sized, the ductility of the composite is preserved as well as the improvements in strength and hardness [14]. Kang et al. [15] states that Al_2O_3 reinforcement increases hardness and mechanical properties in Al/ Al_2O_3 (between 1-7 vol. %) nanocomposites produced by powder metallurgy method. Rahimian et al. [16] reported that the hardness of Al/ Al_2O_3composites produced by powder metallurgy method increased, and the best yield strength was obtained from composites with a reinforcement ratio of 10 wt.%. Thereby, in many studies, properties such as optimum hardness, mechanical strength, ductility, microstructure morphology, depending on the amount of reinforcement phase or process parameters were investigated in nano AMCs produced by powder metallurgy [7,17]. Ezatpour et al. [13] produced A7075/ Al_2O_3 nanocomposites with 0-1.2 wt.% reinforcement ratios by stir casting method and then applied extrusion process and investigated microstructure and mechanical properties. They reported that the extrusion process with nano-particle reinforcement increased the mechanical properties. Manivannan et al. [18] reported that A6061/1,2 wt.% SiC nanocomposites produced by ultrasonic cavitation assisted stir casting method were harder and showed better wear resistance than A6061 alloy. In addition, the amount of reinforcement phase in nano aluminium composites is an effective parameter on hardness and relative density [19]. Tiku et al. [20] produced Al/ Al_2O_3 (1-4 wt.%) composites with Al_2O_3 particles synthesized by sol-gel technique. They reported that as the reinforcement ratio increased, the hardness increased, but the abrasion resistance decreased. Soltani et al. [21] manufactured AMC by addition of 10Ce-TZP (tetragonal zirconia polycrystal) / Al_2O_3 nanoparticles (1-10 wt.%) via powder metallurgy. The results showed that the wear resistance increased up to 7 wt.% reinforced samples and decreased with further reinforcements. Deaquino-Lara et al. [22] studied on the tribological characterization of Al7075/graphite composites produced by mechanical alloying and hot extrusion. They produced their samples using different reinforcement ratios (0- 1,5 wt. %) and mechanical milling times (0-10 hours). They concluded that hardness and wear resistance improved by adding 1,5 wt.% graphite and mechanical milling of 10 hours.

It has been stated in many studies that the reinforcement phase in particle reinforced composites improves the mechanical properties of the matrix alloy [7,15,18]. There is a limited number of studies examining microstructure and wear performance of nano- Al_2O_3 added A356 alloys used in automotive and aviation industry. On the other hand, it is revealed that increasing the amount of reinforcement phase, increases the mechanical properties and wear performance of the composites, but after a certain amount, these properties tend to decrease with effects such as agglomeration [19]. It has also been reported that wear properties are adversely affected by nano-particle reinforcement and the wear rate increases with increasing reinforcement amount [20]. Yildirim et al. are expressed that the most obvious difference between conventional particle-reinforced composites and nano-AMCs is the decrease of some mechanical properties such as hardness and wear behavior in case of increase over a critical ratio in nano-AMCs [23]. It is clearly seen in the literature that nanoparticle reinforcement has variable effects on wear properties. For this reason, there is a need for more work in this area. In this study, nano- Al_2O_3 reinforced A356 aluminium matrix nanocomposites (AMnCs) were produced by powder metallurgy. The microstructure and hardness of the AMnCs were investigated. In addition, the wear performance of nanocomposites was investigated in a pin-on-disc type wear device. The microstructures of the composites and the worn surfaces were investigated by SEM/EDS.

MATERIALS AND METHOD

A356 aluminum alloy powders used as matrix material in this study were obtained from LPW technology Ltd. (particle size range; 20-63 µm), nano- Al_2O_3 powders used as reinforcement phase (purity: >99%, average particle size; 20 nm) were obtained from Nanografi Co. Ltd. A356 and nano- Al_2O_3 powders were prepared by weighing them with a precision balance (precision; 1:10000 g). A356 alloy, 1 wt. % and 2 wt. % nano- Al_2O_3 reinforced nanocomposites were milled for 1 hour in a single chamber Fritsch planetary ball mill with a capacity of 225 ml. Stainless steel balls with a diameter of 8 mm were used in the mechanical milling (MM) process. The ball/powder ratio was determined as 1:10 and the chamber was filled 50% and MM was carried out at a milling speed of 400 rpm. Prior to MM, 1% stearic acid was added to the chamber as a process control chemical. In order to prevent overheating, the milling process was applied with a 15-minute interrupt for every 15 minutes. Nano- Al_2O_3 (reinforcement) powders were milled in ethanol for 5 minutes before mechanical milling of the nanocomposites because it is difficult to disperse the nanoparticles using the conventional grinding process. After MM process, AMnC powders were cold pressed (520 MPa) to obtain cylindrical green compacts with a height of 8 mm and a diameter of 12 mm. Green compacts were sintered at 550 °C in vacuum environment (10^{-6} mbar) for 1 hour. Heating and cooling rates were kept constant at 4 ºC per minute. Density measurements of sintered AMnCs were made according to Archimets' principle using a PRECISA XB200h density measurement kit. The densities of 3 different samples of each reinforcement ratio were measured and averaged. Hardness measurements were performed on a

