Galling in aluminum alloys and Duralcan aluminum matrix composites

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Abstract

Galling behaviour of Duralcan\textsuperscript{TM} aluminum matrix composites (metal matrix composites (MMCs); 20 vol.% SiC in an Al-Si alloy matrix) is compared with that of unreinforced 6061 aluminum alloy and cast iron. Counterface materials were 52100 bearing steel and cast iron with test conditions consisting of cylinders of the ferrous materials sliding on plates of the aluminum based materials, in reciprocating motion without lubrication. The onset of galling was studied in a stepped load test. Neither the 52100 steel sliding on cast iron, nor the cast iron sliding on the MMC exhibited galling through the range of loads tested. Instead they exhibited uniform, rectangular wear tracks consistent with truncation of surface asperities and increasing conformity of the surfaces as wear progressed. The unreinforced 6061 alloy, exhibited galling at low loads with protrusions forming on the hard steel slider that caused abrasion of the aluminum alloy. Thus conformity of contact decreased as wear progressed. Galling is discussed in relation to contact geometry and wear mechanism maps.

1. Introduction

The term galling is often used interchangeably with scuffing [1] and it is the tendency of most aluminum alloys to undergo severe wear due to galling that precludes their use in applications such as cylinder bore surfaces in automotive engines. Indeed, upon examining the rather short list of metals that are considered to be wear resistant (Fe-based, Cu-based and Co-based alloys [2]), it might be suggested that a resistance to galling is the primary prerequisite for wear resistance.

Duralcan\textsuperscript{TM} (owned by Alcan Aluminum Corporation) aluminum matrix composites are a new class of low cost, easily castable metal matrix composite materials with a unique combination of low density, high stiffness and good wear resistance. The objective of this study was to investigate the galling of these materials by comparing their behaviour with that of a couple prone to galling (6061 T6 vs. 52100 steel) and a "galling resistant" couple (cast Fe vs. 52100 steel).

2. Experimental details

The experimental set up is shown schematically in Fig. 1. A cylindrical sample (7.9 mm long by 6.35 mm diameter) was fixed in a holder so that the curved surface of the cylinder was in contact with a rectangular plate sample with the axis of the cylinder perpendicular to the direction of sliding. The cylinder holder was mounted on an axle that allowed it to rotate in order to allow evenly distributed load along the line of contact rather than high loads at one end due to deviation from perfect alignment. The plate sample was mounted on a linear bearing stage driven by a crank mechanism (4.2 cm crank with 1.3 cm radius of rotation) that resulted in a reciprocating sliding motion. Each test consisted of series of load steps. Samples were run for 500 s at 0.5 Hz stroke rate for each of the five load steps, although some tests were stopped at the end of a step if severe galling was observed.

Table 1 shows the loads and the maximum nominal hertzian contact stresses associated with each load. Table 2 shows the material combinations tested.

The contact geometry used in this study has a number of characteristics in common with piston ring on cylinder wall contact in internal combustion engines, namely: (i) similar levels of nominal, imposed stress; (ii) nominal line contact; (iii) reciprocating motion; and (iv) no change in the sliding area of the plate (as uniform wear of the plate occurs). In contrast, the ASTM standard pin-on-disc test (which prescribes an initial hemisphere on flat contact) has enormous nominal stresses at typical normal loads (e.g. for a 3 mm radius ball contact pressure would be 180 MPa with a load of 9 g) which must lead to high initial wear rates and a rapid change in contact geometry in the early stages of the test [3]. The standard block-on-ring test has an initial line contact geometry like the test used here but block wear will increase the area of contact.

3. Results

Figure 2 shows wear scars from the stepped load tests for four of the couples investigated. The 6061 T6 vs. nodular iron couple exhibited severe wear damage localized into two deep score lines; one on either end of the iron cylinder specimen. The score lines formed after only four strokes of the first load step, and it could be seen during the test that a gap had formed between the centre of the iron cylinder and the alu-
Fig. 1. Schematic diagram showing testing apparatus. Insets show geometry of contact and lay of plate specimen with respect to sliding direction.

