Wear 266 (2009) 356–359

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Short communication

Wear behavior of AA1060 reinforced with alumina under different loads

M.R. Rosenberger[a,b,*], E. Forlerer[c], C.E. Schvezov[a,b]

[a] *Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Rivadavia 1917, 1033 Buenos Aires, Argentina*
[b] *Prog. Materiales, Modelización y Metrología, FCEQyN, Universidad Nacional de Misiones, Azara 1552, 3300 Posadas, Misiones, Argentina*
[c] *Unidad de Actividad Materiales-GIDAT-GAEN, Comisión Nacional de Energía Atómica, Av. Gral. Paz 1499, 1650 San Martín, Buenos Aires, Argentina*

ARTICLE INFO

Article history:
Received 24 August 2007
Received in revised form 14 May 2008
Accepted 10 June 2008
Available online 29 July 2008

Keywords:
Sliding wear
Mechanically mixed layers
Wear
Aluminum metal-matrix composite
Hard particle reinforcement

ABSTRACT

The wear behavior of samples of AA1060 aluminum matrix reinforced with 15 vol% of alumina particles in a range of loads between 4.9 and 91.2 N was determined using a pin-on-ring machine at a velocity of 2.7 m/s. The counterface was a carbon steel ring of 272 HB in hardness. Optical and electronic microscopy, X-ray energy analysis and hardness measurement were performed in order to characterize the worn samples. A mild wear mechanism is present for loads lower than 80 N and at larger loads the mechanisms change to a severe mode. In the mild wear regime a mechanically mixed layer (MML), with iron from the counterface and material of the composite, was formed. This MML was responsible of the wear resistance of the composite. Two mechanisms were observed as a way to increase the resistance of the MML; first hardening by mechanical alloying and strain hardening, and then an increase in thickness. At a larger load the conditions produced large instabilities which prevented the formation of a protective mechanically mixed layer.

1. Introduction

The aluminum matrix composites (AMC) reinforced with hard particles combine the ductility and low density of the matrix with the high hardness and stiffness of the reinforcements which results in good dimensional stability, high stiffness and specific mechanical resistance [1,2]. These properties made them suitable for transport application with a reduction in energy costs [3,4]. Many applications require good wear resistance under lubrication and dry conditions. The wear of the parts is produced in many cases, against aluminum alloys, steel or other non-ferrous alloys. Wear of AMC against a steel counterface produces a layer of material in the AMC called mechanically mixed layer (MML), which is produced by transfer and mixing of materials, under certain load and velocity range. It has been observed that the MML increases the wear resistance of the AMC, producing conditions of moderate wear [1,5–11]. The formation of the MML is favored by load pressures less than 5 MPa and wear velocities less than 10 m s^{-1} [5,8,12–14].

It has been reported [15,16] that the generation and attachment of the debris on the fist bodies wear material are necessary for the generation of the MML and a moderate wear regime. It has been indicated as well that for a moderate wear regime the MML acts as a layer that supports and distributes the load over the AMC producing in some cases debris coming from the MML typical of an adhesive wear mechanism [5,11].

It has also been shown that the wear resistance of the MML in AMC for all reinforcing particle tested is essentially independent of the type and volume fraction of the reinforcement and the process used in the production, casting or extrusion, indicating that the wear properties of the material depends on the properties of the MML formed [5].

At higher loads the wear rate increases until a transition to a severe wear regime occurs in which the MML is no longer formed. It has also been demonstrated that the transition from the moderate wear regime with an MML to a severe wear regime is promoted by an increase of the material temperature at higher loads and/or velocity. The critical load for the transition to a severe regime is directly related to the size and volume fraction of the reinforcement, which restricts the flow of composite material that holds the MML [12,17].

In the present report the role and behavior of the MML in AA1060/Al_2O_3/15p is studied and associated to a moderate wear regime. Also, the transition to a severe regime is determined and associated to the inability of the system in forming the protective MML. In addition this inability of the MML to survive

---

[*] Corresponding author at: FCEQyN, Universidad Nacional de Misiones, Azara 1552, 3300 Posadas, Misiones, Argentina. Tel.: +54 3752 427491; fax: +54 3752 425414.

