JMEPEG (2003) 12:390-397

Tensile and Wear Properties of Rolled Al5Mg-Al_2O_3 or C Particulate Composites

A. Daoud, T. El-Bitar, and A. Abd El-Azim

(Submitted 20 June 2001; in revised form 25 March 2003)

Al5Mg alloy matrix composites reinforced with different percentages of Al_2O_3 (60 μm) or C (90 μm) particulates were prepared by the vortex method. The composites were then subjected to hot or cold rolling with different reduction ratios. The microstructures of the rolled composites revealed that the matrix grains moved around the particulate causing deformation. By continuing deformation, the particulates rearranged themselves in the matrix, leading to lensoid distortion. It was found that the addition of Al_2O_3 or C particulates increased the 0.2% proof stress and reduced both the tensile strength and ductility, compared with the monolithic alloy. Scanning electron microscopy (SEM) fractographic examinations showed that the composites reinforced with Al_2O_3 particulates failed through particulate fracture and matrix ligament rupture. However, the failure of the composites reinforced with C particulates was through particulate decohesion, followed by ductile failure of the matrix. Abrasive wear results showed that the wear rate of the Al5Mg alloy decreased with the addition of C particulates. However, increasing the volume fraction of C particulates did not have a prominent effect on the wear rate. The composites reinforced with Al_2O_3 particulates exhibited a higher wear rate than that of the unreinforced alloy. Furthermore, addition of both C and Al_2O_3 particulates into the Al5Mg matrix alloy did not significantly improve the wear resistance. For all composites studied in this work, hot or cold rolling had a marginal effect on the wear results.

Keywords Al5Mg alloy, Al_2O_3 particulates, C particulates, composites, particulate decohesion, particulate fracture, rolling, vortex method

1. Introduction

Aluminum-based alloys are widely used in applications where weight savings are important. The relatively poor seizure wear resistance of aluminum alloys has limited their uses in certain tribological environments. Seizure and wear resistance in aluminum alloys could be substantially improved by incorporating a dispersion of C or hard ceramic particulates (e.g., Al_2O_3, SiC, and ZrO_2).[1,2] Moreover, composites can offer significantly increased modulus of elasticity, strength, and decreased thermal expansion. In addition, the near-isotropic properties of these composites allow them to be processed through the same conventional routes that are applied to the unreinforced alloys.[3-5]

Although several processing methods have been developed to produce MMC[5-7] such as powder metallurgy and spray deposition, casting is the cost-effective one. The composites fabricated by casting processes have already been introduced to applications such as automobile, engine components, and satellite components.[8] In spite of that, cast aluminum alloy composites have serious problems for practical applications. The tensile ductility and fracture toughness at room temperature of composites are significantly poor and their relatively high content of ceramic particulates make them too hard. These problems encourage the establishment of post fabrication processes such as extrusion and rolling, which can efficiently produce engineering aluminum alloy composite components. Harrigan et al.[9] studied the effects of hot rolling on the mechanical properties of 6061 aluminum alloy reinforced with 15-30 vol.% SiC particulates. They reported improved mechanical properties after reduction in thickness by rolling. This was attributed to better particulate distribution and uniformity of the rolled microstructure. However, the microstructural response of these materials to such processes, whether at room or elevated temperatures, has not been widely studied.

Some of particulates reinforced aluminum alloys are used for application where they are subjected to material wear. Such applications include pistons and cylinder linears in car engines, automotive brake rotors, and other wear resistance parts. In many of these applications, the composites may be exposed to the action of hard abrasive particulates. Abrasive wear has been traditionally thought of as a wear process that is caused by mineral particulates or rock surfaces that cut into a wear metal surface, and it has been considered up to recently to be totally different from the adhesive wear of sliding system. However, several studies indicate that the mechanisms that control abrasion are also operating in other types of wear, and vice versa.[10-14] Abrasion wear becomes sliding wear for all these conditions under which the contacting hard asperities are unable to indent the surface to such an extent that substantial removal of material takes place.[11] The benefits of adding soft or hard particulates into aluminum alloy in reducing the abrasive wear rate can be usefully described by a relative wear resistance, defined as the wear rate of the unreinforced matrix divided by that of the composite under the same conditions. Values of the relative wear resistance reported for composites based on aluminum alloys are varied from 1.1-10. Wang and Huchings[15] showed that in coarse abrasive particles there is an

---

A. Daoud, T. El-Bitar, and **A. Abd El-Azim,** Central Metallurgical R&D Institute (CMRDI), P.O. Box 87, Helwan, Cairo, Egypt. Contact e-mail: rucmrdi@rusys.eg.net.

optimal reinforcement content and a higher volume fraction resulting in decreased abrasive wear resistance. It has been clearly shown that the effect of reinforcements depends on material and system parameters such as load, abrasive particulate size, type, and size and volume percent of the reinforcement and matrix hardness.[16-19] Depending upon whether soft or hard particulates are used as reinforcements, the abrasive wear behavior of the composites has been found to be widely different. Clearly, under some circumstances, reinforcing phases lead to a strong increase in the abrasive wear resistance, while under other conditions the reinforcement has a low or even negative effect. Therefore, it can be concluded that no consistent abrasive wear behavior of the composites has been established to date.

The aim of this study was to prepare Al5Mg alloy reinforced with different percentages of C or Al_2O_3 particulates. Particular emphasis was placed to study the effect of hot or cold rolling on the composite microstructure, tensile properties, as well as fracture mechanisms. Moreover, the effect of incorporating soft (C) or hard (Al_2O_3) particulates into Al 5 Mg on the abrasive wear behavior was closely examined.

