The Effect of Removing Worn Particles by Ultrasonic Cleaning on the Wear Characterization of LM13 Alloy

M. Haji Ghassemi[a], V. Abouei[b], M. Moshtaghi[c], M. Talafi Noghani[a]

[a]*Department of Material Science and Engineering, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran*
[b]*Department of Material Science and Engineering, Azad University, Karaj, Iran*
[C]*School of Metallurgy and Materials Engineering, Faculty of Engineering, University of Tehran, Tehran, Iran*
e-mail: masoud.moshtaghi@gmail.com

In this research, three dry sliding wear tests have been carried out with a pin-on-disk apparatus at the sliding speed of 0.17 m/s and under 30 N normal load. The eutectic aluminium-silicon alloy (LM13 alloy) and tool steel have been selected as wearing surfaces. In order to focus on the effect of worn particles, they have been removed periodically by ultrasonic cleaning during one test, while another one has been carried out without applying ultrasonic cleaning. To study the variation of the wear behavior, one more test has been running continuously. During the formation and removal of the tribolayer under the control of the wear behavior without ultrasonic cleaning, a mild wear regime and a lower wear rate have been observed. As to the severe regime, it has been observed at the removal of some parts of the tribolayer when the cleaning was applied.

Keywords: sliding wear, ultrasonic cleaning, tribolayer, tribology, LM13 alloy.

УДК 539.3

INTRODUCTION

The mild wear regime is one of the main regimes when Al-Si alloys are exposed to dry sliding wear [1, 2]. It is generally attributed to the presence of a mechanical mixing layer (tribolayer) and surface oxidation. The formation of this layer is favorable because it prevents the tribosystem from seizure. In the reported investigations on Al-Si alloys, the subjects of the study are transition from mild wear regime to the severe one and metallic wear and seizure behavior [2, 3].

The severe wear regime is described as metallic wear due to the shiny appearance of severely deformed surfaces. Scuffing is associated with the dramatic rise in the wear rate at a critical load, accompanied with the appearance of microweldments on the surface [4].

Seizure has been categorized into the friction seizure and galling seizure. The former occurs when the sliding motion stops as a result of the non-availability of the driving force in excess of the friction force. No severe surface damage is observed in this case. A sharp rise in the wear and extensive surface damage with respect to a small increase in external variables are the signs of the galling seizure [4].

Researchers dealing with wear tests based on the standard test method for wear testing with a pin-on-disk apparatus (such as ASTM G 99) [5] use the ultrasonic cleaning before testing. Cleaning by an ultrasonic bath involves using high-frequency waves (about 18 KHZ) in order to remove a variety of contaminants and other possible particles from pins which have been immersed in an aqueous medium. It is necessary to find whether the pins shall be cleaned or not when the machine is stopped to measure the mean weight loss within the defined intervals and distances. It is supposed that ultrasonic cleaning leads to the removal of a certain amount of worn particles at the each stop. There is some evidence that wear characterization of alloys is affected by the presence of worn particles [2]. Commination, agglomeration, and compaction of worn particles are the main factors in the formation of a tribolayer [2, 6].

The purpose of the present study is aimed to investigate differences which are made by removing of worn particles by ultrasonic cleaning on the wear characteristics of LM13 alloy.

EXPERIMENTAL PROCEDURE

The pin–on-disk configuration was employed as the wear test rig where wear samples of eutectic Al-Si alloy pin (5 × 5 × 10 mm) slide against the counterface of an AISI/SAE 52100 steel disk with a hardness of 60 ± 2 HRC (60 mm diameter and 10 mm thickness). Commercial ingots of Al-12Si were used to cast the pin. The composition of the eutectic Al-Si alloy is given in Table 1. The samples were tested under the normal load of 30 N, at a constant sliding speed of 0.17 m/s, and a constant time of one hour.