SHIMADZU micro-hardness instrument (200gf – 15 sec). Mean values at each reinforcement ratio were calculated by averaging three different measurements performed on three samples. Carl Zeiss Ultra Plus Gemini scanning electron microscope (SEM+EDS) instruments were used in AMnCs' characterization studies. Wear tests were performed on a standard pin-on-disc wear device with AISI 4140 (mean 64 HRC) steel disc. Tests were performed at room temperature and in dry conditions in accordance with ASTM: G99 [24] standards. A356/ Al_2O_3 nanocomposites were tested with 30N load, $1ms^{-1}$ sliding speed and 4 different sliding distances (500, 1000, 1500 and 2000 m). Each test was repeated three times and weight loss values were measured before and after the test. Sample surfaces were cleaned with alcohol before measurements. The samples were weighed on a precision scale with a resolution of 10^{-4} g before and after wear tests, to determine weight losses. Wear rates were calculated using following equation.

$$W_a = \frac{\Delta G}{D.P.S} \quad (1)$$

In equation (1), W_a is the wear rate (mm^3/Nm); ΔG is the weight loss (g); P is the load (N); S is the sliding distance (m) and D is the density (g/cm^3). SEM analyses were carried out to examine the effects of wear on the worn surfaces.

RESULTS AND DISCUSSIONS

Density and Porosity

The relative densities of the nanocomposites are shown in Figure 1. It was observed that with the increase in the amount of reinforcement, there was a decrease in the densities of AMnCs and an increase in the porosity values. Considering these results given in Figure 1, it is understood that the amount of reinforcement has a significant effect on the density. This is likely due to the application of MM. MM starts with cold welding of powder particles that are squeezed between two balls and/or between a ball and the container wall, as high-energy balls crash into one another and the container wall during the process. Then, powder particles undergo work hardening and in the last phase, particles are fragmented. Previous studies reported a slight increase in the powder dimension with the effect of cold-welding taking place in the first stage of the mechanical alloying process [25]. While the size of the powder particles is reduced by deformation with MM, the hardness of the powders increases with the work hardening. In a previous study, it was reported that the compressibility of powders decreased with the MM process [26]. In this case, the presence and increase in the amount of hard reinforcement particles leads further deformation by locating among the ball-powder-ball and ball-powder- container wall in the milling chamber. Thus, the hardness of the powders that undergo plastic deformation with MM increases further. Increasing the hardness of the powders reduces the compressibility by locking each other during pressing. Therefore, it can be said that the amount of reinforcement has an increasing effect on the porosity. In Al/ nano- Al_2O_3 composites produced by powder metallurgy method, due to the high hardness of nano- Al_2O_3 particles, it reduces the relative density of the composites compared to the alloy by reducing the compression capacity [16].

Microstructure

SEM images of the A356 alloy and AMnCs are given in Figure 2. The microstructure of the A356 alloy is given in Figure 2.a. In Figure 2.b, the structure was filtered and grain boundaries, pores and secondary phase particles were emphasized. Figure 2.c and Figure 2.d show the microstructures of 1 wt.% Al_2O_3 and 2wt.% Al_2O_3 nanocomposite materials, respectively. Secondary phase particles were observed in Figure 2.b (blue) and in all microstructures (light gray). The EDS results indicate that these secondary phase particles contain a high amount of silicon. Therefore, these phases are considered to be the silicon phase. In addition, the relatively high Al and O amounts in the EDS data for Figure 2.c (Point 5) and Figure 2.d (Point 4) indicate that these points may be regions with Al_2O_3 reinforcements. Besides, Figure 3 shows the nano-sized alumina particles were distributed in the microstructure. EDS analysis which was applied at 80.000x magnification level reveal that point 1 and point 2 contains considerable amount of Al and O.

