Physical Properties and Associated Tribological Performance of Stir Cast Graphite based Hybrid Al-SiCp Composites

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Abstract- This study investigates mechanical and tribological behavior of Aluminium (Al) – Silicon carbide (SiC_p) metal matrix composite and Al-SiC_p-Graphite (Gr) hybrid composite with silicon carbide particulates (SiC_p) of 10%, 15%, 20% and 5% of graphite (Gr). Composites were fabricated by stir casting process at 800 to 1000°C. The contribution of volume fraction of SiC_p and addition of Gr to physical properties such as hardness and tensile strength of MMC and HMMC is evaluated. Tribological tests were carried out in 10 N to 50 N normal load using pin-on-disk configuration. All the tribological tests were performed at room temperature in dry sliding condition with sliding velocity of 1 m/s. In order to investigate the wear mechanism associated with different tribological conditions, worn surfaces were examined using scanning electron microscopy (SEM). The result reveals that the wear rates of graphite reinforced HMMC composites is lower than that of SiC_p reinforced composites. Among the HMMCs reinforced with 15% of SiC_p show better wear resistance, hardness and tensile strength. Also increasing (15% SiC_p and 5% Gr) increases the friction coefficients.

Keywords: Metal Matrix Composites (MMC), SEM, Hybrid Metal Matrix Composite (HMMC), Wear, Tribology.

I. Introduction

Metal matrix composites (MMCs) represent a new generation of materials with considerable tailorability offering great potential for novel features, associated with significant scientific, technological and commercial importance. The reinforcements used in these composites can take the form of continuous fibres, whiskers and particles. While fibre / whiskers reinforcing facilitates more resistance to load / flexural characteristics, particles dispersed in the composite matrix enhance conduction and wear resistance. Its advantages lie in its simplicity, flexibility and applicability to large quantity production, (Hashim et al., 1999). It is also attractive, suitable for engineering application in terms of production capacity and cost efficiency (Zhou et al., 1997). Among the various types of MMCs, the aluminum matrix based composites have found wide engineering applications such as cylinder block liner, vehicle drive shafts, automotive pistons, bicycle frames and even sport kits.

Aluminium matrix hybrid composites are one of the advanced engineering materials that have been developed for weight- critical applications in the aerospace, and more recently in the automotive industries as well due to their excellent combination of high specific strength and better wear resistance [1–8]. The increasing hardness of MMC is largely due to harder reinforcement dispersed over the matrix space and also due to possible crack arresting tendency, metal matrix composite exhibits lower wear rate. The effect of reinforcements on wear of composites closely depends on the type (such as SiC and Al_2O_3) and form (particle, whisker and fibre). Hosking et al. [1] reported that, SiC_p were more effective than Al_2O_3 particles for the improvement of wear resistance of Al matrix composites due to the high hardness, apart from chemical incompatibility.

Gurcan and Baker [2] and Lee et al. [3] also stated better wear resistance of SiC_p reinforced composites than that of Al_2O_3reinforced composites. Though the wear resistance of Al/SiC_p can be enhanced, addition of solid lubricant like graphite adds to the self-lubricating capacity of the composites, which is essential in applications, where the lubrication is a constrain [3, 7]. Solid lubricant such as graphite (a layer lattice material) contained in the composite can smear on contact region and reduce the wear. However researchers have identified both experimentally and analytically that the incorporation of graphite will reduce the mechanical properties of the composites, which is undesirable for the component used in structural and high-elevated temperature applications. Hence it is imperative to balance the proportion of harder SiC_p particles and lubricating graphite. Tribological and mechanical behavior of the Al alloy reinforced with SiC_p and graphite particles have been evaluated. Details are presented in this paper. The significance of this proportion on the strength and tribological characteristics of Al alloy MMC has been evaluated.

