WEAR MECHANISMS OF ABRASIVE AL – SI ALLOYS+

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Abstract

Chill cast wear pins of Al-Si alloys containing 3,12 and 22 wt% Si have been slid against a continuous SiC emery paper. Bearing pressure was varied on flat bed abrasive wear test in the range 0.006 to 0.072 MPa and the wear rate was in the range 10^{-9}-10^{-8} $cm^3.cm^{-1}$. In the Al-Si alloys wear rate decreased with increasing silicon up to eutectic composition and thereafter increased. In all the alloys, wear rate varied with load in two distinct linear regions separated by a transition point and is interpreted as purely oxidative at low loads and a combined oxidative cum metallic wear at loads higher than the transition point of 2N. Occurrence of subsurface damage was not identified in all the alloys under all condition of testing except at higher loads to 2-3 µm. Evidence has not been obtained to show the mechanical fragmentation of silicon deep in the subsurface region.

المستخلص

لقد تم استخدام عينات اسطوانية من سبائك الالمنيوم – سليكون المصبوبة و الحاوية على نسبة سليكون ٣ و١٢ و٢٢ % بأنزلاقها على اوراق تجليغ من كاربيد السليكون..يقع مدى الضغط المستخدم على اوراق التجليغ ٠,٠٠٦ الى ٠,٠٧٢ MPa (٥,٥-٠,٥ ثقل). يقع معدل البلى ضمن القيم ١٠$^{-٩}$–١٠$^{-٨}$ cm^3 /cm . يقل معدل البلى في سبائك الالمنيوم – سليكون مع زيادة نسبة السليكون حتى تركيب الايوتكتك و بعدها تتم زيادته. فيتغير معدل البلى في كل السبائك التي تم اختبارها مع الثقل المسلط و يقع في منطقتين خطيتين منفصلتين بنقطة انتقال و التي تعزى الى الية البليان الاوكسيدي ضمن مدى الثقل القليل و مزيج من البليان الاوكسيدي - المعدني عند الاثقال العالية و عند اكبر من ٢N . لم يتم الاستدلال على وجود المنطقة التحتية المتاثرة بالبليان وللسبائك كلها و عند كافة المتغيرات التي تم دراستها الا عند الاحمال العالية و لعمق لا يتجاوز ٢-٣ مايكرون. لم يتم الحصول على معلومات تدل على حصول التكسر الميكانيكي لطور السليكون بالمنطقة التحتية.

Introduction

There has been a consistent effort to make increasing use of aluminum in engineering applications especially to replace several scarce non-ferrous metals [1]. Aluminum – silicon particularly, now promise as wear resistant materials. Many studies [2-5] have been carried out to test the resistance to wear and other anti - friction properties. Most of these studies concern the evaluation of the wear rate under dry or lubricated condition as a function of load or speed. There is need for obtaining wear data under all possible conditions of test and

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application in order to formulate specific recommendation for the use of aluminum alloys. A survey of the literature revealed that a systematic study of the dry adhesive behavior of aluminum - silicon alloys had been carried out [6-8].

This investigation was therefore taken up to examine the dry abrasion characteristics of different Al-Si alloys. In comparative study made by different bearing materials, the aluminum-silicon alloy was found to exhibit the lowest wear rate. Several studies [2-10] attempted to determine the influences They are:

1. Presence of silicon progressively reduces the wear rate of aluminum.
2. The eutectic composition exhibits the lowest wear rate among the aluminum-silicon alloys.
3. The wear rate is dependent only on the silicon content and is independent of the initial structure and distribution of the silicon phase.

There is some conflict as regards the last mentioned effect but in general all the conclusions have been confirmed by later studies. It was shown that during the wear of Al - Si alloys, the silicon phase was finely fragmented [7] in the subsurface region, which amply explains the non - dependency of wear rate on silicon structure. Even in other alloys containing a second phase, fragmentation took place in the subsurface region [11]. Addition of a hard particle into the aluminum matrix improved the resistance to adhesive [12,13] In the aluminum-silicon alloys, silicon is present in the elemental form and is harder than the aluminum matrix. Its influence on the abrasive wear of aluminum has not been studied.