TABLE 1. Stepped load sequence

<table>
<thead>
<tr>
<th>Step</th>
<th>Load (g)</th>
<th>Maximum contact stress (hertzian) (MPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>86</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>184</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>284</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>8600</td>
<td>59</td>
</tr>
</tbody>
</table>

minum specimen as material built up on the ends of the cylinder. The 52100 sliding on 6061 T6 showed behaviour which was essentially identical to that of nodular Fe sliding on 6061 T6, i.e. galling occurred early in the first load step.

By contrast, both the cast iron plate specimen sliding against a 52100 steel cylinder and the nodular Fe cylinder sliding on the Duralcan F3N 20S aluminum composite specimen exhibited much more uniform wear. Discoloration of the specimens was consistent with wear damage confined to the tops of asperities on the milled specimens with no scoring, i.e. no deep scars parallel to the direction of sliding.

The aluminum composite material with the lower amount of reinforcement exhibited a different type of wear damage which might be considered to be intermediate between the two described above. There was one bright metallic wear scar present but in addition there were smaller score lines accompanied by the formation of fine black wear debris. Figures 3 and 4 show wear debris associated with two of the couples. The 6061 vs. 52100 steel showed coarse (larger than 50 μm) "machining chip" type of wear debris, while scanning electron microscope examination of the Duralcan F3N 10S showed that the black debris was composed of compacted, fine particles (most particles less than 2 μm). Energy dispersive X-ray analysis showed that the fine debris was predominantly aluminum with small amounts of iron and silicon.

4. Discussion

To begin the discussion of the experimental results, it is worth defining the term galling and commenting on its relation to wear mechanisms. Although ASTM G40-88 [4] declines to define galling, ASTM G98-89 [5] suggests that galling might be defined as "a severe form of wear characterized by localized, macroscopic material transfer, removal or formation of surface protrusions when two solid surfaces experience relative sliding under load". This is the definition that will be used here, although it should be noted that galling-like behaviour can occur under a wide variety of conditions. The ASTM test imposes high loads over a short sliding distance in one pass (a type of sliding that might be found in screw threads) [5] while the situation investigated here imposes lighter loads over longer sliding distances with 250 passes per load step.
TABLE 2. Materials studied

<table>
<thead>
<tr>
<th>Couple</th>
<th>Cylinder</th>
<th>Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52100 steel</td>
<td>6061 T6</td>
</tr>
<tr>
<td>2</td>
<td>Nodular Fe</td>
<td>6061 T6</td>
</tr>
<tr>
<td>3</td>
<td>Nodular Fe</td>
<td>Duralcan F3N 10S</td>
</tr>
<tr>
<td>4</td>
<td>Nodular Fe</td>
<td>Duralcan F3N 20S</td>
</tr>
<tr>
<td>5</td>
<td>52100 steel</td>
<td>Grey cast iron</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness (Rockwell A)</th>
<th>Composition (wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061 T6</td>
<td>38.5</td>
<td>1.0 Mg, 0.6 Si, 0.28 Cu, 0.2 Cr, bal. Al</td>
</tr>
<tr>
<td>52100 steel</td>
<td>83.0</td>
<td>1.0 C, 0.35 Mn, 0.22 Si, 1.45 Cr, bal. Fe</td>
</tr>
<tr>
<td>Nodular Fe</td>
<td>62.0</td>
<td>3.6 C, 0.21 Mn, 2.7 Si, 0.04 Mg, 0.016 P, bal. Fe</td>
</tr>
<tr>
<td>Grey cast iron</td>
<td>50.7</td>
<td>3.1 C, 0.80 Mn, 2.4 Si, bal. Fe</td>
</tr>
<tr>
<td>Duralcan F3N 10S</td>
<td>32.5</td>
<td>10 Si, 1.0 Fe, 0.6 Mg, 0.6 Mn, Cu and Ti 0.2 max, bal. Al</td>
</tr>
<tr>
<td>Duralcan F3N 20S</td>
<td>40.8</td>
<td></td>
</tr>
</tbody>
</table>

