Dursun Özyürek*, Musa Yıldırım and İbrahim Çiftçi

The tribological properties of A356-SiC$_p$ metal-matrix composites fabricated by thixomoulding technique

Abstract: In this study, A356-SiC$_p$ metal-matrix composites were produced through thixomoulding process, and these composites were subjected to wear tests. The composites containing various volume fractions of SiC$_p$ particles (5%, 10%, 15% and 20%) as the reinforcement were produced at two different temperatures of 590°C and 600°C. The influences of processing temperatures and reinforcement ratio on the properties and wear behaviour of the composites were investigated. Prior to the wear tests, microstructural properties and hardness of the composites were determined. For the wear tests, a pin-on-disc-type wear apparatus was employed to carry out the wear tests. The wear tests were carried out at 2.0 m/s sliding speed under 15 N load and for four different sliding distances. A scanning electron microscope (SEM) was used to examine the wear mechanisms on the worn surfaces of the composites. The results indicated that sphericity rate and hardness of the composites produced at 590°C were higher than those of the composites produced at 600°C. In addition, the composites produced at 590°C exhibited lower weight loss and friction coefficient.

Keywords: Al/SiC composite; thixomoulding; tribological properties.

***Corresponding author: Dursun Özyürek**, Technology Faculty, Department of Manufacturing Engineering, Karabuk University, 78100 Karabük, Turkey, e-mail: dozyurek@karabuk.edu.tr
Musa Yıldırım: Technology Faculty, Department of Manufacturing Engineering, Karabuk University, 78100 Karabük, Turkey
İbrahim Çiftçi: Technology Faculty, Department of Manufacturing Engineering, Karabuk University, 78100 Karabük, Turkey

1 Introduction

The thixomoulding process offers several advantages when compared to the other processes such as traditional casting, forging and powder metallurgy methods [1–5]. Formation of much less porosity, lack of microsegregation, ability to carry out production at low working pressures, long service life of moulds and less energy requirements due to low forming temperatures are some of these advantages [6–8]. In the production of the materials with spherical microstructure (nondentritic) through the thixomoulding process, the semisolid processing temperature is an important parameter. Work to date has shown that the semisolid processing temperature has influence on the resulting microstructure [9].

SiC and Al_2O_3 ceramic reinforcement materials are incorporated into monolithic matrix alloys in order to improve the wear resistance of these materials [10–12]. The resulting metal-matrix composite (MMC) materials offer superior wear resistance when compared to the monolithic matrix alloys [13, 14]. The presence of hard reinforcement materials in the form of fibre, whisker and particle improves the wear resistance of MMC materials. SiC- and Al_2O_3-reinforced MMCs have the potential to be widely used in the automotive industry. Depending on the experimental conditions, sliding speed, applied load and sliding distance have influence on wear behaviour of MMC materials [15–17]. Additionally, in some studies, it is stated that the increase in the hardness of the composite materials increases the wear resistance of these materials and this, in turn, improves the wear performance [18–22]. In their study, Lee and his colleague emphasised that the amount of porosity and the reinforcement/matrix interface reactions are effective in the wear performance of MMCs [23].

Work to date has shown that the influence of thixomoulding processing temperature on wear properties of the composites has not been investigated. The aim of this study was to produce A356/SiC$_p$ MMC materials via the thixomoulding process and to examine the influences of semisolid processing temperatures and reinforcement volume fraction on the properties of the resulting MMC materials. This paper also concentrates on the influences of sliding speed on the wear performances of the MMCs.

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Pb	Al
A356	6.5	0.15	0.03	0.03	0.4	0.05	0.2	0.03	92.61

Table 1 Chemical composition of A356 alloy (wt.%).

2 Experimental procedure

2.1 Material

For the production of MMC materials through the thixomoulding process, A356 (Al-Si-Mg) alloy was chosen as the matrix material (≥ 55 μm), while SiC was chosen as the reinforcement material (≤ 34 μm). Both the matrix and reinforcement materials were in particle form. Chemical composition of A356 matrix alloy is given in Table 1.