In most aluminum alloys wear rate has been observed [9] to exhibit at least two regions of linear variation as function of load. These have been explained as “oxidative” wear at low bearing pressure and “severe” metallic wear at high bearing pressure. These two regions are characterized by wear rates of 10^{-8} $m^3.cm^{-1}$ for the oxidative regime and 10^{-7}–10^{-6} $cm^3.cm^{-1}$ for the metallic regime. In a more detailed study on the effect of pressure in the low ranges [8] it is shown that the oxidative region is actually made up of two different regions: (a) a purely oxidative wear at very low pressures and (b) an oxidative cum metallic regime at moderate pressure. The transition from one type of wear to another is dependent on several parameters of testing such as relative interface hardness, surface roughness, presence of foreign materials at the interface, humidity, temperature etc [6].

Some of the studies have been amply supported by results obtained from the examination of the surface topography of worn specimens, subsurface damage and debris particles studied by scanning electron microscope. But such studies have not been carried out on abrasive conditions of wear. The present paper is an attempt to fill this gap.

Materials And Experimental Procedures

Commercial 2S grade aluminum was used for making the alloys used in the present investigation. For making silicon addition on aluminum-silicon, master alloy containing 22% silicon was used. The chemical analysis of the raw materials used is given in Table I. Three alloys were made for the study containing nominal silicon contents of 3,12,and 22% Si. These alloys represent the hypo-eutectic, eutectic and hyper-eutectic compositions respectively. The aluminum ingot was melted and cast directly to provide the pure aluminum specimen for reference and comparison. Wear pins 10 mm in diameter and 15 mm in length were machined out of the rods. Tests were carried out with all the materials in the as cast condition without any further thermal or mechanical treatments. The two end faces of the cylindrical wear pins were ground on successively finer emery papers down to 240 grades. Care was taken to see that the faces remained parallel to each other and perpendicular to the pin axis.

Table I Chemical analyses of commercial aluminum, aluminum - silicon master alloy, and the various aluminum - silicon binary alloys used in the investigation*.

Material	Chemical analyses in wt. %		
	Silicon	Iron	Titanium
Commercial Aluminum	0.18	0.17	0.009
Master alloy	21.8	0.18	….
Al- 3% Si alloy	3.2	0.16	0.008
Al- 12% Si alloy	12.3	0.14	0.009
Al- 22% Si alloy	20.8	0.18	0.007

* In each material the percentage of aluminum can be obtained by difference.

The wear behavior of the alloys was studied in a modified flat bed abrasive wear tester shown schematically in Fig.1 An endless abrasive belt is maintained in constant motion in one direction continuously by the motor driven shaft M. The wear pin S was carried by a lever a supported at the fulcrum F held in such a way that when there is no load on the specimen the lower face of the pin remains horizontal and close to the abrasive surface without touching it. On application of the dead weight L on to the pin the bearing pressure is directly equal to the gravitation force of the load. The lever arm is so mounted that it can be moved in direction perpendicular to the motion of the belt at a desired constant speed.

At the start of the test the specimen is made to bear on one edge of the abrasive belt. As the belt is set in motion the specimen is moved towards the opposite edge of the abrasive belt at a constant speed such that when the test ends the specimen reaches the other edge of the belt. The speed of movement of the specimen is so selected that it takes exactly 5 minutes to traverse the width of the belt. This time is kept constant for all tests. Wear rate was computed as the volume worn per unit sliding distance ($cm^3.cm^{-1}$) [9]. The sliding speed was maintained at 540 $m.min^{-1}$ for all the tests.