*Composition is that of the matrix alloy for both Duralcan F3N 10S and Duralcan F3N 20S. The former contains 10% SiC, and the latter contains 20% SiC. The SiC reinforcement has a median size of 9.3 μm. The Aluminum Association Nomenclature System for Aluminum Metal Matrix Composite Materials (Washington, 1990) would designate these composites as A380/SiC/10p and A380/SiC/20p, respectively.

A distinction can be made between wear mechanisms and wear processes, with a process being a sequence or combination of wear mechanisms [1]. Within this framework, the galling observed here when iron slides on 6061 aluminum can be considered as a process which consists of a two step sequence: the first step is the formation of surface protrusions as aluminum is transferred to the iron slider; adhesion is the mechanism of importance in this step. In the next step, two-body abrasion is the operating mechanism. Two-body abrasion typically produces the "machining chip" type of wear debris such as that shown in Fig. 4.

It is apparent that 6061 T6 sliding against either 52100 steel or grey cast Fe exhibits severe galling at light loads commencing at very short distances slid, while the Duralcan vs. Fe couple and the 52100 vs. Fe couple did not exhibit galling throughout the imposed test sequence. The contact geometry used here makes the effect of galling quite obvious. The formation of protrusions on the hard slider decreases the conformity of contact, making the surface of the slider rougher as wear progresses. The two body abrasion associated with the protrusions produces the "machining chip" type of wear debris.

The distribution of wear debris from the non-galling couples is consistent with "wear-in" behaviour where the conformity of contact increases with increasing distance slid. The formation of fine, black debris is similar to that observed in mild wear of Al-Si alloys sliding on steel [6, 7].

These observations lead to a number of questions regarding galling. What is the criterion for galling in terms of material selection and in terms of imposed load/stress; and how is galling suppressed in the Duralcan composite specimen?

Material properties affecting galling have been summarized earlier [8] and these arguments will not be repeated here except to note that mutual solubility, or mutual miscibility of materials does not appear to be as important in determining the tendency towards galling as relative oxide/metal properties and oxide thickness.
Fig. 3. Optical micrographs (30x) of ends of wear scars and
wear debris for: (a) nodular Fe vs. 6061 T6; (b) nodular Fe vs.
Duralcan F3N 10S.

The 52100 steel sliding on cast iron is galling-resistant
despite the fact that both materials are Fe-C alloys,
while the 6061 T6 on either Fe based material proved
to be very prone to galling.

In this study, galling was studied in a stepped load
test and thus the test seeks a relation between the
onset of galling and the imposed load. A central issue
in understanding most wear behaviour is the relation
between imposed load and the actual stresses produced
in the sliding contact. Analysis based upon contacting
asperities suggest that even before sliding commences
yielding will occur at asperities even for minute loads,
leading to an upper bound for the contact stress similar
to that encountered with a hardness indentation: a
normal traction of the order of three times the flow
stress of the softer of the two materials. Increasing
load just raises the area fraction of these real contacts

Fig. 4. SEM image of ends of wear scars and wear debris for:
(a), (b) nodular Fe vs. 6061 T6; (c) nodular Fe vs. Duralcan
F3N 10S.
by increasing their size or their number. A lower bound estimate for the imposed stress is the nominal stress, e.g., simply the imposed load over the nominal contact area for a planar conformal contact, or the hertzian contact stress for curved surfaces in contact. Wear maps have been introduced (for both steels [9] and aluminum alloys [10]) which describe load effects in terms of the nominal stress for planar conformal contact, and severe wear at high loads has been delineated in terms of a seizure limit occurring for both materials when the nominal imposed stress is about 0.2 times the yield stress.