II. Experimental Procedure

A. Materials and Fabrication

Al/SiC_p -Gr composites, 10%,15%,20% of SiC_p and 5%Gr by weight were prepared by stir casting technique. A measured amount of silicon carbide particles was preheated at around 800°C for 2 hrs to make their surfaces oxidized to achieve better weldability and also to prevent decarburization of SiC_p at high temperature. A measured amount of Aluminium alloy (ingots) was melted in an electrical furnace. Pre-heated silicon carbide particles were added to the aluminium melt. After that, the melt was stirred for 20 min at an average mixing speed of 300-400 rpm to make a vortex in order to disperse the particles uniform in the melt. The SiC_p particles and G_r are uniformly distributed in the matrix when the processing temperature is around 700°C to 800°C as a hold of 10 minutes. Higher temperature mostly leads to agglomeration of SiC_p and can even induce chemical reaction between matrix aluminium and SiC_p particles forming silicon aluminium compound. After thorough stirring, the melt was poured into steel moulds of 25 mm diameter and 100 mm length and 10mm diameter 60 mm length and allowed to cool to obtain cast rods. The cast specimen of 25mm diameter and 100mm length was used for tensile strength evaluation, while 10mm diameter, 60mm length specimen was used for tribological study using pin- on- disk setup.

B. Mechanical and Tribological Characteristics – Evaluation

The as cast MMC hybrid tensile test cylindrical specimens of 6 mm diameter cylindrical and gauge length 30mm as per ASTM B557M were axially loaded hydraulically in an universal testing machine. Tensile elongation was measured using standard extensometer. The Brinell hardness test was carried out using a Brinell hardness testing machine (MAKE: Avery).

A standard pin-on-disc test apparatus was used to evaluate the dry sliding wear characteristics of MMC Al_2O_3-10% SiC_p and hybrid composites of Al_2O_3-10% SiC_p -5%Gr, Al_2O_3-15% SiC_p -5%Gr, Al_2O_3-20% SiC_p-5%Gr as per ASTM E 1251, IS 1500 standards. Wear specimens of 8 mm diameter and 50 mm height were made from the stir cast samples, machined, and then polished. Wear tests were conducted with loads ranging from 10 to 50 N with sliding speed of 1m/s, and for a sliding distance of 600 m. All tests were conducted at room temperature. The initial weight of the specimens was measured using a single pan electronic weighing machine with an accuracy of 0.0001g. During the test, the pin was mated / slid against counterpart, EN32 steel (disc hardness 65 HRc) with a specified normal load. Friction force was measured through strain gauge dynamometer, online by a PC-based data logging system. The specific wear rate of the composite specimens was studied as a function of the volume percentage of reinforcement, sliding distance, applied load, and sliding velocity. From the wear rate the Specific wear rate is calculated according to the following equation 1.

$$K_0 = \frac{\Delta m}{L.F.\rho} \tag{1}$$

Where, Δ_m=Average weight loss (g), L=Sliding Distance (mm), F=Applied Load (N), ρ=density of the material (g/mm^3).

III. Results and Discussions

A. Observation on Tensile Strength

Figure 1 shows the tensile strength of specimen with different amounts of reinforcing SiC_p and Gr. It indicates that the tensile strength increases with increase in volume fraction from 10 to 20% SiC_p and 5%Gr in Al-matrix in the composite.

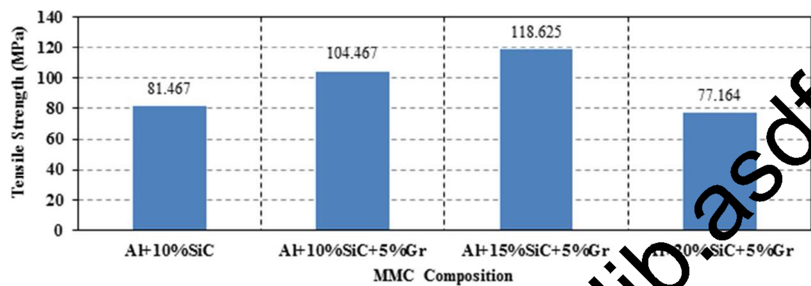


Fig. 1 Monitored Tensile strength of different amounts of reinforcing evaluations for different amounts of reinforcing SiCp and Gr

With increasing volume fraction, more load is transferred to the reinforcement which also results in a higher yield strength. This is in agreement with the work carried by Yung et al. (2004). However, with volume fraction of SiC_p increasing above 15%, a reduction in tensile strength can be seen. Due to increase in volume fraction of hard particles (SiC_p) in Al-matrix composite tends to become brittle. Also increasing volume fraction of SiC_p can result in agglomerates of reinforcement, leading to high structural heterogeneity and reduction in load capacity.