2. Experimental Procedure

Composites based on an Al5Mg alloy containing different percentages of Al_2O_3 (60 μm) or C (80 μm) particulates were processed via molten metal mixing route. The particulates were chemically activated before adding them into the molten aluminum alloy to improve the wetting between them and the molten alloy. After incorporation of the particulates into molten metal, the materials were cast into cast iron molds preheated at 200 °C. The size of the cast billets was 20 × 40 × 200 mm. The cast specimens were homogenized at 420 °C for 1 h and then hot rolled at the same temperature by the several passes technique up to a reduction ratio of 20%. Other specimens were subjected to cold rolling on several passes up to a reduction ratio of 20%. Both hot and cold rolled billets were annealed at 420 °C for 1 h after each pass.

Metallographic specimens of both hot and cold rolled composites were prepared for microstructural observation by grinding up to 600 grits with SiC abrasive paper and then consecutively polishing by diamond pastes of sizes 30, 2, and 0.1 μm. The polished surface was etched with 10% NaOH solution and examined by using an optical microscope. The volume fraction of the particulates was determined by a point counting technique.

Cylindrical tensile test specimens were machined from the rolled billets in the rolling direction in accordance with DIN 50125 (round short specimen with 4.0 mm diameter). The tensile tests were carried out at room temperature using a servo-hydraulic universal test machine with 10 mm/min cross head machine speed in accordance with DIN 50145. The fracture surfaces were examined by a Jeol 5410 (JEOL, Tokyo, Japan) scanning electron microscope (SEM).

Abrasive wear tests were preformed using a pin-on-ring apparatus. The tests involved abrading pin specimens, which were made from Al5Mg reinforced with Al_2O_3 or C as well as unreinforced alloy, against a rotating mullite ring (3 Al_2O_3.2SiC) of 390 mm in diameter. The pins were 10 mm in diameter and 30 mm in length. During testing, the flat end of the pin was pressed against the rotated mullite disc under a load of 480 N. The speed of the disc was 25 r.p.m. The pins were abraded against the mullite ring at a constant speed of 0.5 m/s for a distance of 61.2 m under dry conditions. Before and after testing, the weight of the pin was measured to an accuracy of 10^{-4} g to determine the weight loss. After testing, the abraded surfaces of the pins and wear debris were studied by using SEM. The abraded surface was coated with a thin layer of carbon before examination by SEM.

3. Results and Discussion

3.1 Microstructure

Representative optical micrographs of the rolled Al5Mg matrix and composites are shown in Fig. 1. It can be seen that the presence of the particulates in the matrix alloy affects the matrix grain size. The composite grains are finer than those of the monolithic alloy. This refinement is caused by the accu-

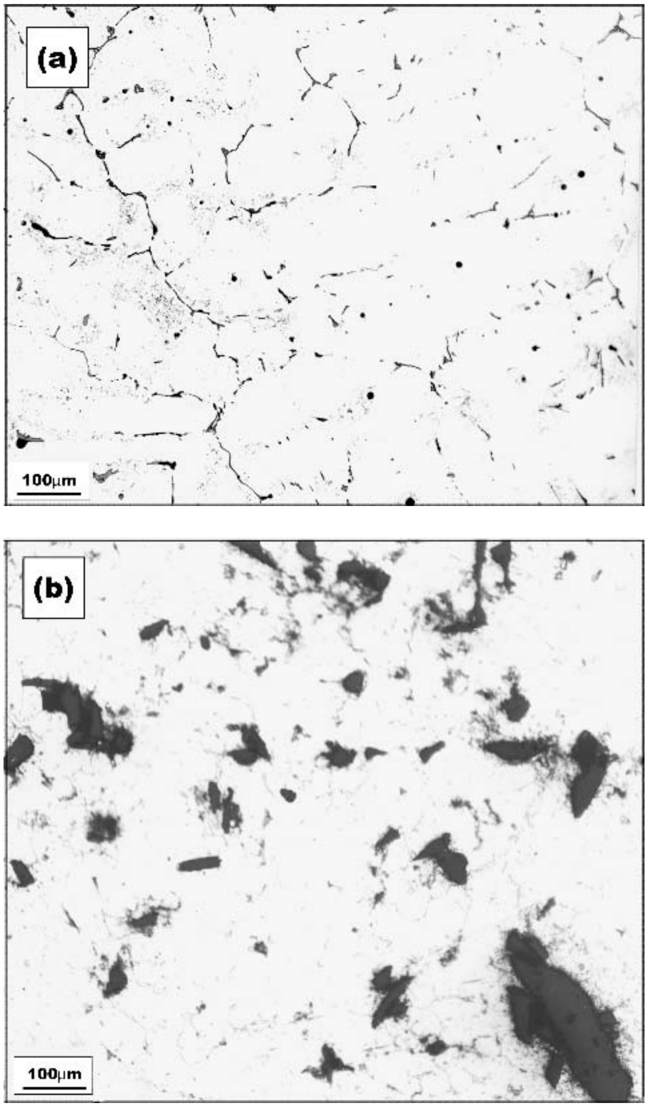

Fig. 1 Microstructures of hot rolled Al5Mg matrix alloy and composites

mulation of the particulates in the liquid between the growing solidification fronts, which would inhibit continued grain coarsening. Furthermore, the composite has a lower value of latent heat per unit volume due to the presence of solid (Al_2O_3 or C) particulates compared with the matrix alloy, leading to a higher cooling rate during solidification and consequently finer grains.

Although the rolling process improved the distribution of either Al_2O_3 or C, there is still local clustering of the particulates. This inhomogeneity is due to pushing of the particulates into the last solidified regions by the solidification fronts. Note that the particulates having a high aspect ratio were partially aligned in the rolling direction and the matrix material is observed to flow around them. Al_2O_3 particulates are harder and more brittle than C particulates. Consequently, the matrix grains of Al_2O_3 composites were able to move freely during the rolling process around the particulates in a wave-like motion, forming a linsoid structure. However, C particulates can deform plastically and strangle during the rolling process (Fig. 2).