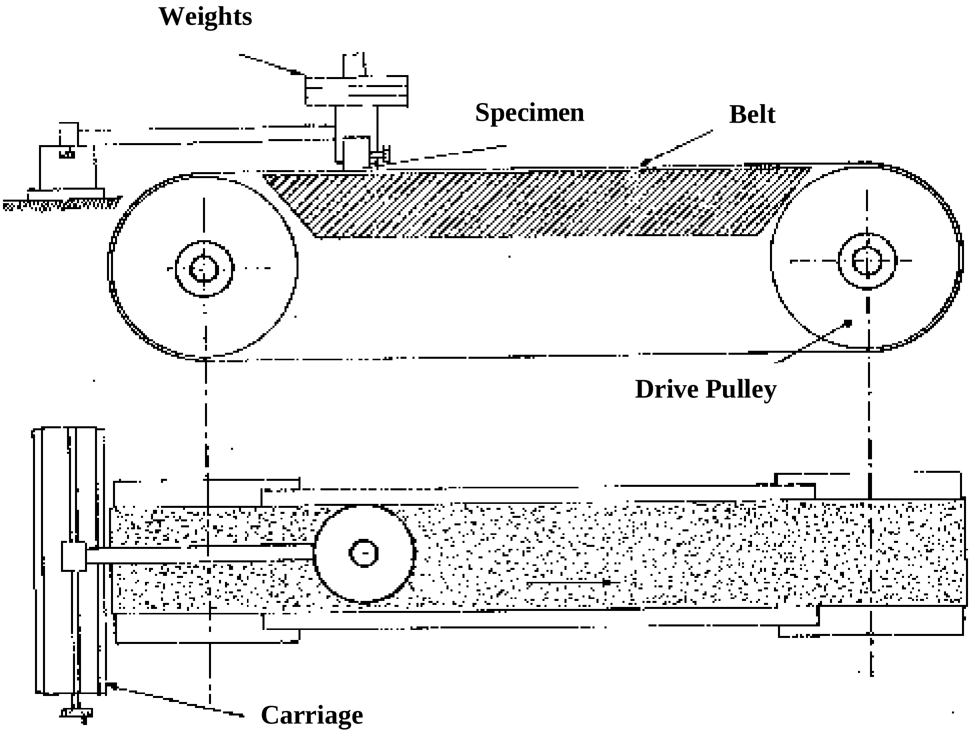

Fig.1 Pin-on-belt abrasive wear testing machine**.**

Wear tests were conducted by changing the bearing load in the range of 0.5 to 6N in step of 0.5N, which corresponds to a bearing pressure range of 0.006 to 0.072 MPa. Scanning electron microscope was used to examine the worn surfaces. Subsurface damages were evaluated from the polished 5° oblique mounted of the worn surface. The debris particles generated during the test were collected and examined under the optical microscope for shape, size and size distribution.

Results

Wear Rates

Fig.2 shows the abrasive wear rates of the aluminum and Al-Si alloys as a function of bearing load. . When wear loss was plotted as a function of running time it was observed that the wear rate slowly increased and attained a constant value in about 30-40 sec.