2.2 MMC production

Four different A356-SiC$_p$ MMCs containing four levels of SiC particles of 5, 10, 15 and 20 vol.% were produced at 590°C and 600°C. These temperatures were chosen by taking into consideration that semisolid region of A356 alloys is between 577°C and 610°C. In order to enable the homogeneous dispersion of the A356 and SiC$_p$ particles, the predetermined amount of mixtures was mixed for 30 min. After the mixing process, 1% zinc stearate was added to the mixtures, and then, the mixtures were preshaped by cold forming under 800 MPa pressure in a mould. The preshaped compacts were 12 mm in diameter and 35 mm in height. The cold formed compacts were held in the semisolid processing unit for 30 min, and then 10 kN load was applied to them for 1-min duration in order to obtain their final shape. The temperature of the semisolid processing unit was 550°C. Small specimens for microstructural examination and MSQ Plus image analyses were prepared from the produced MMCs. By doing so, their sphericity rate was determined. A Meiji brand optical microscope was used for microstructural examination. The hardness measurements (HV2) were carried out on a universal Affri hardness measuring unit. For each MMC, five hardness measurements were taken, and these were averaged. Figure 1 schematically shows the semisolid processing unit (thixomoulding processing unit) used in this study and the processing steps for MMC production. Density values of the produced MMCs were determined through Archimedes' principle.

2.3 Pin-on-disk tester and test procedure

The wear specimens (10 mm diameter and 7 mm in length) were obtained from the produced MMCs through the turning process. Prior to wear tests, the wear surfaces of the specimens were ground by 1200 grit emery paper. A pin-on-disc-type wear apparatus was used in order to determine the wear and friction behaviour of the A356-SiC$_p$ MMCs. As the counter material, an AISI 4140 steel disc hardened to 64 HRc was used. The wear tests were carried out at 15 N applied load, at 2 m/s sliding speed and for four different distances of 500, 1000, 1500 and 2000 m. An electronic scale with ±0.0001-g accuracy was used to determine the weight losses of the worn specimens. After the wear tests, the wear surfaces were examined by a scanning electron microscope (SEM).

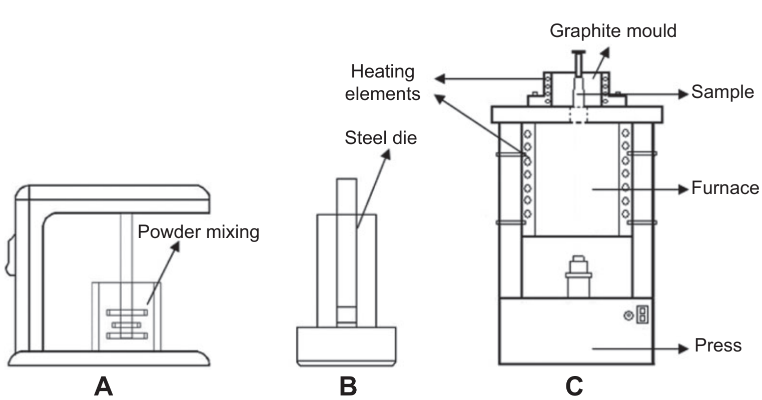

Figure 1 Schematic illustration of the thixomoulding unit used for the production of MMCs (A) the mixture of A356 alloy and SiC$_p$ powder. (B) Preshaping of powder by cold pressing, and (C) the application of the semisolid process.