3.2 Tensile Properties

The results of tensile tests of hot and cold rolled Al5Mg alloy reinforced with different volume fractions of Al_2O_3 or C are shown in Fig. 3(a-c). It can be noticed that the addition of either Al_2O_3 or C particulates into the matrix alloy increases the yield strength. This increase in the yield strength of the composites over the monolithic alloy can be related to two strengthening mechanism groups. The first one is due to direct effects of the particulates: the transfer of stress from matrix to the particulate, the interaction between individual dislocations and the particulates, and the difference in texture between the composites and matrix material. The second mechanism group includes the indirect effects of the particulates such as the grain size strengthening mechanism due to grain refinement (shown previously in Fig. 1), high initial work hardening rate of composites,[20] the generation of a high dislocation density in the matrix due to differences in thermal expansion between metal matrix and the particulates, geometrical constraints,[21] and plastic deformation during rolling. However, the ultimate tensile strength (UTS) and elongation of the composites are lower compared with those of the matrix alloy. Meanwhile, hot rolled composites show slightly higher tensile properties than those of the cold rolled. The reason for the lower UTS of the composites in comparison with that of the unreinforced can be explained as follows: the composites matrix does not have sufficient internal ductility to distribute the very highly localized internal stresses. As a result, the composite failed before being able to reach stable flow and normal UTS. Moreover, the presence of the particulates, especially Al_2O_3, restrict the plastic flow of the matrix, initiating failure at lower strains by the formation of

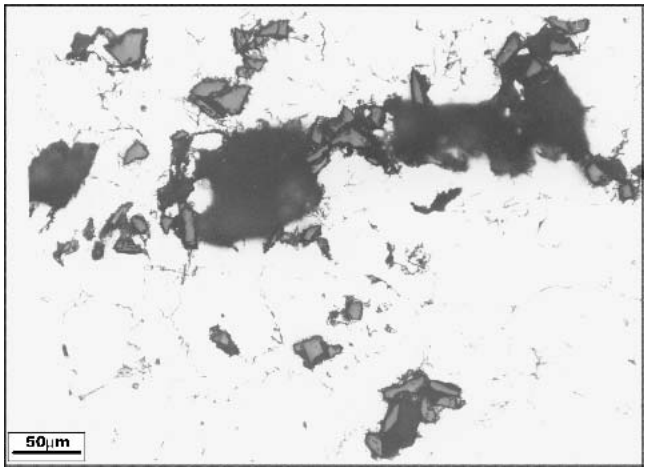

Fig. 2 Deformed C particulate during hot rolling

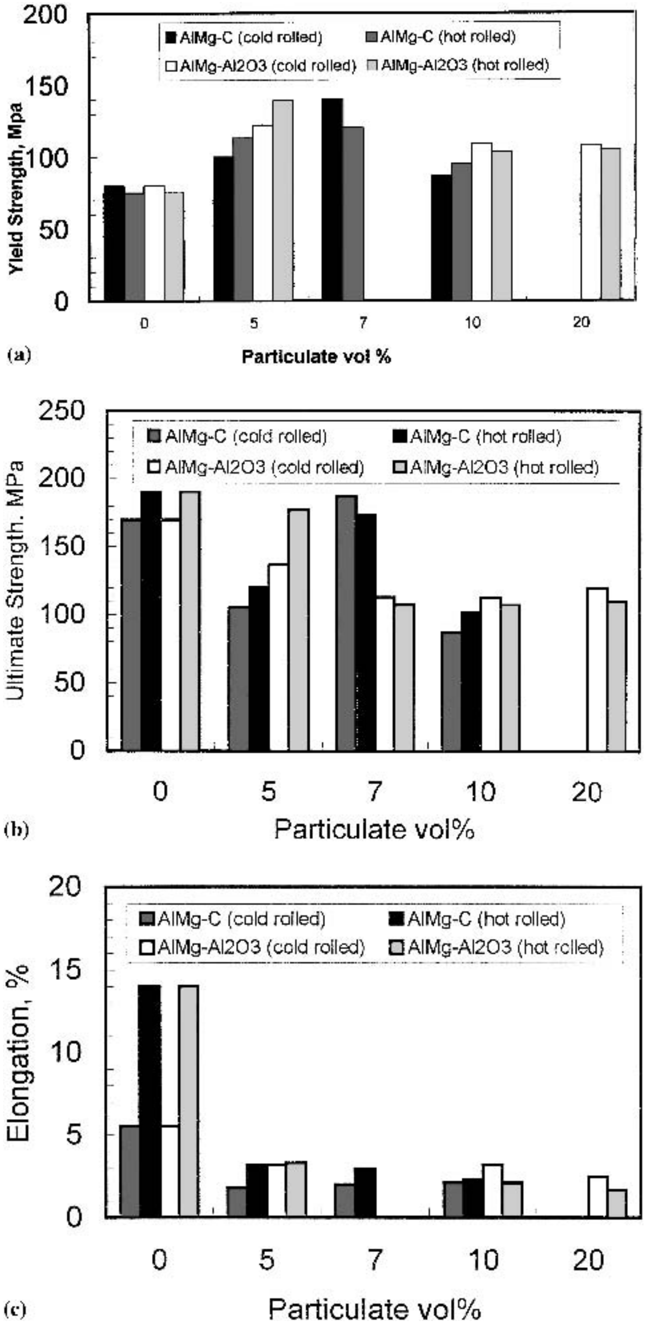

Fig. 3 (**a**) yield strength of rolled matrix and composites; (**b**) ultimate strength of rolled matrix and composites; (**c**) elongation % of rolled matrix and composites