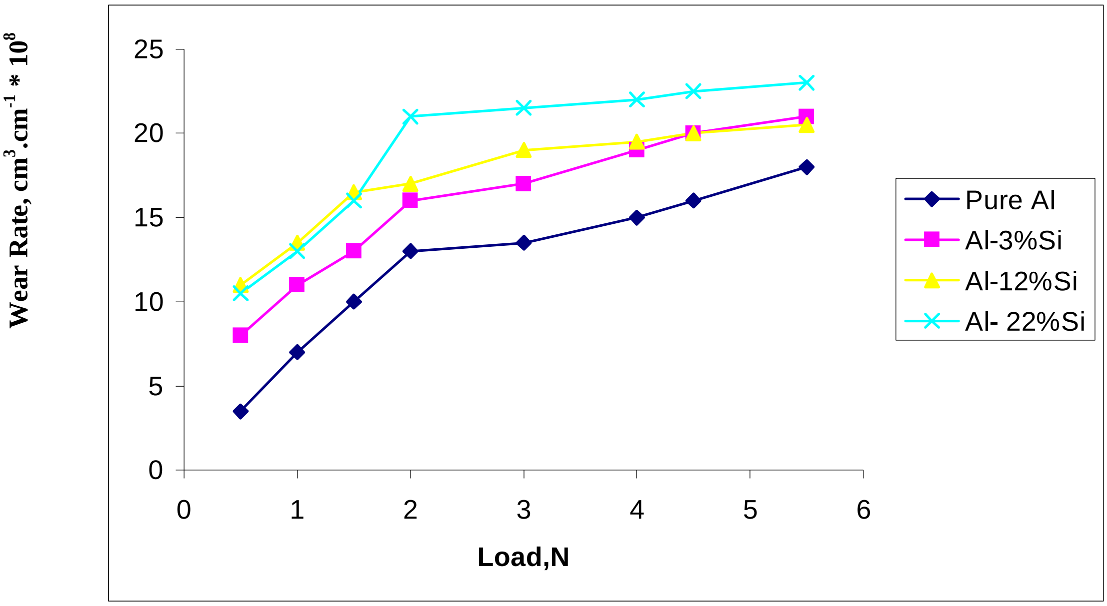

Fig.2 Abrasive wear rate of Al-Si alloys as a function of bearing load.

The total test period of 300 sec was therefore considered to be largely adequate to generate steady state wear condition. Fig.3 shows the effect of varying the specimen diameter from 4 to 10 mm. Except for the lowest diameter used, the wear rate calculated from weight loss measurement was independent of specimen diameter. Fig.3 gives a typical set of data. A similar result was obtained with all the material investigated. Thus direct comparison of results was justified although the diameters of all the specimens were not the same.

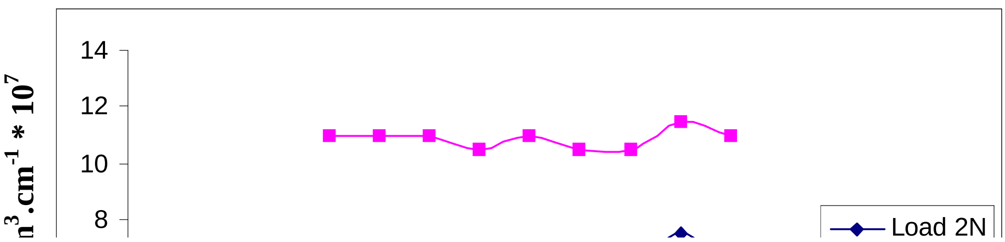

Fig.3 Abrasive wear rate of Al-22wt% Si as a function of Pin diameter.

Topography of Worn Surface

All freshly worn surfaces were examined in the SEM to determine the nature of the track patterns of abrasion and material removal. Fig.4 shows a set of secondary electron images of a worn surface in an Al-12%Si alloy worn at 4N loads. IN load represents a low load region of wear and 4N represents a high load region.