Table 1. Chemical compositions of the experimental alloy (Wt %)

Si	Fe	Ni	Cu	Mg	Zn	Al
12.64	0.41	1.1	1.01	0.98	0.018	balance

In order to investigate the effect of ultrasonic cleaning on the wear behavior of the alloys, three

© Haji Ghassemi M., Abouei V., Moshtaghi M., Talafi Noghani M., Электронная обработка материалов, 2015, **51**(4), 76–83.

series of wear tests were conducted. In the first experiment, named A1 mode, the wear test was running continuously without cleaning, and mean weight loss was measured at the end. In the second one. A2 mode, the pin was weighed periodically (every fifteen minutes) without applying ultrasonic cleaning. In the last one, A3 mode, before the test initiation, the pin was cleaned by an ultrasonic bath to remove contaminants and acetone selected as aqueous medium. Then during the A3 test, each fifteen minutes the pin was removed from the test rig to check the weight and apply ultrasonic cleaning. Next, A2 and A3 test conditions were compared and each mode was repeated three times to evaluate reliability and the mean weight loss determined as a function of the sliding distance to a precision of 0.1 mg, then wear rates were calculated by the mean weight loss.

The tests were done in air atmosphere at a relative humidity of 40 ± 2% at room temperature (25°C). A scanning electron microscope (SEM) equipped with the energy dispersive X-ray spectroscopy (EDS) was used to characterize compositions and morphologies of the worn surfaces, the cross-section below the worn surfaces of the pin, and the loose debris particle generated during sliding wear. In each test the condition of the disk remained constant and the study of the wear behavior of the disk was neglected to focus on the wear behavior of pins.

RESULTS AND DISCUSSION

Wear rate

Figure 1 displays a comparison between the mean weight loss of the pin in A1, A2, and A3 modes. In both A1 and A2 modes, the amount of the weight loss remains steady. It can be observed that the maximal weight loss is during A3 mode. So, it can be inferred that the periodical cleaning creates a detrimental effect on the wear behavior of the alloy.

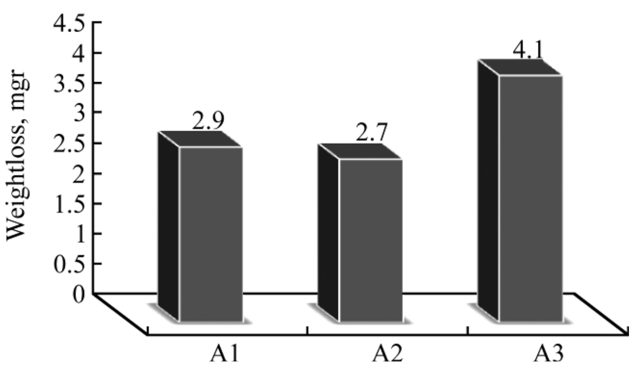


Fig. 1. Comparison between mean weight loss of A1, A2, and A3 modes.

Figure 2 shows the variation of the wear rate of A1, A2, and A3 modes as a function of the sliding distance (153, 306, 409, and 612 m) with the constant normal pressure and sliding speed. Since the beginning of the test at 153 m of the sliding distance, the wear rate of A3 mode has been higher than at A2 mode. However, there was no difference in conditions apart from ultrasonic cleaning. It is known that removing contaminants from surface before starting the test, causes a higher opportunity of a direct contact and also affects the ability of contacts between asperities. In general, contaminates weaken the power of asperities in the interface [7].

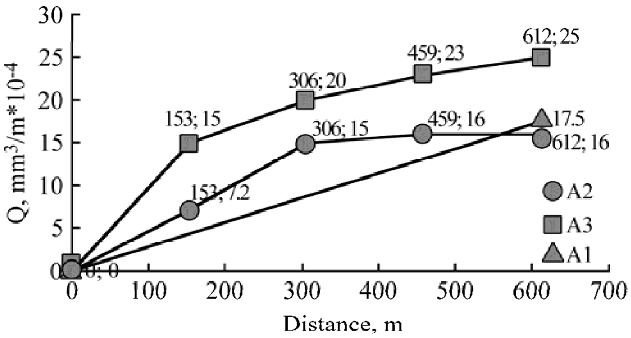


Fig. 2. Variation of wear rate versus distance for A2 and A3 modes.