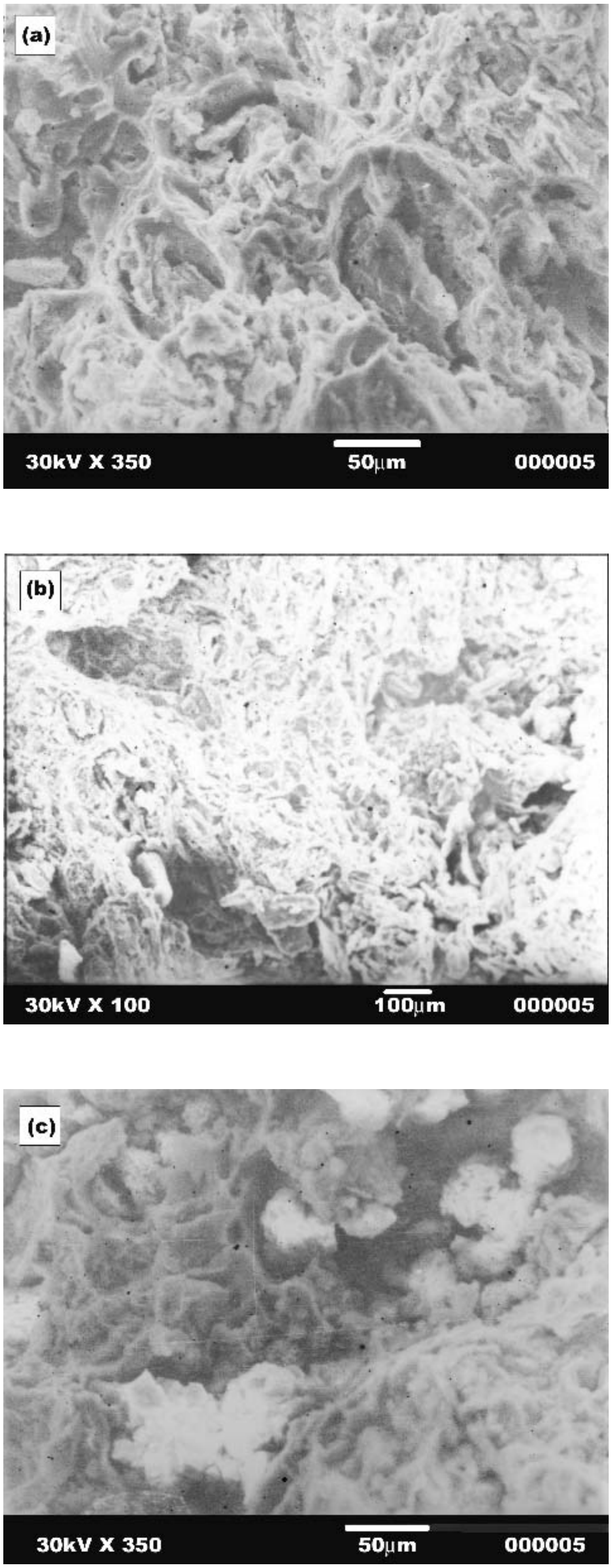

Fig. 4 SEM micrographs of fractured surface of matrix alloy and composites: **(a)** Al5Mg alloy, **(b)** Al5Mg-7 vol.% C composite, **(c)** Al5Mg-10 vol.% Al_2O_3 composite

cavities near the particulates. For the same volume fraction of particulates, the composites reinforced with Al_2O_3 exhibit higher UTS and yield strength in comparison with the composites reinforced with the C particulates due to the higher strength of the Al_2O_3 particulates. Meanwhile, hot rolled composites show higher tensile properties than the cold rolled ones. This may be due to large elastic stresses during cold rolling, which accumulate in the particulate as a result of the incompatibility between the particulate and deforming matrix. These stresses may lead to particulate fracture and consequently lower mechanical properties.

3.3 Fractography

SEM micrographs of the fractured matrix alloy and composites are shown in Fig. 4. It can be seen that the fracture

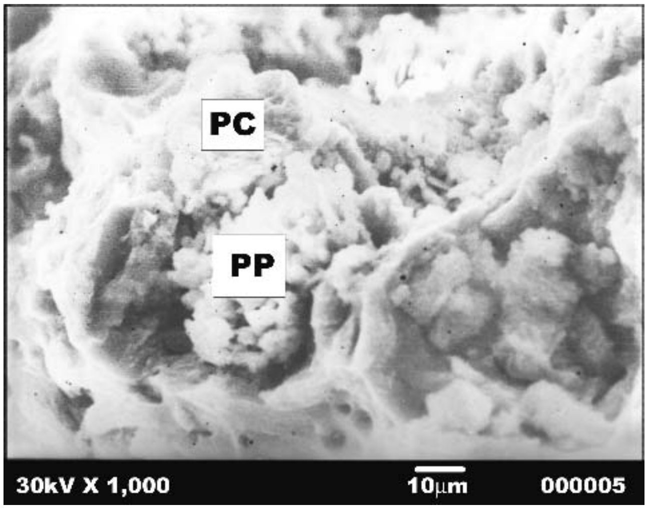

Fig. 5 SEM micrograph of Al_2O_3 particulate covered with metallic matrix, (X350)