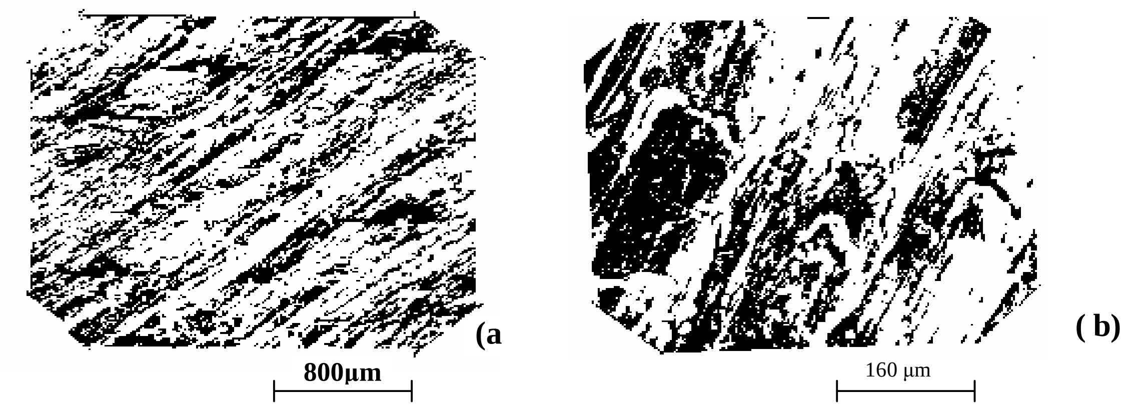

Fig.4 Low magnification worn-surface SEM photographs at different bearing loads (a) 1N and (b) 4N.

Subsurface Effects

All worn specimens were examined by the taper sectioning technique [7]. Fig.5 shows the structures observed in typical specimens of Al- 3% Si alloy for applied loads of 1N and 6N. It was observed that unlike the case of adhesive wear [9,11] practically at all loads structural changes were not extensive at the interface. It was noticed that the specimen became measurably hot during the experiment, but the structure of the material close to the interface nearly remained unchanged. In the high load experiments a shallow region of change was observed which was 2-3 *mm* in depth.

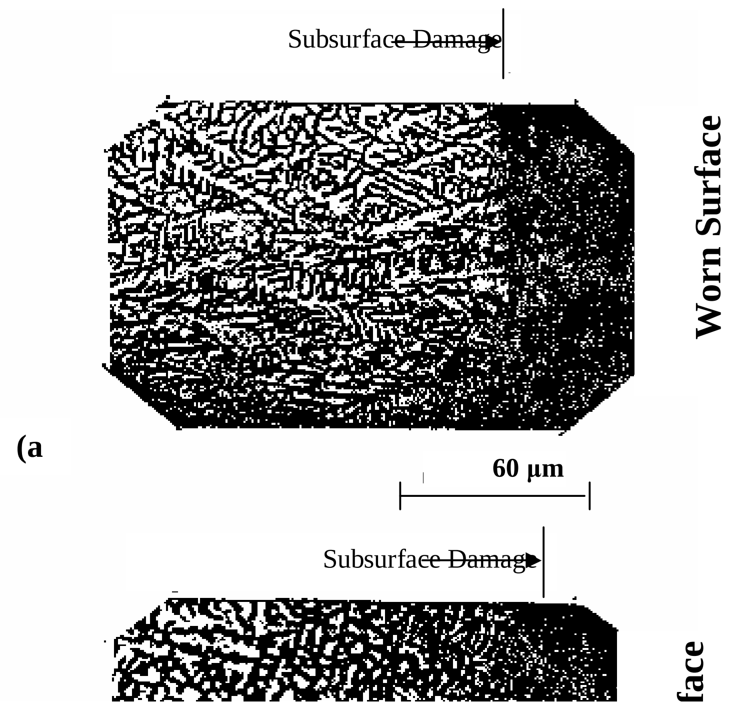

Fig.5 Structure of subsurface damage of Al-3% Si at different bearing loads, (a) 1N and (b) 6N.

Debris Examination

Debris analysis forms an important part of wear testing. Typical structures of debris collected are shown in Fig.6 for the alloys investigated. Representative samples were examined to confirm both the low and high loads regions. It is seen that most of the debris particles have lengths larger than the width or the thickness expressive of the purely abrasive nature of the wear. This also confirms that adhesive type of wear is nearly absent in these experiments. Fig.7 shows high magnification photographs of some individual debris particles to reveal the structural features.