Another point in Fig. 2, worth of discussion is attainment of the steady state in A2 mode after a certain transient period. But this state was not observed in A3 mode and there is an increasing trend in this case and severe-mild transition did not occur. The attachment of wear particles is necessary for the severe-mild regime transition. The steps of this transition are: (i) mild wear particle formation; (ii) its attachment to the surface; (iii) its spreading over the sliding surface [8].

Initiation of the steady state is attributed to the presence of a tribolayer. Once the steady state is reached after a certain transient period, the mechanically mixed layer (MML) formation rate and the fracture rate shall be necessarily equal. Consequently, the thickness of the tribolayer will remain constant and independent of time/sliding distance [6].

Study of Wear in A1 mode

According to Fig. 3a, there are two distinct regions over the pin surface in A1 mode: smooth and crater regions. It is clear that these regions are covered by some equiaxed particles (Fig. 3b) which had oxide in their composition as examined by the EDS (Table 2). These particles over the smooth region could be entrapped between the sliding surfaces and get compacted due to the repetitive sliding. Then, a tribolayer can be formed over the surface [9].

During sliding, high tangential stresses take place at the sliding surface, resulting in the nucleation of cracks within the plastically deformed material beneath the surface. The cracks can be propagated and their connection to each other can lead to delamination of metallic particles and oxide film from the surface [9, 10]. This delamination can result

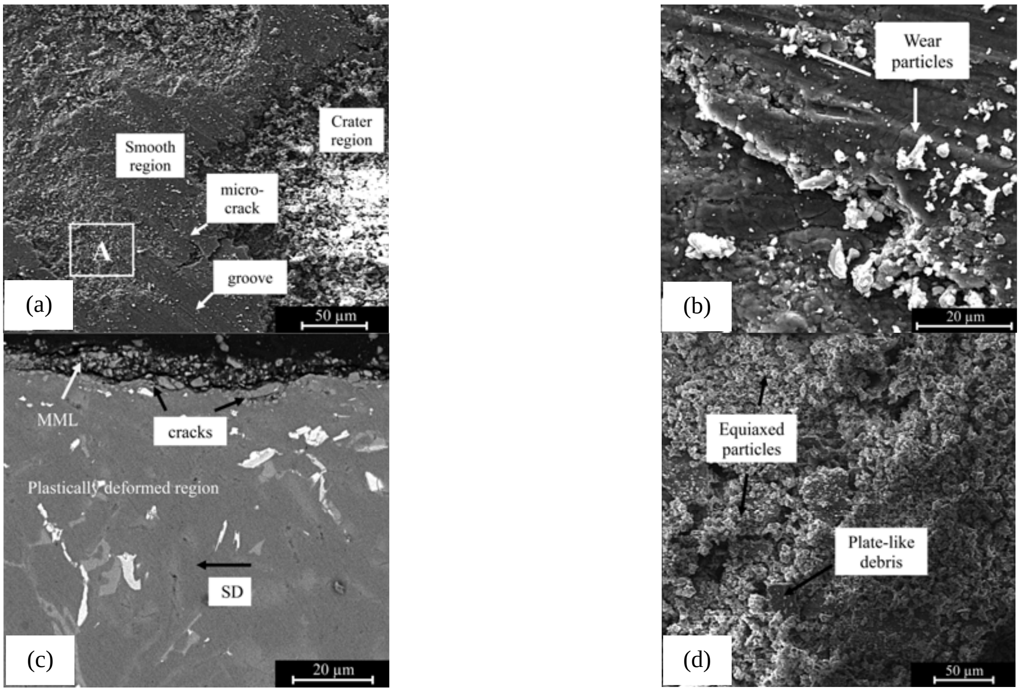
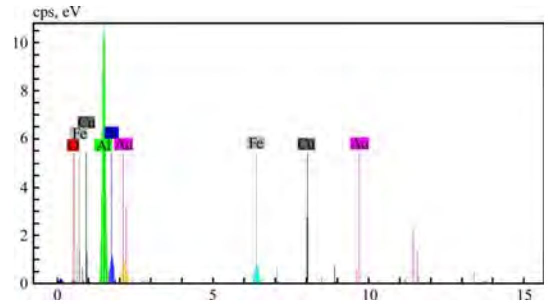