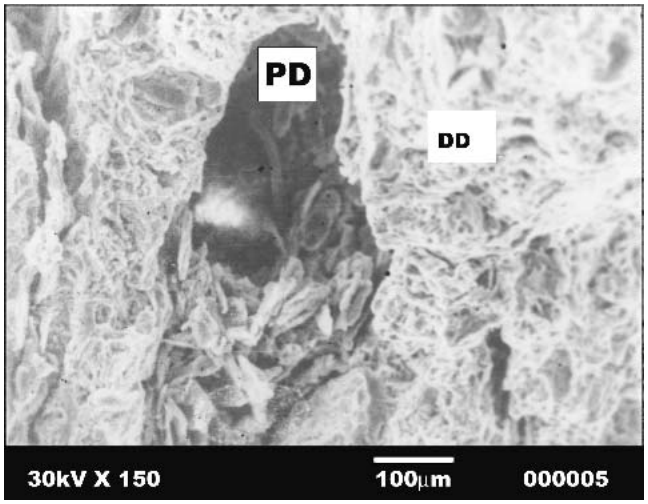

Fig. 6 SEM micrograph of Al5Mg-C composite fracture surface with dimple rupture associated with ductile failure of the matrix

surface of the matrix alloy consists of fine dimples, revealing ductile fracture of the matrix. However, the fracture surface of the composites reinforced with Al_2O_3 particulates essentially consists of a bimodal distribution of dimples. The large size dimples are associated with the particulates and small dimples are associated with ductile fracture of the matrix. In most cases, the large dimples contain Al_2O_3 particulates and are formed with a size relative to the particulates responsible for their formation. In addition, some of the Al_2O_3 particulates are covered with metallic matrix (marked as PC) (Fig. 5).

The micrograph of the particulate surface in Fig. 5 shows planer particulate surfaces (marked as PP) indicating that this portion of the particulate was cut. This demonstrates that high interfacial strengths are being dominated in these composites, which is also evidenced by the torn-off matrix left on the interface. In such cases, the composites failed through particulate fracture and matrix ligament rupture.

Contrarily, the fracture surface of composites reinforced with C predominantly exhibits dimple rupture (marked as DD) associated with ductile failure of the matrix and debonding at the particulate/matrix interface (marked as PD) (Fig. 6). Tearing of the particulates is quite uncommon, signifying that the interface between C particulate and matrix is not strong. This means that the failure of the composites reinforced with C particulates was through particulate decohesion, followed by ductile failure of the matrix.

3.4 Wear Properties

The relationship between the wear rate (weight loss divided by the sliding distance) of Al5Mg-Al_2O_3 or Al5Mg-C particulate composites and the volume fraction of particulates is shown in Fig. 7(a-c). The results show that the wear rate of the Al5Mg alloy decreases with the addition of C particulates. But, increasing the volume fraction of C particulates does not have a prominent effect on the wear rate because the wear rate of the composite with 10 vol.% C is slightly higher that that of 7 vol.% C (Fig. 7a). However, the composites reinforced with Al_2O_3 particulates exhibit higher wear rate than that of the unreinforced alloy (Fig. 7b). Addition of 5 vol.% C and 10 vol.% Al_2O_3 into the matrix alloy does not significantly improve the wear resistance. For all composites studied in this work, either hot or cold rolling has a marginal effect on the wear results (Fig. 7c).