E-mail addresses: rrmario@fceqyn.unam.edu.ar (M.R. Rosenberger), forlerer@cnea.gov.ar (E. Forlerer), schvezov@fceqyn.unam.edu.ar (C.E. Schvezov).

0043-1648/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.wear.2008.06.007

under the severe regime is confirmed by observing its destruction.

2. Experimental methods

The AMC were prepared employing powders of aluminum alloy AA1060 (with a minimum of Al of 99.6% and impurities of Si and Fe mostly), and alumina particles with an average size of 20 μm and faceted shape. The powders were mixed in a ball mill, compressed and extruded in cylinders 150–200 mm in long and 6.35 mm in diameter. The particle volume fraction of the MMC was 15%. The test samples were cuts of the above cylinders with a length of 15 mm.

The samples were tested in a pin on ring apparatus, with a steel disc with hardness of 272 HB, at a tangential speed of 2.7 m s^{-1} and loads of 4.9–91.2 N without lubrication. The loads employed were 4.9, 14.9, 23.7, 32.4, 52.0, 71.6, 81.4, and 91.2 N and a minimum of two tests were performed by each load. All the tests were carried out in a discontinuous fashion, i.e. the test was interrupted every 100–500 m to measure the sample length, until a steady-state regime of wear was reached; the wear distance was registered in all cases.

The amount of wear was determined by measuring the change of length of the sample and calculating the linear wear rate as the change of length in millimeters divided by the respective wear distance in meters. The temperature of the sample surface was determined *in situ* and continuously, with a thermocouple located 6 mm below the wearing surface, and connected to a PC-based data acquisition system.

The worn samples were characterized at the surface and subsurface by optical (OM) and scanning electron microscopy (SEM). The observations in the subsurface were done in the longitudinal section of the pin. Each longitudinal section was mounted, polished and etched to reveal the microstructure. In addition to the SEM observation a semi-quantitative energy dispersive X-ray analysis (EDX) was performed on the surface. The mechanical properties were determined using Vickers microhardness measurements performed with a Durimet by Leitz instruments, in different regions of the sample.

3. Results and discussion

3.1. Wear rate

The results obtained for the wear rate as a function of load are shown in Fig. 1. As observed in the figure, the load range was broader than one order of magnitude; 4.9–91.2 and the wear rate was in a range which spread an interval of four orders of magnitude; 3.9×10^{-6} to 1.2×10^{-2} mm/m.

Table 1
Fitting parameters of the regression functions of Fig. 1, according to Eq. (1)

Parameter	Region 1 (low loads)	Region 2 (high loads)
a	-3.45×10^{-4}	-6.44×10^{-2}
b	2.60×10^{-5}	8.39×10^{-4}

In Fig. 1 it is possible to identify two linear behaviors with different slopes which change at a load of about 80 N; in each section it is possible to fit the experimental point by linear regression to analytical functions of the form:

$$W = a + b \cdot F \tag{1}$$

where W is the linear wear rate, F the applied load, and a and b are the fitting parameters.

The values obtained for the above parameters in each section for low and high loads are listed in Table 1. The results shown in Fig. 1 and Table 1 describe the typical behavior of an AMC which has been attributed to a combination of different wear mechanisms [5,10,18–21]. There is a pronounced change of slope at a load of about 80 N which indicates two different wear regimes; moderate and severe. The criteria employed to characterize each regime is not only based on the relation between wear rate and load but also in other aspects such as: the composition, the mechanical properties and the morphology of the worn surface [5,22]. These results are presented below.