Hardness

The hardness graph of AMnCs' is given in Figure 4. While the average hardness of the A356 alloy samples was 42.4 HV, the average hardness of 1 wt.% and 2 wt.% Al_2O_3 reinforced nanocomposites were measured as 61.4 HV and 54 HV, respectively. According to the hardness results, the lowest hardness was obtained in the matrix material, while the highest hardness was obtained in 1 wt.% nano- Al_2O_3 reinforced composite. While the hardness of 2 wt.% Al_2O_3 reinforced composites is higher than that of A356 alloy, it is lower than 1 wt.% Al_2O_3 reinforced composites. This increase in hardness of 1 wt.% Al_2O_3 reinforced nanocomposites can be explained by the orowan mechanism [13]. Reinforcement particles inhibit dislocation movement, causing an increase in dislocation density, thus increasing the stresses required for plastic deformation. Yildirim et al. [23] state that there are four reasons for this behavior of nano- AMCs; particle dimensions, particle shape, inter-surfaces formed between matrix/nano-particle, and agglomeration. The tendency to decrease in the hardness of 2 wt.% Al_2O_3 reinforced composites is also thought to be due to their lower relative density compared to other composites. In a previous study, it was reported that increasing the reinforcement ratio from 1-3 vol% to 5% vol% in A6061- alumina nanocomposites, the hardness decreased depending on the decrease in the relative density [19].

Wear properties

It has been observed that the weight loss values increase almost linearly with the increase of the sliding distance in A356 matrix materials and AMnCs. In Figure 5, the weight loss results of A356 alloy and A356/ Al_2O_3 nanocomposites were given. It is understood that the weight losses of A356/ Al_2O_3 nanocomposites are lower than the matrix material A356 alloy. These results show that the wear performance of AMnCs is better than the wear performance of the A356 alloy. It was observed that the reinforcement ratio had a varying effect on the average weight loss. It has been determined that there is an average weight loss of 11.7 mg in the A356 matrix alloy.

With 1 wt.% reinforcement, a significant reduction in average weight loss was obtained (7.625 g). However, when the reinforcement ratio was 2 %, this value (11.4) increased again. It is clearly seen that 2 wt.% Al_2O_3 reinforced nanocomposites are subject to higher weight loss than 1 wt.% Al_2O_3 reinforced nanocomposites. This may be due to the differences in density and hardness values. AMnC with 2 wt.% Al_2O_3 reinforcement showed higher hardness compared 1 wt.%. In addition, it is understood that the weight loss results of the 2 wt.% Al_2O_3 reinforced nanocomposites and the hardness results given in Figure 4 support each other. Significant fluctuations in wear rates are often due to variations in hardness [19]. Relatively higher porosity amounts in 2 wt.% Al_2O_3 reinforced composites may adversely affect wear performance. During the wear test, fractures may occur at the edges of the pores. Therefore, weight loss tends to increase. It was also reported that the decrease in the relative density amount in A6061/ alumina composites causes a significant decrease in hardness, which is the main reason for the upward trend in wear rate [19]. In addition, wear debris is known to play an abrasive role and increase wear [20]. It has been stated that wear resistance is related to hardness, but the relationship between wear rate and microstructure of the material is not considered [27]. It is also reported that the wear resistance of AMCs reinforced above 7wt.% by weight decreases and this is due to increased porosity, particle aggregation, interfacial properties and thermal expansion difference [21].

Figure 6 shows the friction coefficient results of aluminium alloy and nanocomposites. When the weight loss and wear rate results given in Figure 6 are correlated with the friction coefficient results, it is understood that 1 wt.% Al_2O_3 reinforced nano composites, which have the lowest weight loss and wear rate, have the lowest friction coefficient. The force generated by friction is highly dependent on the hardness of the specimen. The higher hardness of the nano-composite sample compared to the matrix alloy A356 sample causes smaller plastic deformation on the nano-composite sample surface and reduces the friction coefficient [18]. The 1 wt.% Al_2O_3 reinforced samples showed better wear performance as they were harder than the 2 wt.% Al_2O_3 samples. In other words, 1wt.% Al_2O_3 reinforced composites have lower friction coefficient values than 2 wt.% Al_2O_3 reinforced composites. This is due to the low relative densities of 2 wt.% Al_2O_3 reinforced nanocomposites. Particles detached from the porous regions during wear cannot go out of the tribological system and increase the friction coefficient. In AMCs, hard reinforcement particles expand on the material and act as a lubricating layer against abrasives. By preventing direct contact of metallic surfaces, both the coefficient of friction and wear rate are reduced [21]. In Figure 7, SEM images of worn surfaces of alloy and Al_2O_3 reinforced nanocomposites after 2000 m sliding distance are given. When the SEM images of the worn surfaces are examined, areas of ruptures, micro-cracks, delaminations, grooves and cavities can be seen during the wear test.