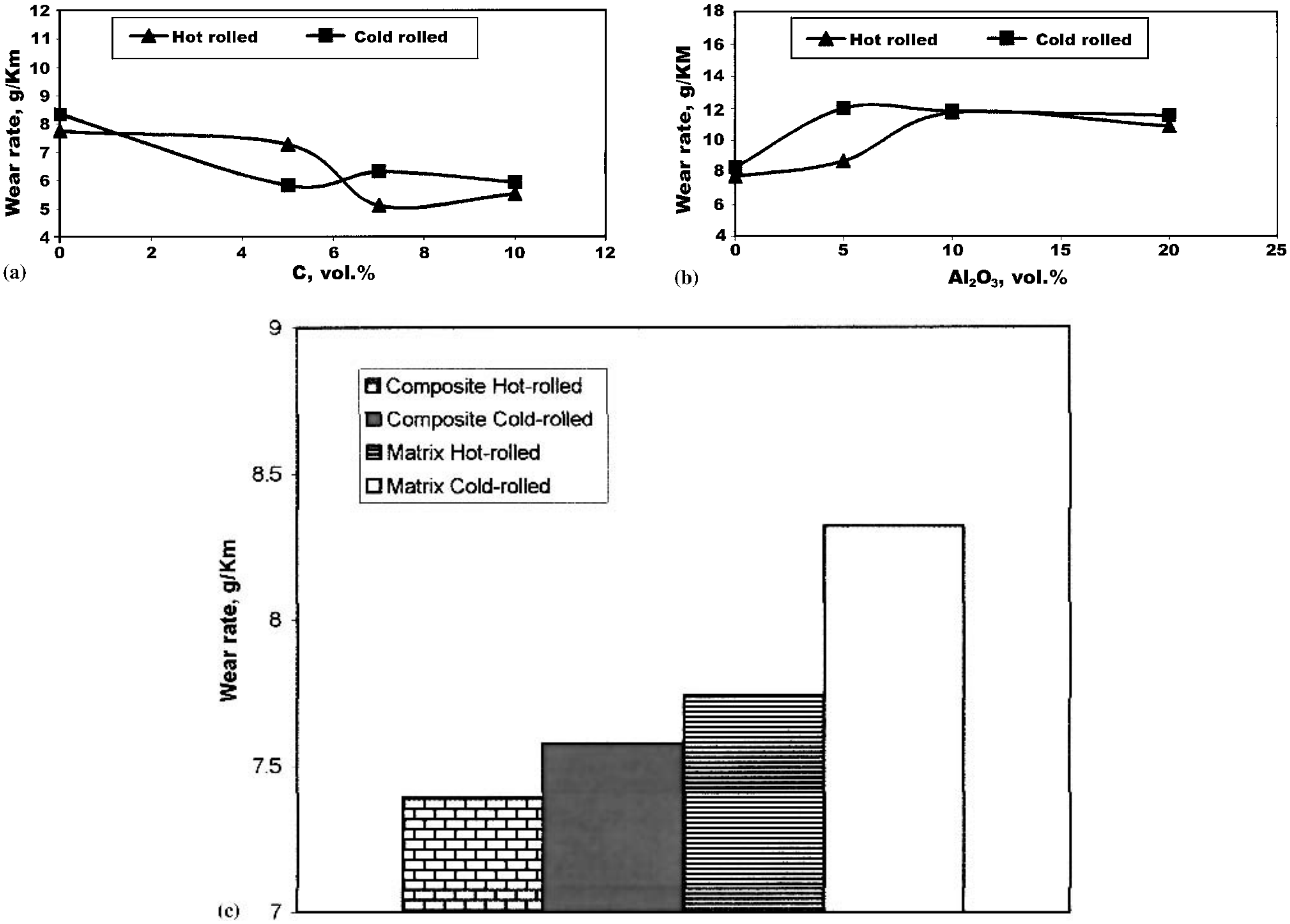

Fig. 7 **(a)** wear rate as a function of C vol.% of Al5Mg-C composites; **(b)** wear rate as a function of Al_2O_3 vol.% of Al_5Mg-Al_2O_3 composites; **(c)** wear rate of cold or hot matrix and Al5Mg-7C vol.% = +10 vol.% Al_2O_3 composite

The results of SEM examinations of the worn surfaces of the composites and matrix alloy are shown in Fig. 8(a-c). The micrograph of the Al5Mg matrix alloy (Fig. 8a) shows that the worn surface is characterized by long continuous grooves (marked as LOG), which form as a mullite slider plough across the surface removing or pushing material into ridges along sides of the grooves. An extensive plastic deformation and obvious evidence of cutting and smearing can be noted. In the case of Al5Mg-Al_2O_3 composites, the abraded surfaces appear much rougher, with grooves and numerous signs of the fracture of the Al_2O_3 particulates (marked as FP) on the surface as shown in Fig. 8(c). However, the severity of microploughing is substantially less marked on the worn surface of the Al5Mg-C composites in comparison with that of the unreinforced alloy or Al5Mg-Al_2O_3 composites (Fig. 8b). The surface of the mullite slider was smeared with a thin layer of C. Also, the worn surface of the Al5Mg-C composite was covered almost entirely with a layer of C fragment film. The wear tracks of the Al5Mg-C composites exhibit a relatively smooth worn surface in comparison with that of the unreinforced alloy.

The wear debris of the unreinforced matrix and Al5Mg-Al_2O_3 composites were blocklike and exhibited very obvious shear bands (marked as SB; Fig. 9a,b). However, the wear debris of the Al5Mg-C composites revealed less noticeable shear bands and the debris was an aggregate consisting of small pieces (Fig. 9c).

The conditions of abrasive wear are classified as either low stress or high stress abrasion: these terms are usually used to denote the extent to which the reinforcing particulates fracture under the applied load. Under conditions of low stress abrasion, the composites are usually found to provide appreciably better wear resistance than that of the unreinforced matrix alloy. In the present Al5Mg-Al_2O_3 composites, the extent of fracture of Al_2O_3 particulates is increased as the applied load in the abrasion test is raised. Hence, the lower wear resistance of the composites containing Al_2O_3 particulates in comparison with the matrix alloy can be attributed to the fracture of the Al_2O_3 under high load used in the present investigation. The broken Al_2O_3 particulates are entrapped between the composite pin and the SiC, and act as abrasive particulates. However, the Al5Mg-C composite pins were covered by a C film. The origin of the carbon film can be attributed to the fracture and pull out of C from the composite pins. Also, the mullite ring was smeared with C film, which transferred from the composite pin to the mullite ring. Once the C film is established on the SiC mullite ring and composite pin, the wear resistance is improved due to the lubrication effect of the C.

In abrasive wear because the unreinforced matrix alloy was much softer than the mullite slider, the slider could penetrate and cut deeply into the surface, causing extensive plastic deformation of the surface (Fig. 8a-c), resulting in a great amount of material loss. Under the load (480 N) used in the present work, the push and crush effect of the slider on the surface caused extensive shear deformation of the surface layer and resulted in the formation of wear debris exhibiting shear band features (Fig. 9a-c). Also, in some areas, the slider cut deeply into the surface, causing the direct removal of the material in the form of blocklike wear debris. In summary, all the materials studied here were worn by a combination of ploughing and