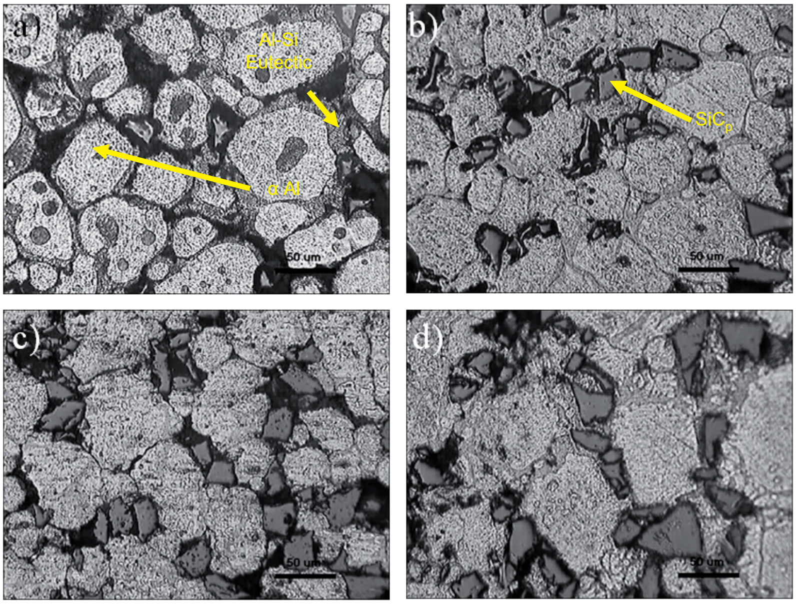

Figure 2 The optical microscope images of MMC materials reinforced with SiC_p at the rate of 590°C (a) 5%, (b) 10%, (c) 15% and (d) 20%.

3 Results and discussions

3.1 Microstructural studies

In Figure 2, optical microscope images of the four composites reinforced with 5, 10, 15 and 20 vol.% SiC_p are given. Generally, a spherical matrix alloy grain structure is seen. It is seen from all these images that SiC_p is homogenously distributed within the matrix. These particles are seen to be located mainly along the grain boundaries. However, some little porosity is also seen from these images.

As can also be seen in Figure 2, the volume fraction of SiC_p has an influence on the morphology of the matrix alloy grains. At lower fractions, the grains are seen more spherical in shape. However, the higher volume fraction of SiC_p added into the A356 matrix alloy causes a decrease in the sphericity rate of the grains. The sphericity rates and the hardness values of the A356-SiC_p MMCs materials (HV2) are given in Table 2. As the volume fraction of SiC_p increases in the MMCs, the hardness increases as well. This condition is attributed to the fact that the hardness of SiC_p is much greater than that of the matrix.

The results indicate that the MMC containing 5 vol.% SiC_p and produced at 590°C has the most spherical grains when compared to the other MMCs. As can be seen in Table 2, this MMC has a sphericity rate of 82%, while the sphericity rates of 10 and 20 vol.% SiCp added composites produced at the same temperature are 79% and 72%, respectively. Similarly, the MMCs produced at 600°C exhibit a similar trend in terms of sphericity. This decreasing sphericity with increasing SiC_p volume fraction can be attributed to the increasing viscosity due to the presence of SiC_p in Al-Si eutectic. For this reason, the sphericity rate in primary α-Al grains decreases. As can be seen in Figure 2, SiC_p particles are mainly seen in the eutectic of liquid phase (Al-Si) surrounding micro α-Al grains and in the grain boundaries (grey areas). The other point that attracts the attention is the interface that formed between the SiC_p particles and the matrix interface [23].

The results of hardness tests on the MMCs are given in Table 2. It is seen from the table that the hardness values

Samples Number	Furnace temperature (°C)	SiC Rate (Vol.%)	Hardness (HV2)	Sphericity Rate (%)	Density (g/cm³)
5% SiC	590	5	54	82	2.61
5% SiC	600	5	51	79	2.56
10% SiC	590	10	60	79	2.62
10% SiC	600	10	59	78	2.64
15% SiC	590	15	66	77	2.65
15% SiC	600	15	63	72	2.65
20% SiC	590	20	73	72	2.69
20% SiC	600	20	70	75	2.71

Table 2 The production conditions of the MMCs and hardness, sphericity and density results.

of the MMCs produced at 590°C are higher than those of the MMCs produced at 600°C. It is also seen from the table that a higher semisolid processing temperature (600°C) decreases sphericity rate, and this, in turn, leads to grain growth. That is, less spherical grains are formed at 600°C. The decrease in hardness with increasing temperature can be attributed to the grain growth with increasing temperature.

3.2 Wear tests

Weight losses of all the MMCs against the four different sliding distances are given in Figure 3. It is clearly seen from the wear curves in Figure 3A and B that the weight losses of the MMCs decrease with increasing SiC$_p$ volume fraction. However, increasing the sliding distance increases the weight losses. These results are in good agreement with the previous studies [15, 18, 19]. There is a good agreement between the hardness values given in Table 2 and the wear behaviour of the MMCs. Wear resistance of the MMCs increases depending on the increase in their hardness values. It should also be noted in Figure 3 that semisolid processing temperatures significantly affects the wear resistance. The MMCs produced at 590°C have almost twice the wear resistance of the MMCs produced at 600°C. This study reveals that semisolid processing temperature in the thixomoulding process has significant influence on wear resistance of the MMCs.