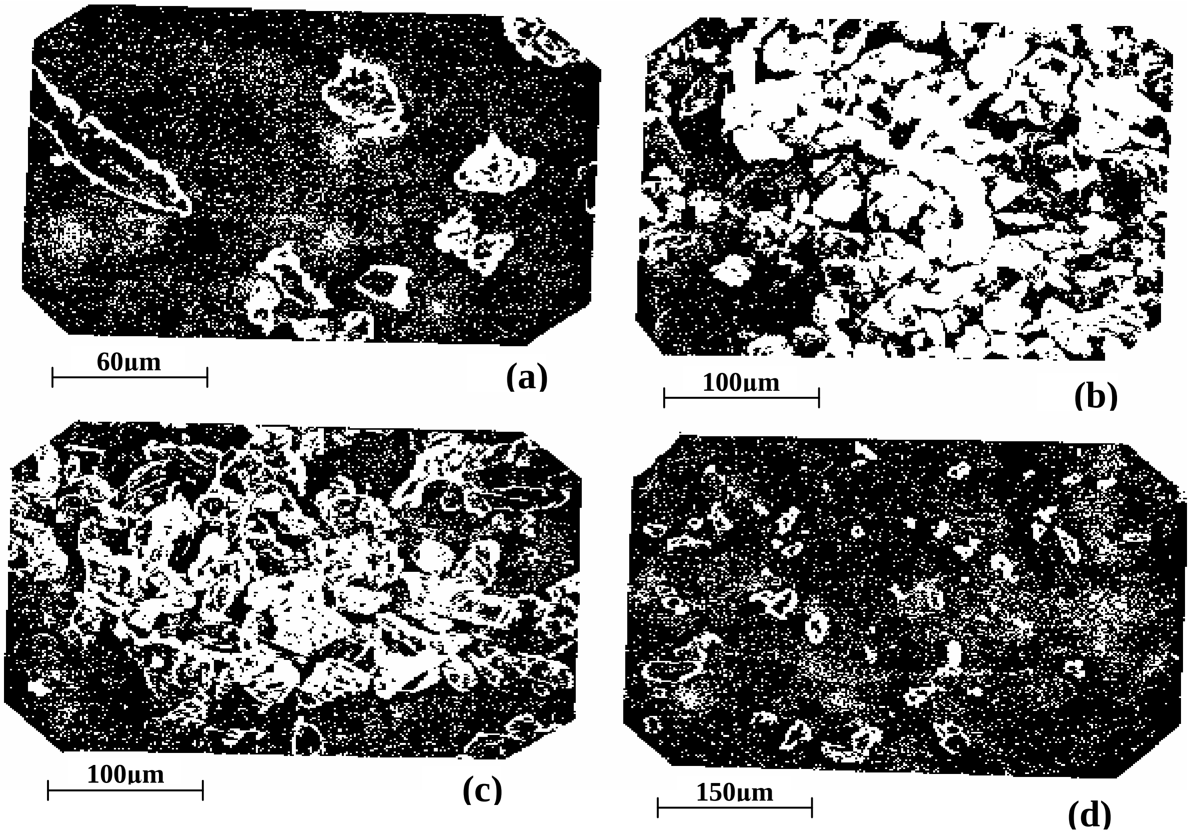

Fig.**6** General distribution of wear debris of Al-13% Si (a),(b) 1N,(c) and (d) 6N.