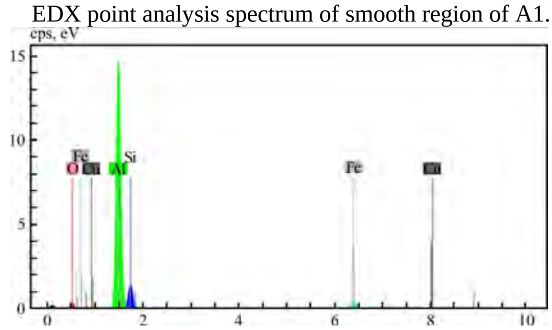
Fig. 3. In A1 mode: (a) SEM micrograph of worn surfaces; (b) enlarged view of the marked region (A) in the micrograph; (c) longitudinal cross-section of the worn surface; (d) SEM micrograph of wear debris.

Table 2. EDX point analysis of A1

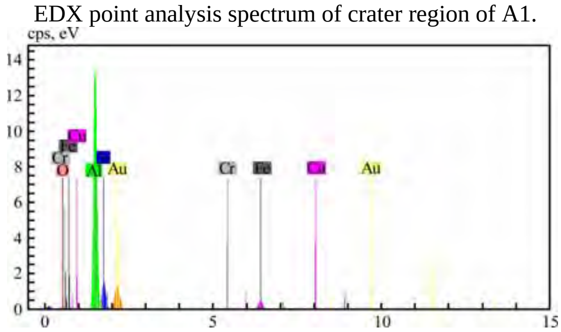
	Element (at%)			
	Al	Si	O	Fe
Smooth region	67.74	8.64	10.47	10.06
Crater region	67.10	8.49	19.09	4.79
Wear debris	67.07	9.58	9.88	7.69



EDX point analysis spectrum of smooth region of A1.



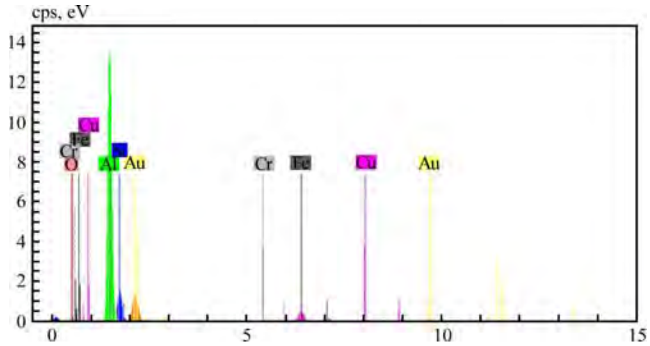
EDX point analysis spectrum of crater region of A1.



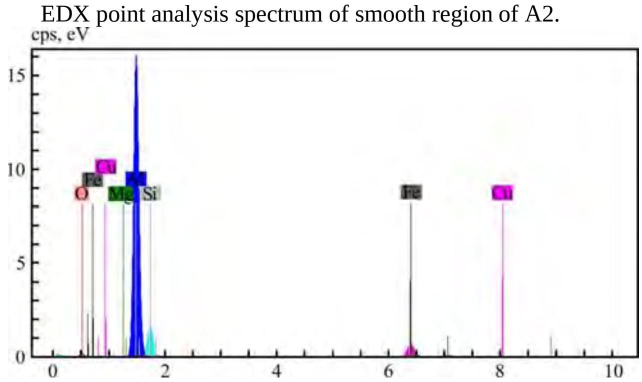
EDX point analysis spectrum of wear debris of A1.