3.2. Temperature measurement

The temperature measured at 6 mm from the wearing surface in a steady state of wear, is shown in Fig. 2, as a function of applied load. The results show a monotonic linear increase of temperature with load, which converges to ambient temperature at zero loads. At the highest load the temperature could be as high as 150 °C. Similar results have been reported in the literature [17,19,21] and it was demonstrated that temperature influences the wear resistance of the material and that there exists a critical temperature for the initiation of the severe wear regime [12,17,23]. In the present experiments it is possible to define a load for the transition from moderate to severe wear at about 80 N; at this load and according to Fig. 2 the temperature of the sample is of 129 °C, which is very similar to the value of 125 °C reported by Wilson and Alpas for an aluminum alloy AA356 [19] and close to other temperatures for Al–20% Si of 100 °C, Al–20% Si/SiC/20p of 150 °C [23] and finally for AA6061 of 122 °C [12].

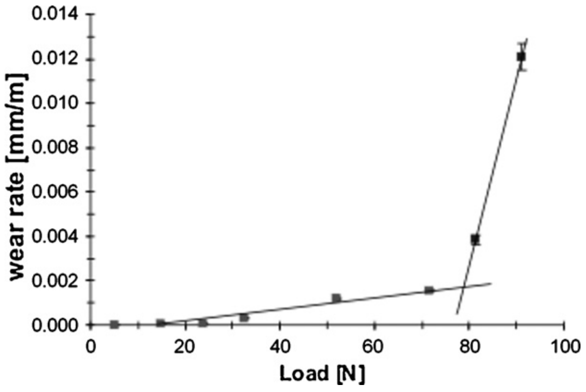

Fig. 1. Wear rate as a function of applied load.

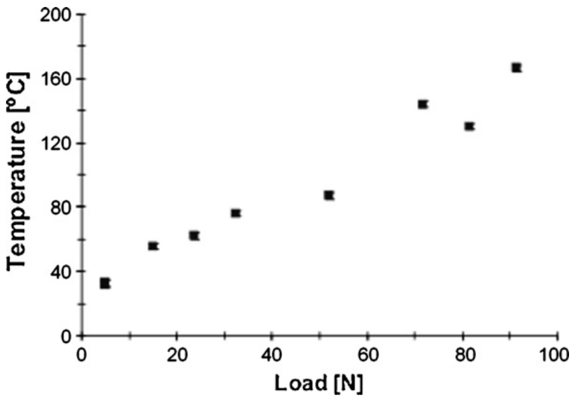

Fig. 2. Maximum temperature achieved during the steady-state wear.

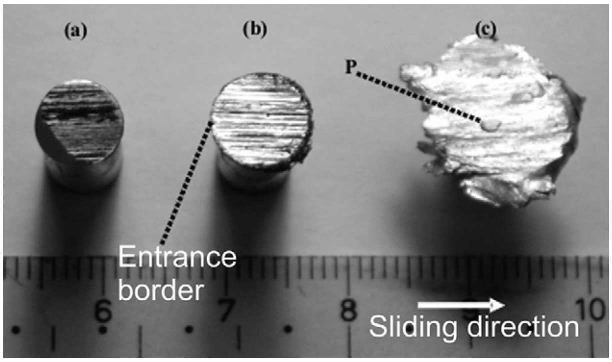

Fig. 3. Worn surfaces of selected samples: (a) 4.9 N, (b) 14.9 N, and (c) 91.2 N. Letter P marks a patch of MML adhered to the worn surface. The scale of the rule is the centimeter.

3.3. Analysis of worn surfaces

The morphology of the worn surface is strongly dependent on load and therefore on the wear mechanism. The change in morphology may be observed in Fig. 3 where three samples are shown after wear under loads of 4.9, 14.9, and 91.2 N. In the three cases one common feature is the accumulation of worn material in the surface protruding as burr. The amount of material for high loads increases as the load increases, moreover, the amount of material is also significant at the leading edge.

With respect to the surface itself, the appearance also changes with load; at low loads the surface shows large, regular and clearly defined parallel grooves; however, at high loads the grooves are not clearly defined.