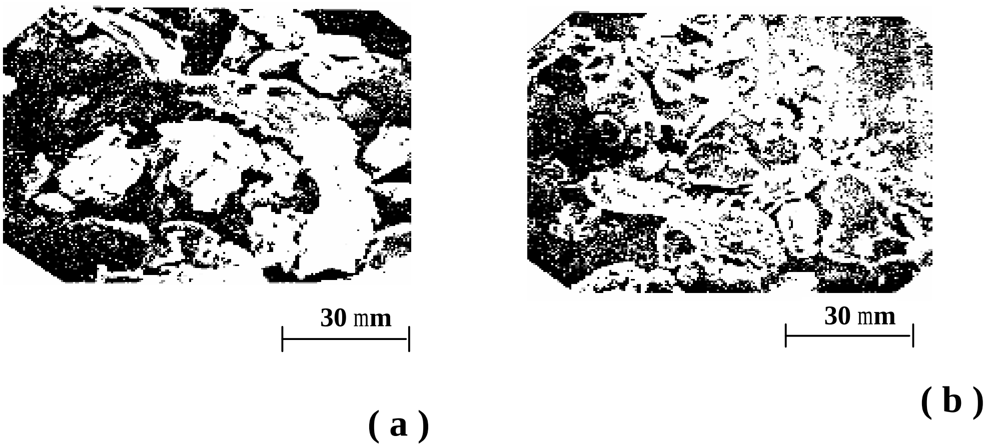

Fig.7 Higher magnification SEM photographs of Al-13% Si showing a long debris**.**

Discussion of Results

Abrasive Wear Behavior

The wear rates observed in Al and the various Al - Si alloys are in the range of 10-7 to 10-6cm3.cm-1, which for abrasive conditions may be considered as moderately severe. The first observation made is that for all values of applied load the wear rate in aluminum is smaller than in the Al-Si alloys. This behavior is readily traced to the presence of the brittle silicon phase, which easily fractured under the impact of the protruding abrasive particles and chip off forming the debris particles.

All the wear rate-load relations (Fig.2) exhibit a bilinear behavior in the load range tested with a transition point at a load 2N in all the alloys. In the interpretation of wear data, a change in the slope in a linear relation between wear rate and load has been taken to indicate a change in the mechanism of wear. On the same premise, in pure aluminum as well as in binary aluminum - silicon alloys there is thus a change in the mechanism of material removal at load of 2N under abrasive conditions of wear. Interestingly a similar bilinear relationship was also observed for adhesive conditions in Al-Si alloys [6-8]. On the other hand Al–Al2O3 and Al–Al2O3–MgO [14] composites exhibited single linear relationship up to a load of 12N. In these composite materials and Al-22%Si- Al2O3 the presence of the non-coherent oxide material was shown to produce a large number of asperities and exposed surfaces and thereby shifted the transition point to a high value of load [14,15]. However the data for high load conditions is not available to confirm this viewpoint. It can be said that bilinear variation of wear rate with load is a typical behavior of all aluminum-based alloys, but not of composites.

By analogy with the data obtained with several other aluminum-based alloys it can be said that the wear in the low load region is somewhat related to the oxidation behavior of the material and the wear is under oxidative control. in the high load region gross material removal makes oxidation only secondary so that wear is under sever wear region On the other hand , Why exactly this change should take place at a load of 2N is still not clear.

Effect of Silicon Content

Reference to Fig. 2 reveals that the slope of plots below the transition load of 2N is nearly the same for all the alloys, while above the transition load the slope of the line is dependent on the composition of the alloy. The slope increases with increasing silicon content of the alloy. In the case of the Al- 22% Si alloy, the wear rate for all loads larger than in all other alloys. Clegg and Das obtained a similar result and interpreted it to be typical of all hypereutectic Al-Si alloys, especially at load values higher than 5N.

The present set of data is an extension into the low load region below 5N. One can therefor comment on the behavior of the Al-Si alloys [16] in the complete load region from 0.5 N to about 20N. While under conditions of purely adhesive wear, the Al-Si alloys are more resistant to wear under purely abrasive conditions of wear .The Al-Si alloys show a higher wear rate. Thus in applications involving surface finishing operations, Al-Si alloys are better than commercial aluminum and its other single phase alloys. Among the Al-Si alloys the eutectic and hyper - eutectic compositions are superior to the hypo - eutectic alloys.

Presence of silicon in the alloy gives an observable change in the wear behavior. These changes may readily be observed in a plot of wear rate vs. silicon content shown in Fig.2. Wear rate clearly increases with increasing silicon content at all bearing loads more or less in a similar manner. The maximum efficiency of removal seems to be reached at about the eutectic.