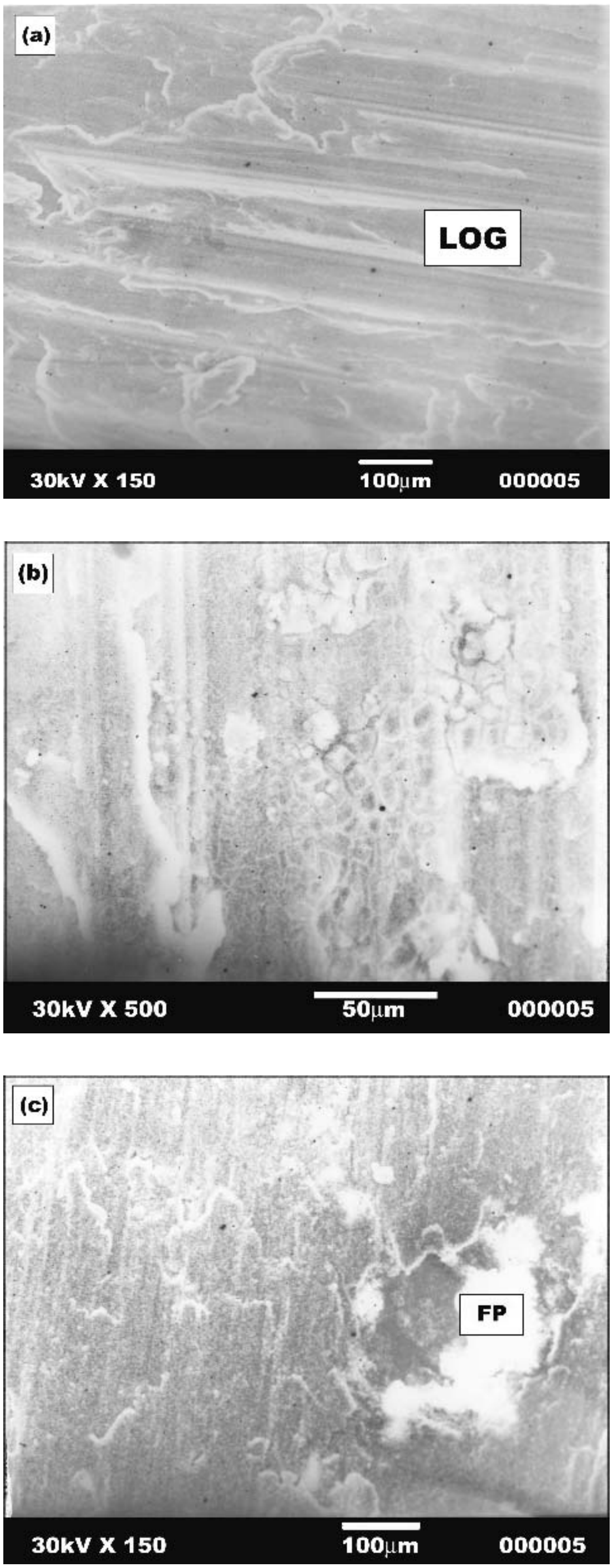

Fig. 8 SEM micrographs of the worn surface of the matrix and composites: **(a)** Al5Mg alloy; **(b)** Al5Mg-7 vol.% C composite; **(c)** Al5Mg-10 vol.% Al_2O_3 composite

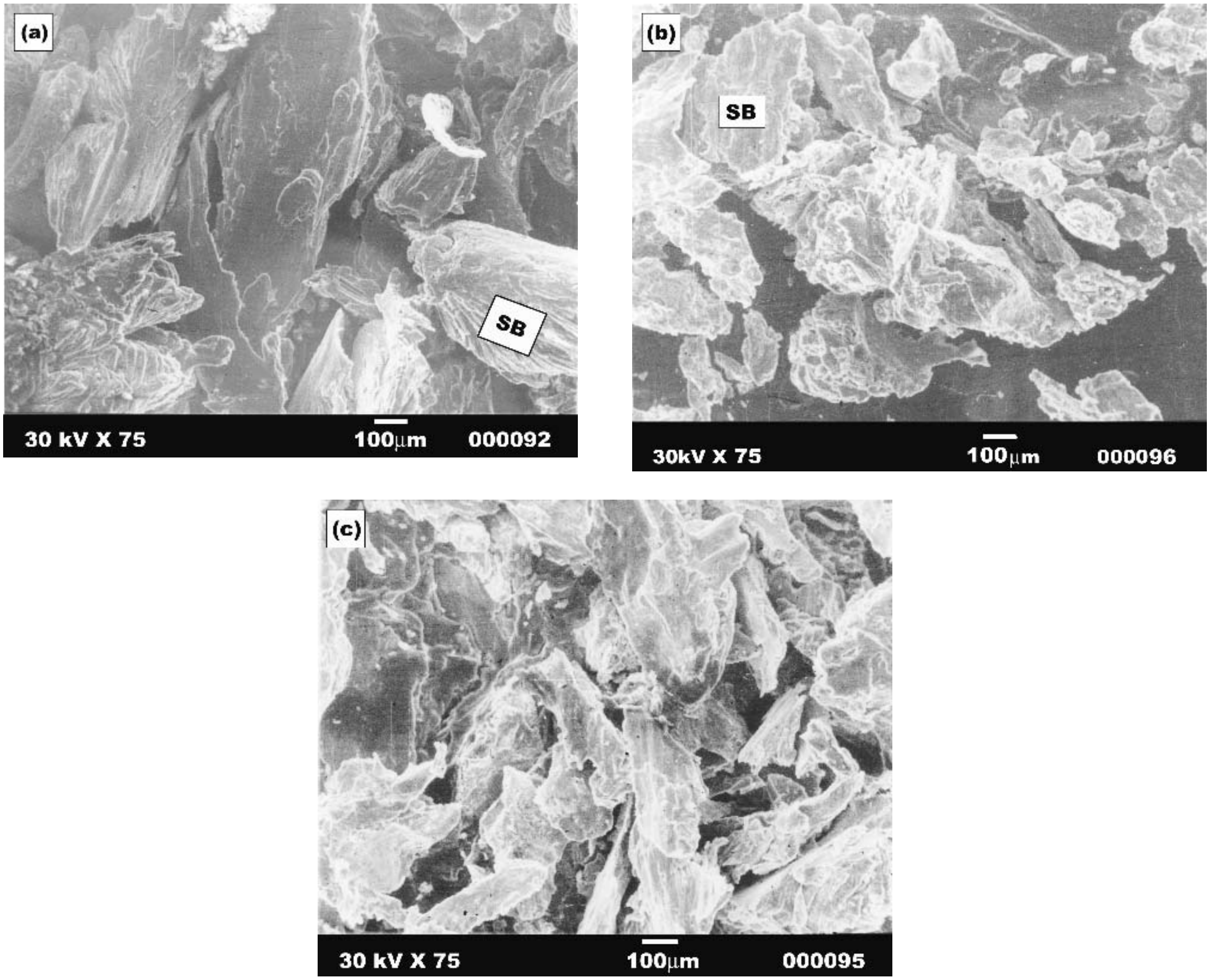

Fig. 9 SEM micrographs of the wear debris of the matrix and composites: **(a)** Al5Mg alloy; **(b)** Al5Mg-7 vol.% C composite; **(c)** Al5Mg-10 vol.% Al_2O_3 composite

cutting of the matrix, fracture of Al_2O_3, or pull out of C particulates.