The accumulation of material as burr, when the amount of wear is determined by differences in sample weight, could result in important errors. This is not the case for the measurement of wear rate determined by the change in length, where the morphological changes are used as measure of wear, rather than a change in mass. The burr of material typical of plastic materials has been reported in the literature [5,12,13,24,25]; however, the effect on wear rate has not been considered.

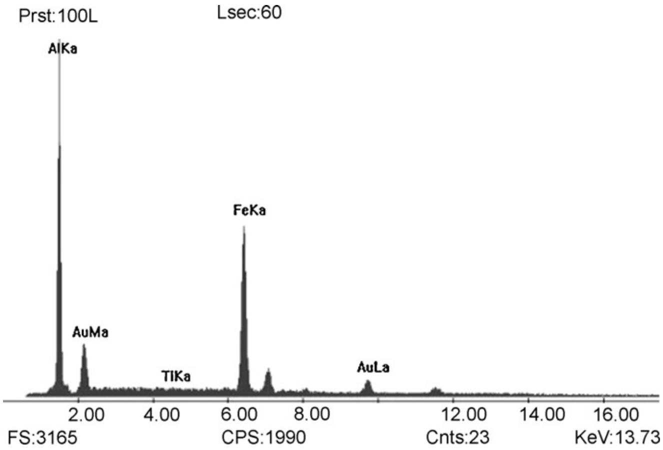

Fig. 4. EDX spectrum of the worn surface of the sample tested to 23.7 N.

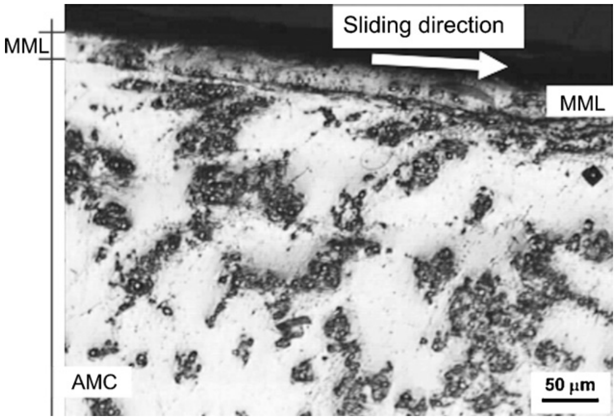

Fig. 5. Longitudinal section of the sample tested to 23.7 N. The darker grey layer is the mechanically mixed layer (MML).

The results of the semi-quantitative element analysis of a surface wore at a load of 23.7 N is shown in Fig. 4. The main observation is the amount of iron present in the surface, which is also found in the surface of samples wore at loads 4.9–52 N. On the other hand, this element is not present in samples worn at higher loads between 81.4 and 91.2 N. Iron is transferred from the wearing counterface [5,25] by a mechanism of mechanical alloying which results in the formation of a mechanically mixed layer in the wearing surface. The presence of the MML can be visualized in longitudinal sections of the samples by optical microscopy as it is shown in Fig. 5. In all cases the MML is slightly darker than the matrix material when observed by the optical microscope [5].

The microhardness of the MML formed under different loads was measured by Vickers indentation, the average values of at least five impressions in the MML are shown in Fig. 6 as a function of the applied load.

In the same figure it is shown the thickness of each MML formed as function of the applied load. The thickness was measured in sections longitudinal to the sample axis, transversal to the MML thickness and near the sample axis.

The values are average of 10 measures obtained by optical observation which were confirmed by hardness measurements.

It is observed that the microhardness of the MML is 3–10 times higher than the microhardness of the matrix, which is of 30 HV (0.015). On the other hand, the thickness of the MML as function of the applied load is constant for loads less than 23.7 N and, for higher loads it increases monotonically from 20 μm to about 80 μm. The microhardness shows a nearly step evolution, with a value of around 200 HV in the lower step and 310 HV for the higher step. This shows two different behaviors, at the lower loads there is a stable MML of constant thickness and hardness, and as the