Topography of the Worn Surface

All the worn specimens revealed the formation of grooved track patterns generated by the scuffing from the abrasive (Fig.4). On a closer examination of the high magnification photographs (Fig.4 a and b) The presence of micro cracks with their length perpendicular to the sliding direction was observed. The appearance of these cracks was different for the two load regions. In the low load region the cracks were shallow and there was no indication of plastic deformation on the surface. Fig.4 a and b are typical of wear surfaces in this region. In the high load region, in addition to the scuffing marks, evidence was seen for some amount of plastic deformation having taken place. Cracks formed were deeper and longer. Often the cracks were wilder than the wear tracks.

Thus at low loads the abrasive edges stood proud of the surface on the emery cloth cuts through the metal. In the high load region some of the debris particles may roll through the interface causing deformation at the interface. The size and characteristics of the debris particles afford further evidence for this observation.

Subsurface Damage Effects

In all adhesive type of wear processes, existence of subsurface effects has been reported. In this study on abrasive wear structure in the subsurface region (Fig.5) did not reveal any such change in the structure. In the single phase ductile materials this effect is manifested as a plastically deformed layers so that material removal takes place by crack formation, its propagation parallel to the interface, crack branching normal to the surface, delamination and detachment.In the aluminum-silicon alloys the subsurface region was marked by the fragmentation of the silicon phase. In the present case at low loads, no subsurface effect was identified (Fig.5a). Even in the high load experiments the structure below the surface was only suggestive of some effect having occurred (Fig. 5 b).

From observation of the debris (Fig.6) it was noted that the size of the debris particles formed was much larger than the subsurface depth measured. It may therefore, be concluded that the protruding abrasive particles were cut through the metal to produce the grooves and any plastic deformation is only possible due to the debris particles rolling in the interface. This again is confirmed by the smooth surface of the debris particles when observed at high magnification. This fact suggest that as far as abrasive wear concerned the internal structure and mechanical properties of the material exert a significant influence on the wear behavior. While in purely adhesive wear it has been shown that the wear is to a considerable extent controlled by the structure of the subsurface, and by the interface properties.

On an overall consideration of result presented here, it may be said that wear by abrasion in aluminum-based alloys is controlled by the interface characteristics at very low loads. At high loads it is, at least partly, controlled by the intrinsic mechanical properties. Also at loads below the transition point, by analogy with theories proposed for adhesive wear, it may be said that oxidation of the alloys controls the wear rate. While at higher loads, it is the failure of the alloy that controls the wear rate. Presence of silicon, which is weak, and brittle gives rise to a higher wear than in pure aluminum.

The above set of data have been obtained with a 240 grade emery paper it must be added here that when the roughness of the emery papers was changed the major characteristics of the findings remained unaltered except in the absolute value of the wear rate. As the emery was changed from 80 to 600 meshes, the wear rate decreased continuously up to 240 mesh and they're after it remained nearly constant. For 240 grade and finer emery paper, the wear rates are typical and are similar to values reported in this study.

Conclusions

1. Both aluminum and binary aluminum-silicon alloys containing up to 22% silicon show two linear regions of wear in the load range 0.5 to 6 N with a transition at 2N.
2. In the low load regions wear is under oxidative control while, at high loads metallic failure takes place resulting in large debris particles being removed from the surface by the protruding abrasive particles.
3. In the oxidative region, surface wear tracks are smooth and do not show any signs of plastic deformation. Micro cracks are observed to be present.
4. At high loads, the wear tracks exhibit larger cracks, and show evidence of plastic deformation having taken place and metal failure.
5. Debris particles show characteristics reminiscent of the wear process described and lend support to the hypothesis drawn.
6. Subsurface effects are not observed in the worn specimens. Only in specimens worn at very high loads a shallow region of 2-3 mm is observed.

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