Figure 2 presents various types of tensile fracture occurring with different compositions of Al matrix composites. In the case of Al-10%SiC_p, there is slow deformation, slow propagation of deformation stress and absorption of deformation energy before fracture like many ductile materials (pure aluminum, steel etc). In this ductile fracture extensive plastic deformation (necking) takes place before fracture as observed clearly in Figure 2a. But in the case of hybrid MMC, the addition of graphite particles (self-lubrication) reduces stress concentration and crack propagation during ductile fracture which will improve the tensile strength of hybrid composite materials. It is clearly observed from the fracture of Al-10% SiC_p-5%Gr and Al-15%SiC-5%Gr tensile test specimens (Figure 2b and Figure 2c). From Figure 2d the brittle fracture of tensile specimen of Al-20% SiC_p-5%Gr can be seen.

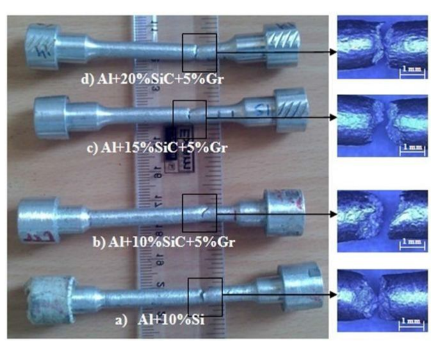


Fig. 2 Tensile tested specimen with different type of fracture

Figure 2 illustrated the response of the different MMC's to tensile loading. Normally tensile loaded specimen experiences necking, exhibits a cup-cone fracture. The addition of 10%SiC_p shows a consequent enhancement of the strength of MMC, to exhibit a fracture of quasi tensile-brittle mode of fracture (little amount of necking) Figure 2a. Addition of graphite (Al-10%SiCp-5%Gr) Figure 2b, tends to exhibit a dominant ductile fracture more appearance of cup-cone fracture. Increasing the content of SiCp leads to dominant brittle mode of fracture (2c and 2d).

B. Reinforcement Hardness of MMC

Typical monitored influence of reinforcement on hardness of aluminum matrix composites is illustrated in Figure 3. It is also seen that the hardness of the composite increases up to certain % addition (15%) of SiC_p. With higher addition it is likely that agglomerates of particulate reinforcement can occur leading to structural heterogeneity and consequent reduction in hardness. Also with higher concentration the heat partition between the matrix metal (liquid) and the reinforcement can lead to localized / discrete solidification and creation of porous structure.

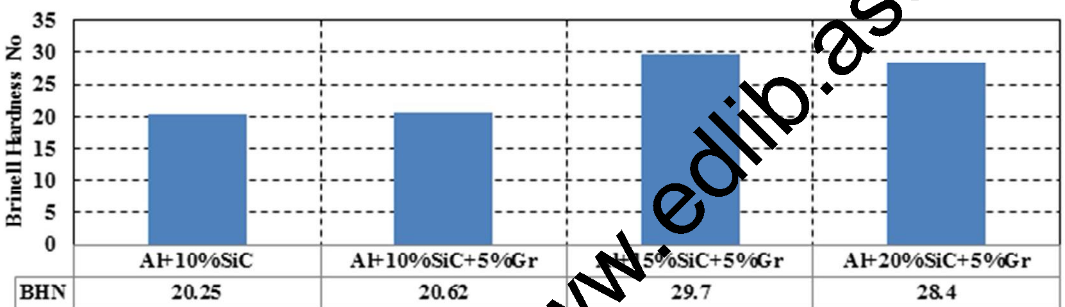


Fig. 3 Brinell hardness evaluations of MMC and Hybrid composites

C. Observation on Sliding Friction:

During the sliding wear trials, the traction force was monitored; the respective coefficient of friction was evaluated. Typical observed coefficient of friction influencing by normal load for different composites is illustrated in Figure 4.