In the absence of any other severe form of wear at high loads, one is left with equating the “seizure” region of the wear map with galling. It then becomes apparent that there is a discrepancy between the observation of galling in the current study and the proposed seizure limit for aluminum alloys [10]. Galling for 6061 T6 was observed when the imposed nominal stress was less than 0.07 times the yield stress of the alloy (albeit, the nominal stress is for a hertzian contact not a planar contact). Further, it is difficult to rationalize any quantitative similarity between the seizure limit of aluminum and that for steels, when clearly the former material is much more prone to galling.

It is not clear where any nominal stress criterion is sufficient for defining the onset for the onset of galling without reference to other details of contact geometry such as various measures of roughness. When 6061-T6 was slid on 52100 steel in this study, the protrusions formed at the end of the slider, an obvious site of stress concentration. In duplicate trials with the same couple these sites of protrusion growth were usually reproducible, although occasionally a protrusion would form much closer to the centre of the line of contact. In the latter instance it is likely that a large peak in the combined roughness caused a protrusion to form.

These observations suggest that a certain minimum amount of deformation at a small number of points of asperity contact might be a criterion for the initiation of galling of aluminum on steel at light loads. This is consistent with previous descriptions of galling in terms of formation and breakage of cold welds [8]. For such welds to occur at asperities there must be sufficient deformation to break the thin oxide on the aluminum and to extrude the aluminum between the cracks thus formed [11]. The question remains as to how small such contacts can be before sliding can occur without material transfer and galling. Further study is required to understand the criterion for the onset of galling in aluminum based alloys. Such studies should use contacts loaded at low stresses that are well characterized with respect to roughness.

The effect of reinforcement on galling may be rationalized in terms of its effect on the direction of material transfer and its ability to remove protrusions by abrasion during the early stages of protrusion formation. The fine wear debris observed in this study is similar to that observed in the mild wear regime of Al-Si alloys sliding against steel [6, 7]. The Fe content of this debris is indicative of transfer of material from the steel slider to the aluminum, instead of in the other direction. Since the reinforcements are capable of abrading the steel (or its oxide), it is likely that the reinforcements are capable of abrading away any protrusions formed from the aluminum matrix in the early stages of protrusion growth. To better understand such a mechanism, it would be useful to determine how strong the protrusions are and how strongly they adhere to the steel surface.

Most aluminum alloys contain hard constituent particles, typically 2 or 3 μm in size, but it is not clear that such small particles are capable of significantly affecting galling behaviour. Hypereutectic aluminum silicon alloys are used for scuffing resistance but they contain primary silicon particles above 10 μm in size (similar in size to reinforcement particle used in the Duralcan composite [12]). This leads to the question of what determines the size of constituent required to suppress galling and whether that dimension can be related to other quantities such as counterface roughness.

5. Summary

Galling was studied using a reciprocating cylinder on flat contact with light loads and nominal contact stresses well below the yield stress of the aluminum alloys studied. A wear resistant couple (52100 steel cylinder on grey cast iron plate) showed uniform wear consistent with increasing conformity of contact as wear progressed. Similar behaviour was observed in a Duralcan aluminum matrix composite that contained 20 vol.% SiC reinforcement. Aluminum alloy 6061-T6 exhibited severe galling at light loads commencing after only a short distance slid. The existence of a critical load criterion for the onset of galling when aluminum slides on steel is not clear. It is doubtful whether the “seizure limit” criterion proposed for wear maps of aluminum is accurate, nor is it clear whether any nominal normal stress criterion would apply to the onset of galling for a broad range of contact geometries and roughnesses. Increased understanding of galling when aluminum or aluminum matrix composites slide on steel requires characterization of the mechanism by which aluminum protrusions form on steel in terms of protrusion strength, the force with which protrusions adhere to steel and the interaction of protrusions with hard abrasive constituents in aluminum alloys and composites.
Acknowledgments

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References