High temperatures lead to an increase in the gas absorption characteristics of the materials. This, in turn, increases the volume fraction of porosity. On the contrary, low temperatures lead to a decrease in the gas absorption characteristics. For this reason, the volume fraction of porosity decreases at low temperatures during the semisolid processing. Moreover, the Si content of the matrix

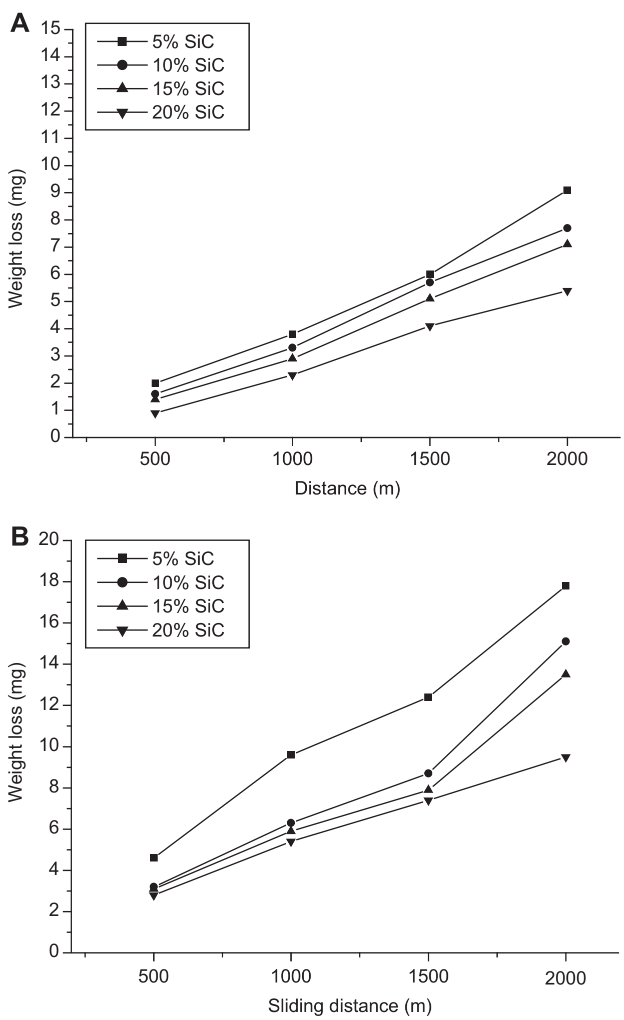

Figure 3 The weight losses of the MMCs produced at 590°C (A) and 600°C (B).