Worn surfaces of A356 alloy (Figure 7.a-c), A356/1 wt.% (Figure 7.d-f) and A356/2 wt.% Al_2O_3 (Figure 7.g-i) reinforced nanocomposites are shown in Figure 7 detailly. It is known that plastic deformation that occurs with cavities and grooves on the material surface is a characteristic of abrasive wear [15]. The wear with wide ruptures and cracks are thought to be the results of adhesive wear mechanism. It can be seen that ruptures and cavities are more dense especially in the A356 matrix shown in Figure 7.a, b and c. This is obviously due to the fact that the hardness of the A356 matrix alloy is lower than that of the composites. The low hardness of A356 alloys could lead adhesive wear mechanism and the ruptures and cavities were generated by adhesion. It is seen that the grooves formed parallel to the sliding directions are less on worn surfaces of 1 wt.% Al_2O_3 reinforced nanocomposites. Abrasive wear mechanism clearly shown in Figure 7.d-f with infrequent cavities, ruptures and delaminations for 1 wt.% Al_2O_3 reinforced nanocomposites. It is observed that material loss and delamination due to abrasion increase in 2 wt.% Al_2O_3 reinforced nanocomposites. Micro-pores in the material act as a trigger for the formation and growth of micro-cracks on the wear surface. Micro-cracks grow with advancing sliding distances, causing partial ruptures from the material surface. The higher porosity value of 2 wt.% Al_2O_3 reinforced nanocomposites also explains the high material loss. It has also been stated in some previous studies that plastic deformation and delamination occur with abrasive wear in SiC and alumina particle reinforced composites [28,29]. Porosity, agglomeration and inter-facial properties could be the reasons why wear resistance decrease for AMCs with higher reinforcement ratios than a critical ratio. That critical ratio depends on the size, type and the distribution of the reinforcement in the matrix.

CONCLUSIONS

The wear performance of AMnCs produced by reinforcing nano- Al_2O_3 into A356 aluminium alloy were investigated and the general results obtained from the study are given below.

- A decrease in the relative densities of AMnCs was observed with the increase of the reinforcement ratio, while an increase in the porosity values was observed.
- In SEM microstructures and EDS examinations, it was determined that there were second phase particles containing high amount of silicon in the structure.
- While the highest hardness was obtained in 1wt.% Al_2O_3 reinforced nanocomposites, it was determined that there was a decrease in hardness when the reinforcement ratio was increased to 2 wt.%.
- The wear loss values increased proportionally with the sliding distance. In wear tests, the weight loss of A356/ Al_2O_3 composites was lower than that of the matrix material, A356 alloy. The lowest weight loss was obtained from 1wt.% Al_2O_3 reinforced nanocomposites.

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NOMENCLATURE

W_a	wear rate (mm^3/Nm)
ΔG	weight loss (g)
P	load (N)
S	sliding distance (m)
D	density (g/cm^3)

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Figure Captions List

Fig. 1	Mean relative density values of A356/alumina nanocomposites
Fig. 2	SEM images of microstructures of A356/ alumina nanocomposites; A356 alloy (a), A356 color filtered (b), A356/1 % alumina composite (c) and A356/2 % alumina composite (d)
Fig. 3	SEM image and EDS analysis of the microstructures of nanocomposites
Fig. 4	Hardness of A356 alloy and alumina reinforced nanocomposites
Fig. 5	Weight loss (a) and wear rate (b) of aluminium nanocomposites tested at different sliding distances
Fig. 6	Friction coefficients of A356 alloy and alumina reinforced nanocomposites depending on the sliding distance.
Fig. 7	SEM images of worn surfaces of A356 alloy and Al_2O_3 reinforced nanocomposites after 2000 m sliding distance a,b,c) A356 alloy, d,e,f) A356/1 wt. % alumina, g,h,i) A356/2 wt. % alumina