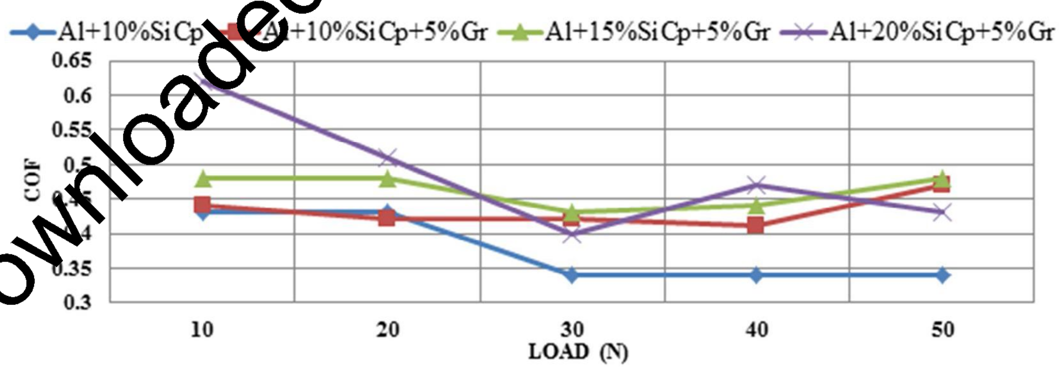


Fig. 4 COF evaluated for different amounts of reinforcing SiCp and Gr at different wear load

It is seen that all the composited exhibit relatively higher coefficient of friction with low load; this is attribute to possible plowing and smearing of aluminum matrix on the composite surface. With the increasing load, the sliding is more stable, associated with the observed reduction in coefficient of friction. With increasing load especially above 30N the coefficient of friction sets in owing to possible influence of graphite forming a solid lubrication film. Stir casting of Al-SiC_p composite tends to form a compound, and eutectic – alloy of Al-Si called as Silalumin alloy. Formation of this alloy results in creation of porous site in the casting and consequent reduction in hardness experiences with higher % reinforcements.

Relative frictional characteristics of the different composite are illustrated in Figure 4. It is seen that with 10 % of SiC_p reinforcement, the composite exhibits a coefficient of friction around 0.35 with higher load and around 0.4 with smaller load. With the addition of graphite, the composite (Al+10%SiC_p+5%Gr) exhibits mostly around 0.45 over the entire traverse length. With increasing SiC_p (15%), the hybrid composite exhibits closely varying coefficient of friction (over 0.42 - 0.45). With higher SiC, the composite exhibits a scatter with the frictional response. The observed higher coefficient of friction with smaller loads (10 and 20N) in the case of Al-SiC_p(10%) composite can be attributed to plowing dominant sliding to the observed scatter in coefficient of friction and (Al-20% SiC_p-5%Gr) composite can be due to agglomerates of SiC and consequent heterogeneity and scatter in coefficient of friction.

D. Observation on Wear Characteristics

Typical monitored variation of specific wear rate with normal load for different composite is illustrated in figure.5. It is seen that all the composites exhibit a drop in specific wear rate up to 20N of loads; with higher load owing a marginal variation can be seen. The transition around 20N can be attributed to change from plowing dominant sliding to steady sliding condition. Among the composite, Al-SiC_p (15%+5%Gr) exhibits better performance. Also, it is seen that hybrid composite with 20% SiC_p exhibits best wear resistance among the entire composite; attributable to possible creation of porous sites in the cast structure could have contributed to this.