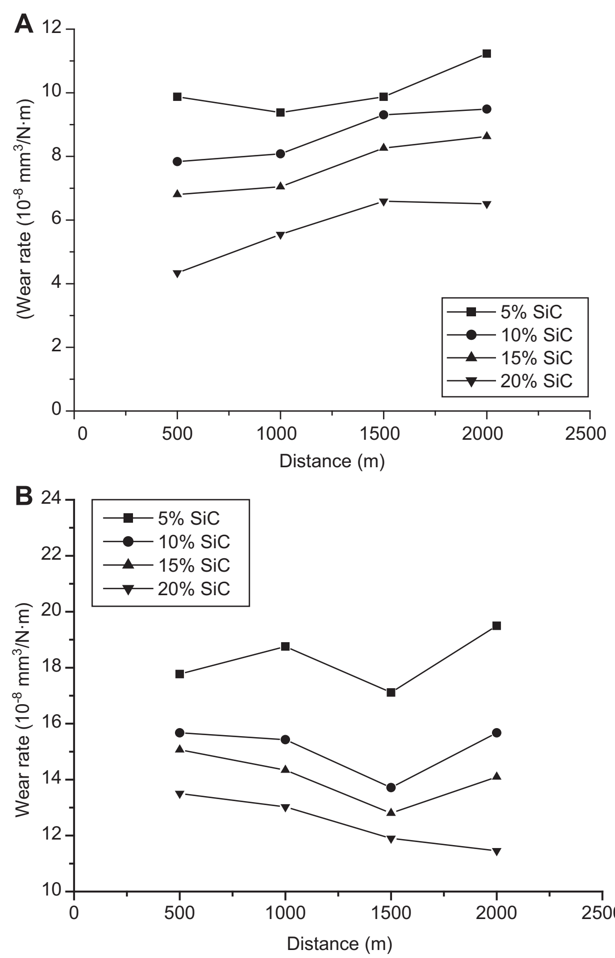

Figure 4 The wear rates of the MMCs produced at 590°C and 600°C.

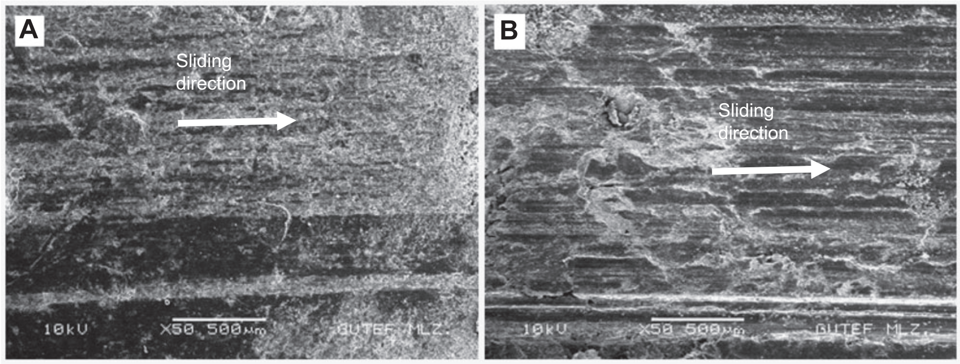

Figure 5 The wear surface SEM images of the MMCs containing 20 vol.% of SiC and produced at 590°C (A) and 600°C (B) through semisolid processing.

increases in parallel with the increasing temperature. As this increase in Si content prevents the reaction between Al and SiC_p, a good bonding cannot be effected [23]. For this reason, weight losses increase further.

In Figure 4, wear rates of the MMCs produced at 590°C and 600°C are given. As is seen in Figure 4, the wear rate also increases with increasing sliding distance. However, as the SiC_p volume fraction increases, wear rate decreases. The increase in the wear rate with increasing sliding distance is thought to be in relation with the wear mechanisms effective during the wear process. In the ceramic particle-reinforced composite materials, different wear mechanisms can be active due to the sliding speed, to the reinforcement fraction and to the load applied [15]. Shivanath et al. [24] reported the presence of oxidative and adhesive wear mechanisms for the Al-Si matrix composites. Wear rate is low in the oxidative wear mechanism that occurs during the low load applications. As the temperature of the worn surface and counter disc interface increases, a thin oxide film layer is formed on the wear surface. As this oxide film layer constantly breaks as the sliding distance and the applied increase, it increases the wear rate, too. On the other hand, a different condition is observed for the composites produced at 600°C. The wear rate, which generally depicts a decrease up to the sliding distance of 1500 m, prominently increases henceforward. This condition is believed to be in relation with the increase in the temperature, which is a significant parameter for the thixomoulding process.

Figure 5 shows the SEM images of the wear surfaces. These surfaces belong to the MMCs containing 20 vol.% SiC_p and produced at 590°C and 600°C. From these images, tracks of abrasive wear and heavy plastic deformation are seen. In the materials containing the second phase hard particles, there becomes an effective plastic deformation, which is directly proportional to the load applied and the microcracks present in the parts near the surface. The hardness of the material and the friction coefficient play an important role on the wear process. On the worn surfaces, heavy plastic deformation and the temperature increasing with the friction increases the oxidation tendency of the material. Because of this reason, it causes that the abrasive wear and delamination wear is seen as the dominant wear on the wear surfaces. Alpas and Zhang [25] indicate that the crack propagation taking place in MMCs with the wear effect gives prominence to the wear mechanism.