4. Conclusions

1) The matrix grains of Al5Mg-Al_2O_3 composites are able to move freely during the rolling process, around the particulates in a wave-like motion, forming lensoid structure. However, C particulates can deform plastically and strangle during rolling process.
2) The addition of either Al_2O_3 or C particulates into the matrix alloy increases the yield strength. However, the ultimate tensile strength and elongation of the composites are decreased in comparison with those of the matrix alloy.
3) The hot rolled composites show higher tensile properties than that of the cold rolled ones.
4) The composites reinforced with Al_2O_3 particulates failed through particulate fracture and matrix ligament rupture; however, failure of composites reinforced with C particulates was through particulate decohesion, followed by ductile failure of the matrix.
5) The wear rate of the Al5Mg alloy decreases with the addition of C particulates. But, increasing the volume fraction of C particulates does not have a prominent effect on the wear rate. The improvement in the wear resistance of Al5Mg-C composites is mainly attributed to the formation of C film on the surface of the composite pin and mullite slider, which acts as a solid lubricant.
6) The composites reinforced with Al_2O_3 particulates exhibit higher wear rate than that of the unreinforced alloy due to the fracture of the Al_2O_3 under high load used in the present investigation.
7) Addition of both C and Al_2O_3 particulates into the Al5Mg matrix alloy does not significantly improve the wear resistance.
8) Hot or cold rolling has a marginal effect on the wear results of the present composites.

References

1. S.J. Liu and K.S. Liu: "Effect of Aging on Abrasion Rate in an Al-Zn-Mg-SiC Composite," *Wear,* 1988, *121,* pp. 1-14.
2. A.T. Alpas and J. De Embury: "Sliding and Abrasive Wear Behavior of an Aluminum (2014)-SiC Particle Reinforced Composite," *Scr. Metall. Mater.,* 1990, *24*, pp. 931-35.
3. S. Corbin and D. Wilkinson: "The Tensile Properties of a Particulate Reinforced Al Alloy in the Temperature Range 196-300 °C," *Can. Metall. Q.,* 1996, *35*(2), pp. 189-98.
4. Y. Kim, S. Lee, N. Kim, and K. Cho: "Effect of Microstructure on the Tensile and Fracture Behavior of Cast A356/SiCp Composite," *Scr. Metall. Mater.,* 1994, *31*(12), pp. 1629-34.
5. B.F. Quigley, G.J. Abbaschian, R. Wunderlin, and R. Mehrabain: "A Method for Fabrication of Aluminium-Alumina Composites," *Metall. Trans. A,* 1982, *13A,* pp. 93-100.
6. D. Lloyd, H. Lagace, A. McLeod, and P. Morris: "Microstructural Aspects of Aluminium-Silicon Carbide Particulate Composites Produced by a Casting Method," *Mater. Sci. Eng.,* 1989, *A107*, pp. 73-80.
7. M. McKimpson and T. Scott: "Processing and Properties of Metal Matrix Composites Containing Discontinuous Reinforcement," *Mater. Sci. Eng.,* 1989, *A107,* pp. 93-106.
8. J. Hertzog: *Proceedings Int. Symposium on Metal Matrix Composites, 25-30 June, 1967,* ASTM, Boston, MA, 1968.
9. W. Harrigan: *Mechanical Behavior of Metal Matrix Composites,* Metallurgical Society, Warrendale, PA, 1983, p. 169.
10. A. Wang and H.J. Rack: "Abrasive Wear of Silicon Carbide Particulate- and Whisker-Reinforced 7091 Aluminum Matrix Composites," *Wear,* 1991, *146,* pp. 337-48.
11. D. Lioyd: "Aspects of Fracture in Particulate Reinforced Metal Matrix Composites," *Acta Metall.,* 1991, *39,* pp. 59-71.
12. M.A. Zamzam: "Abrasive Wear of Aluminium-Matrix Composites," *Metall,* 1991, *45,* pp. 250-54.
13. P.K. Rohatgi, Y. Liu, and S. Ray: *ASM Handbook: Friction, Lubrication and Wear Technology,* Vol. 18, 1992, p. 801.
14. J. Larsen-Basse: "Role of Microstructure and Mechanical Properties in Abrasion," *Scr. Metall. Mater.,* 1990, *24,* pp. 821-26.
15. M.A. Martinez, A. Martin, and J. Lorca: "Wear of Al-Si-SiC Composite at Ambient and Elevated Temperatures," *Scr. Metall. Mater.,* 1993, *28,* pp. 207-12.
16. A.G. Wang and I.M. Huchings: "Wear of Alumina Fiber-Aluminum Metal Matrix Composites by Two-Body Abrasion," *Mater. Sci. Tech.,* 1989, *5*, pp. 71-75.
17. I.M. Huchings and A. Wang: "Wear of Aluminum-Alumina Metal Matrix Composites by Abrasion and Erosion," in *New Materials and Their Applications,* D. Holland, ed., Inst. Phys. Conf. Ser. No. 111, IOP, Institute of Physics, University of Warwick, UK, 1990, p. 91.
18. N. Axen and S. Jacobson: "A Model for the Abrasive Wear Resistance of Multiphase Materials," *Wear,* 1994, *174,* pp. 187-99.
19. N. Axen, A. Alahelisten, and S. Jacobon: "Abrasive Wear of Alumina Fibre-Reinforced Aluminum," *Wear,* 1994, *173,* pp. 95-104.
20. N. Axen and K.H. Zum Gaher: *Mater.wiss. Werkst.tech.,* 1992, *23,* p. 360.
21. W. Simm and S. Freti: "Abrasion Wear of Multiphase Materials," *Wear,* 1989, *129*, pp. 105-21.