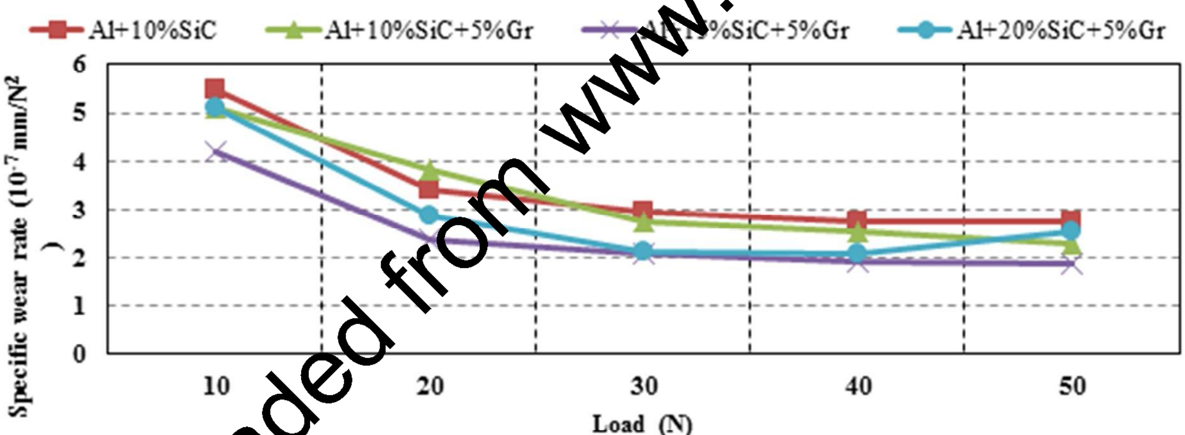
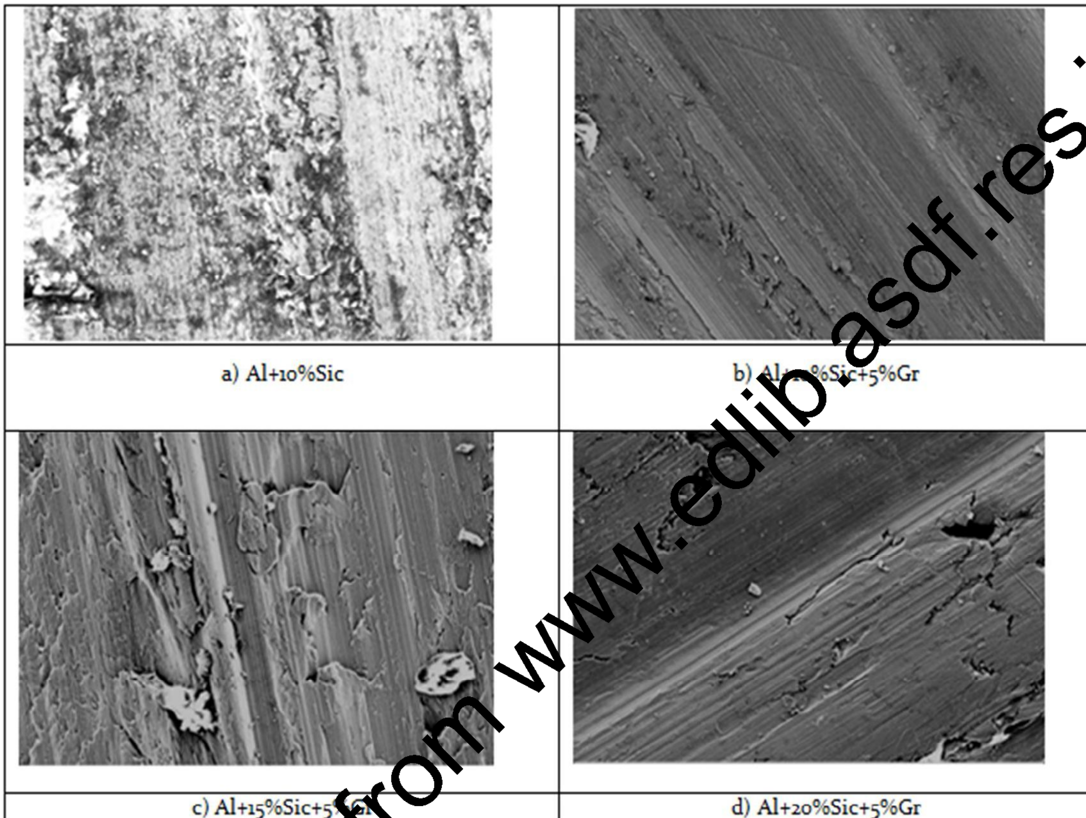


Fig. 5 Specific wear rate evaluations for different amounts of reinforcing SiCp and Gr

From the Figure 5 due to reinforcement of SiC_p and Gr the wear rate goes to a minimum as the load increases up to 50N. When the load increases (from 10N to 50N), the ploughed surface of the counter face / Disc (made of EN38 will react and form Fe_3O_4 and SiC particles will crush and form very minute particles. It is similarily observed by Raiahi et al. (2001) and Tiejum et al. (2003). The Fe_3O_4, Fe and minute fractured particles of the SiC form a layer between the work hardened pin and the counter face and reduce the wear rate up to a 50N.