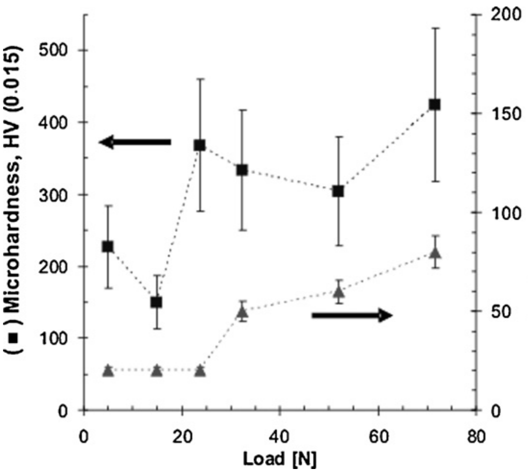

Fig. 6. Microhardness and thickness of the mechanically mixed layer as a function of the applied load. Squares correspond to microhardness; triangles correspond to thickness.

load increases the thickness increases but the hardness of the MML remains constant. This notable behavior shows that a maximum hardness compatible with the wear system consisting of the materials and the environment is reached at a given load and when this maximum is reached the wear resistance of the AMC is increased by increasing the thickness of the MML. However, the thickness can not increase indefinitely because as the load increases, it also does the temperature due to friction, which softens the substrate matrix and to a less extent the MML until it is detached from the AMC. After this, and for higher loads, the MML is no longer formed and the wear regime becomes severe. In the present investigation this transition occurs for a load between 70 and 80 N, since at this load and higher the MML is not formed. This could be attributed to the fact that the formation of the MML requires deposition of mechanically mixed material until a steady layer is formed in which the rate of deposition equals the rate of material lost by wear, this cannot be achieved at higher loads when the loss rate is higher than the deposition rate.

The wear rate vs. load behavior of Fig. 1 with two different linear relations, and the observation of very similar morphology for the wearing surface at low loads with an MML containing iron, which is very different than the morphology for high loads, the absence of iron and the MML consistent with the different behavior in the wear rate, indicate a drastic change in wear mechanism at the transition point.

4. Conclusions

The main conclusions of the dry sliding of $AA1060/Al_2O_3/15p$ against steel on a pin-on-ring tester, under applied load of 4.9–91.2 N and 2.7 $m\,s^{-1}$ are

- Two regimens of wear were found; one moderate and another severe which were characterized by two different relations between wear rate and applied load.
- A mechanically mixed layer, with iron, was found on the surface of the materials worn at loads lower than 80 N, in the moderate wear regime.
- The mechanically mixed layer on the aluminum matrix composite protects the original composite.
- The worn surface of the materials tested at a load larger than 80 N does not accumulate iron.
- The maximum temperature, measured at 6 mm from the contact surface, in the steady state of wear increases monotonically with the applied load.
- The critical load of transition from moderate to sever wear regimes is 80 N, and the corresponding temperature is 129 °C.
- The relation between hardness and thickness of the MML indicates that at the lower loads the resistance of the MML is achieved by hardening through mechanical alloying and strain hardening. It achieves a maximum value limited by microstructural factors, then the MML increases its resistance by increasing its thickness.

References

[1] A.P. Sannino, H.J. Rack, Dry sliding wear of discontinuously reinforced aluminum composites: review and discussion, Wear 189 (1995) 1–19.

[2] T.W. Clyne, An introductory overview of MMC systems, types and developments, in: T.W. Clyne (Ed.), Comprehensive Composite Materials, vol. 3, Elsevier, Amsterdam, The Netherlands, 2000, pp. 1–26.

[3] V. Kevorkijan, Engineering wear-resistant surfaces in automotive aluminum, JOM 55 (2) (2003) 32–34.

[4] S. Rawal, Metal-matrix composites for space applications, JOM 53 (4) (2001) 14–17.

[5] M.R. Rosenberger, E. Forlerer, C.E. Schvezov, Wear of different aluminum matrix composites under conditions that generate a mechanically mixed layer, Wear 259 (1–6) (2005) 590–601.