4 Conclusions

In this study, the tribological (friction and wear) properties of A356-SiC_p MMCs containing various volume fractions of SiC_p particles (5%, 10%, 15% and 20%) as the reinforcement were examined. The MMCs were produced through thixomoulding process at 590°C and 600°C and subjected to adhesive wear tests. The following conclusions can be drawn from the present study:

1. A uniform SiC_p particle distribution within the matrix and sound interfacial bond between the reinforcement phase and the matrix were observed.
2. The thixomoulding temperature was found to have a significant influence on the grain morphology of A356 matrix material. The sphericity rate of the MMCs produced at 600°C was found to be lower than those of the MMCs produced at 590°C.
3. The hardness values of the MMCs produced at 600°C was found to be lower than those of the MMCs produced at 590°C.
4. The MMCs produced at 600°C encountered more weight loss than the MMCs produced at 590°C.

Received March 10, 2012; accepted June 23, 2012; previously published online July 26, 2012.

References

[1] Seo PK, Kim DU, Kang CK. *J. Mater. Process. Technol.* 2005, 162–163, 570–578.
[2] Kang CK, Seo PK, Jeon YP. *J. Mater. Process. Technol.* 2005, 160, 59–69.
[3] Zoqui EJ, Paes M, Robert MH. *J. Mater. Process Technol*. 2004, 153–154, 300–306.
[4] Zoqui EJ, Shehata MT, Paes M, Kao V, Es-Sadiqi E. *Mater. Sci. Eng*. 2002, A325, 38–53.
[5] Kang CK, Son YI, Youn SW. *J. Mater. Process Technol*. 2001, 113, 251–256.
[6] Ozyurek D, Aktar N, Aztekin H. *Mater. Design*. 2008, 29, 1070–1074.
[7] Aztekin H, Ozyurek D, Cetinkaya K. *High Temp. Mat. Pr-Isr.* 2010, 29, 169–178.
[8] Ozyurek D. *Sci. Res. Essays* 2011, 6–29, 6222–6226.
[9] Dong J, Cui JZ, Le QC, Lu GM. *Mater. Sci. Eng*. 2003, A345, 234–242.
[10] Demir A, Altinkok N, Findik F. *Key Eng. Mater.* 2004, 264–268, 1079–1082.
[11] Mutlu I, Eldogan O, Findik F. *Tribol. Int.* 2006, 39, 317–325.
[12] Soy U, Demir A, Findik F. *Ind. Lubr. Tribol.* 2011, 63–65, 387–393.
[13] Ruiz-Navas EM, Fogagnolo JB, Velasco F, Ruiz Prieto JM, Froyen L. *Compos. Part A-Appl. S*. 2006, 371, 2114–2120.
[14] Son HT, Kim TS, Suryanarayana C, Chun BS. *Mater. Sci. Eng.* 2003, A348, 163–169.
[15] Deuis RL, Subramanian C, Yellup JM. *Compos. Sci. Technol.* 1997, 57, 415–435.
[16] Dogan H, Findik F, Morgul O. *Ind. Lubr. Tribol.* 2002, 54, 5–10.
[17] Dogan H, Findik F, Oztarhan A. *Ind. Lubr. Tribol.* 2003, 55, 2–3, 76–83.
[18] Suresh KR, Niranjan HB, Jebaraj PM, Chowdiah MP. *Wear* 2003, 255, 638–642.
[19] Akhlaghi F, Lajevardi A, Maghanaki HM. *J. Mater. Process. Technol*. 2004, 155–156, 1874–1880.
[20] Ozyurek D, Tekeli S. *Sci. Eng. Compos. Mater.* 2010, 17, 31–38.
[21] Ozyurek D, Tekeli S, Güral A, Meyveci A, Gürü M. *Powder Metall. Met. C.* 2010, 49, 5–6, 289–294.
[22] Ozyurek D, Ciftci I. *Sci. Eng. Compos. Mater.* 2011, 18, 1–2, 5–12.
[23] Lee JC, Seok HK, Lee HI. *Mater. Res. Bull*. 1999, 34, 35–42.
[24] Shivanath R, Sengupta PK, Eyre TS. *Foundryman* 1997, 70, 349–356.
[25] Alpas AT, Zhang J. *Mater. Sci. Eng. 1993*, A160, 25–35.