E. Observation on Worn Surfaces

Figure 6 SEM images of worn surface for different amounts of reinforcing SiC_p and Gr with sliding distance 600 m, load 50 N, sliding speed 1.0 m/s. Typical micrograph of worn out composition with varying % reinforcement is illustrated in Figure 6. MMC with 10% SiC_p, exhibits a worn out surface with discrete glazed texture and pull out of material. The MMC sliding with the steel counter surface will encounter surfacial heating ($\Theta \propto p^{n1} \propto v^{n2}$ p – pressure, v – velocity) and consequent transfer of aluminium to steel surface and subsequent back transfer. However, the hybrid MMC with 5% Graphite presents a relatively smoother texture due to presence of graphite film over the interface. The relatively brighter texture of MMC, Al+15%Sic+5%Gr presenting a fairly uniform surface texture, with discrete retransferred particle is associated with least sliding wear.



a) Al+10%Sic | b) Al+10%Sic+5%Gr | c) Al+15%Sic+5%Gr | d) Al+20%Sic+5%Gr

Fig. 6 SEM of worn surface of 100KX Magnification for different amounts of reinforcing SiCp and Gr with sliding

The hybrid composite containing higher % of SiCp (20%) exhibits a worn out surface, with discrete glazed texture and pull out of material. This is associated with marginally higher order wear Figure 6a large amount of plastic deformations can be seen. Micrograph exhibits partially glazed texture with localized / discrete pull out of material. Figure 6b relatively smoother texture, due to formation of graphite on the surface can be seen. (Al-10%SiCp5%Gr). Figure 6c Increased SiC_p reinforcement 15% surface illustrates uniform texture associated with material flow over the surface; crest flattened, wear track can be seen. Figure 6d Discrete pull out of material, with surface crack can be seen. Relating roughness texture (compared to (15%SiCp5%Gr) can be seen. MMC up to 15%SiC_p and 5%Gr exhibits best performance components. The worn out surface presents a typical texture due to adhesion wear. In this absence of graphite, adhesion wear results in partially glazer texture. Addition of graphite, results in relatively small crest flattened texture for (Al-10%SiCp-5%Gr).

IV. Conclusion

From the study on physical properties and tribological response of stir cast Al-SiC_p composite, the following conclusions are drawn: Addition of Graphite to the Al-SiC_p composite enhances the tensile SiC_p composite by above 25%. Increases SiC_p content (from 10% - 15%) enhances the strength only by above 10%. Beyond 15% SiC_p content, the MMC experiences appreciable loss of tensile strength. This is reflected in the mode of change in fracture of tensile test specimen with increasing SiC_p content. With increasing content of SiC_p, the MMC exhibits enhancement in hardness. The addition of graphite does not contribute the hardness. A marginal reduction in hardness observed with MMC by high % SiCp is attributable to the formation of Silalumin alloy and consequent increases porosity. Both Al-SiC_p (10%) composite and Al-20%SiC_p-5% Graphite composite exhibit a wide variation in coefficient of friction stiffness by normal load. Composites Al-SiC_p <10% - 15%) with 5% Graphite exhibits a close variables of coefficient of friction with change in normal load. All the composites exhibit a plowing dominant sliding up to normal load of 20N, followed by an setting in trend. Among the composites Al-20% SiC_p-5%Graphite composite exhibits least sliding wear, despite a marginal drop in hardness of the composite. Presence of partial glazed texture and discrete material pull-out indicating dominant adhesion mode of wear.