[6] A.R. Riahi, A.T. Alpas, The role of tribolayers on the sliding wear behaviour of graphitic aluminum matrix composites, Wear 251 (2001) 1396–1407.

[7] Y.S. Chiao, F.M. Pan, C.A. Lin, J.L. Horng, S.J. Lin, Studies of Al[2]O[3](p)-6061Al composites under dry sliding conditions using scanning electron microscopy, energy-dispersive spectrometry and X-ray diffractometry, Wear 161 (1993) 155–160.

[8] A. Wang, H.J. Rack, Transition wear behavior of SiC-particulate- and SiC-whisker-reinforced 7091 Al metal matrix composites, Mater. Sci. Eng. A 147 (1991) 211–224.

[9] B. Venkataraman, G. Sundararajan, Correlation between the characteristics of the mechanically mixed layer and wear behaviour of aluminium, Al-7075 alloy and Al-MMCs, Wear 245 (2000) 22–38.

[10] C. Subramanian, On mechanical mixing during dry sliding of aluminium–12.3 wt.% silicon alloy against copper, Wear 161 (1993) 53–60.

[11] D.A. Rigney, Transfer, mixing and associated chemical and mechanical processes during the sliding of ductile materials, Wear 245 (2000) 1–9.

[12] J. Zhang, A.T. Alpas, Transition between mild and severe wear in aluminium alloys, Acta Mater. 45 (2) (1997) 513–528.

[13] J.K.M. Kwok, S.C. Lim, High-speed tribological properties of some Al/SiC_p composites. II. Wear mechanisms, Comp. Sci. Technol. 59 (1999) 65–75.

[14] D.P. Mondal, S. Das, R.N. Rao, M. Singh, Effect of SiC addition and running-in-wear on the sliding wear behaviour of Al–Zn–Mg aluminium alloy, Mater. Sci. Eng. A 402 (2005) 307–319.

[15] K. Hiratsuka, M. Goto, The role of changes in hardness of subsurfaces, transfer particles and wear particles in initial-steady wear transition, Wear 238 (2000) 70–77.

[16] K. Hiratsuka, K. Muramoto, Role of wear particles in severe–mild wear transition, Wear 259 (2005) 467–476.

[17] A. Wilson, A.T. Alpas, Effect of temperature on the sliding wear performance of Al alloys and Al matrix composites, Wear 196 (1996) 270–278.

[18] S.C. Lim, M.F. Ashby, Wear mechanism maps, Acta Metall. 35 (1) (1987) 1–24.

[19] S. Wilson, A.T. Alpas, Wear mechanism maps for metal matrix composites, Wear 212 (1997) 41–49.

[20] R. Antoniou, C. Subramanian, Wear mechanism map for aluminium alloys, Scr. Metall. 22 (1988) 809–814.

[21] A.T. Alpas, J. Zhang, Effect of microstructure (particulate size and volume fraction) and counterface material on the sliding wear resistance of particulate-reinforced aluminum matrix composites, Metall. Mater. Trans. A 25 (1994) 969–983.

[22] J.A. Williams, Wear modelling: analytical, computational and mapping: a continuum mechanics approach, Wear 225–229 (1999) 1–17.

[23] M.A. Martinez, A. Martin, J. Llorca, Wear of Al–Si alloys and Al–Si/SiC composites at ambient and elevated temperatures, Scr. Metall. Mater. 28 (1993) 207–212.

[24] M. Sundberg, R. Sundberg, S. Hogmark, R. Otterberg, B. Lehtinen, S.E. Hornstrom, S.E. Karlsson, Metallographic aspects on wear of special brass, Wear 115 (1987) 151–165.

[25] M. Rosenberger, N. Martínez, M.D. Salvador, E. Forlerer, V. Amigó, C. Schvezov, Estudio comparativo del desgaste de materiales compuestos por diferentes condiciones y equipos (A comparative study of the wear of composite materials under different conditions and tester machines), in: Proceeding of the Congress SAM-CoNaMet, Chile, 2002, pp. 953–958.