References

1. Hosking, F.M., Portillo, F. F., Wonderlin, R., Mehrabian, R., "Composites of aluminium alloys: fabrication and wear behaviour", J Mater Sci, 17 (1982), 477–98.
2. Gurcan AB, Baker TN. Wear behaviour of AA 6061 aluminium alloy and its composites. Wear 1995; 188:185–91.
3. Lee CS, Kim YH, Han KS, Lim T. Wear behaviour of aluminium matrix composite materials. J Mater Sci 1992; 27:793–800.
4. Zongyi M, Jing B, Yuxiong L, et al. Abrasive wear of discontinuous SiC reinforced aluminum alloy composites. Wear 1991;148:287–93.
5. Park HC. Wear behaviour of hybrid metal matrix composite materials. ScriptaMetall Mater 1992;27:465–70.
6. Song JJ, Bong HD, Han KS. Characterization of mechanical and wear properties of Al/Al 2 O 3 /C hybrid metal matrix composites. ScriptaMetall Mater 1995;33:1307–13.
7. Ted Guo ML, Tsao C-YA.Tribologicalbehaviour of self-lubricating aluminium/SiC/graphite hybrid composites synthesized by the semi-solid powder-densification method. Composites Sci Tech 2000;60: 65–74.
8. Riahi AR, Alpas AT. The role of tribo-layers on the sliding wear behaviour of graphitic aluminum matrix composites. Wear 2001;251:1396–407.
9. Kocer T. Investigation of wear behaviour of Al 2 O 3 and SiC reinforced Al–Mg metal matrix composites produced by pressure infiltration technique, MS thesis, Istanbul Technical University (in Turkish); 2002.
10. Candan E, Ahlatci H, Cimenog H. Abrasive wear behaviour of Al- SiC composites produced by pressure infiltration technique. Wear 2001;247:133–8.
11. Ahlatci H. The effect of reinforcing particle size and matrix composition on the mechanical properties and wear behaviours of aluminium-silicon carbide composites, PhD thesis, Istanbul Technical University; June 2003.
12. Voort GFV. Metallography: principles and practice. Ohio: ASM International; 1999.
13. Hashim J, Looney L, Hashmi MSJ. The wettability of SiCparticlesby molten aluminium alloy. J Mater Processing Tech 2001;119:324–8.
14. Shorowordi KM, Laoui T, Haseeb ASMA, et al. Microstructure and interface characteristics of B 4 C, SiC and Al 2 O 3 reinforced Al matrix composites: a comparative study. J Mater Processing Tech 2003;142: 738–43.
15. Candan E, Attkinson HV, Jones H. Effect of alloying additions on threshold pressure for infiltration and porosity of aluminium-based melt infiltrated silicon carbide powder compacts. Key Eng Mater 1997;127:463–70.
16. Narciso J, Alonso A, Pamies A, et al. Wettability of binary and ternary alloys of the system Al–Si–Mg with SiC particulates. ScriptaMetall Mater 1994;31:1495–500.
17. Oh SY, Cornie J, Russel KC. Wettability of ceramic particulates with liquid aluminium alloys: part I experimental techniques. Metall Trans A 1989;20:527–32.

18. Yang M, Scott YD. Microstructural studies of aluminium silicon alloy reinforced with alumina fibers. J Mater Sci 1991;26:2245–54.
19. Liu MY, Kang SB, Kim HW. The complex microstructures in an as- cast Al–Mg–Si alloy. Mater Lett 1999;41:267–72.
20. Ahlatci H, Karakas ¸ MS, Candan E, Cimenoglu H. Effect of magnesium addition on wear behaviour of Al-70 vol. % Al 2 O 3p Composites. Mater Sci Tech 2003;19:949–54.
21. Rohatgi P, Cast metal matrix composites, ASM Handbook, 15, 840– 854, USA, 1992. ISBN, 0-87170-0.077 [22] Roy S. Synthesis of cast metal matrix particulate composites. J Mater Sci 1993;28:5397–413.
22. Raiahi, A. R., Alpas, A. T. The Role of Tribo-Layer on the Sliding Wear Behaviour of Graphitic Aluminium Matrix Composites *Wear* 251 2001: pp. 1396 – 1401.
23. Tiejum, Hideki Yamaura, Donald Koss, A., Robert Voigt, C. Dry Sliding Wear Behaviour of SiC Reinforced Al MMCs *Material Science and Engineering A* 360 2003: pp. 116 – 125.
24. Hashim, J., L. Looney, M.S.J. Hashmi, 1999. Metal matrix composites: production by the stir casting method, Journal of materials processing technology, Elsevier B.V., Netherlands, Volume92-93, pp. 1-7.
25. Zhou, W., and Z. M. Xu, 1997. Casting of SiC reinforced metal matrix composites. Journal of material processing technology, Elsevier B.V., Netherlands, Volume63, pp.358-363.