Table 3. EDX point analysis of A2

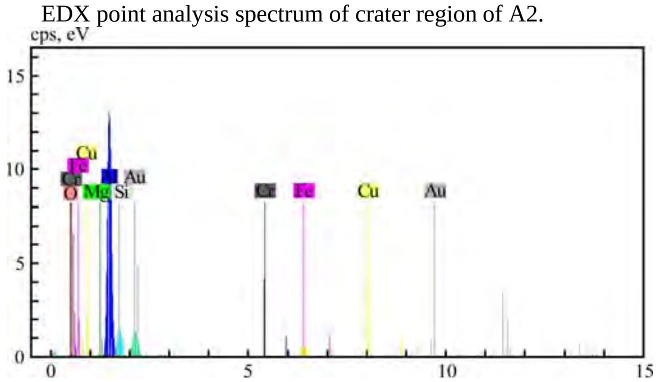
	Element (at%)			
	Al	Si	O	Fe
Smooth region	67.07	9.58	9.88	7.60
Crater region	67.86	9.47	11.76	10.52
Wear debris	66.64	9.05	9.64	9.04



EDX point analysis spectrum of smooth region of A2.



EDX point analysis spectrum of crater region of A2.



EDX point analysis spectrum of wear debris of A2.

in the formation of a crater region. Besides, a number of other damage mechanisms are exhibited such as micro-cracks and grooves in the surface of pin. It is reasonable to admit that the presence of grooves is attributed to a ploughing effect of eutectic silicon.

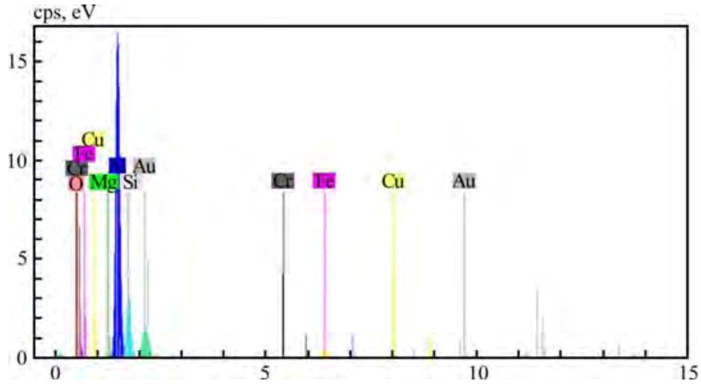
Fig. 3c shows the subsurface micrograph of A1 mode. There, a tribolayer with distinctly different morphology from that of the substrate can be observed. It is due to the presence of fragmented particles formed by the delamination mechanism. Those particles can be reduced in size due to a load and mechanically mixed with the oxides in the contact zone, thus forming a tribolayer. Also, extensively cracks in the layers and plastic deformation in the substrate metals as a second region were observed. In the third region no deformation was observed. The stress on the surface during sliding can weaken the tribolayer and consequently lead to the delamination and fracture of the oxide film which is generated through the wear debris. Fig. 3d depicts two types of morphologies of wear debris, gathered in A1: (i) agglomeration of very fine equiaxed particles and (ii) plate-like debris. Table 4 reveals that there is a significant amount of iron, aluminium and oxygen in the wear debris, which is approximately similar to the elemental analysis of the worn surface (Table 2).

Studies of wear in A2 mode

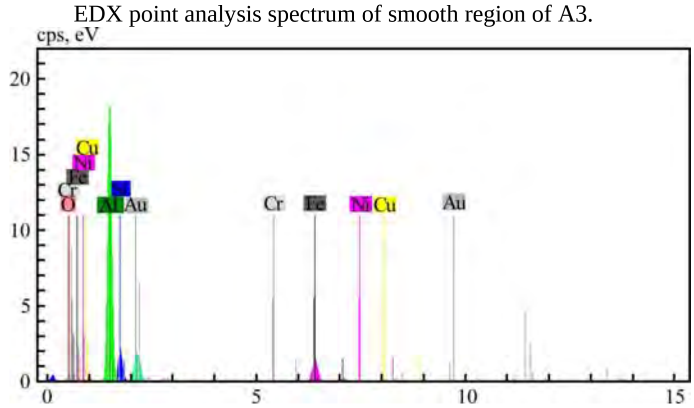
The SEM micrograph of the worn surface in A2 mode reveals some damages which were observed also in A1 mode (Fig. 3a, Fig. 4a). According to the EDS analysis (Table 3) and SEM micrograph (Fig. 4a), microstructural features of particles pre-

Table 4. EDX point analysis of A3

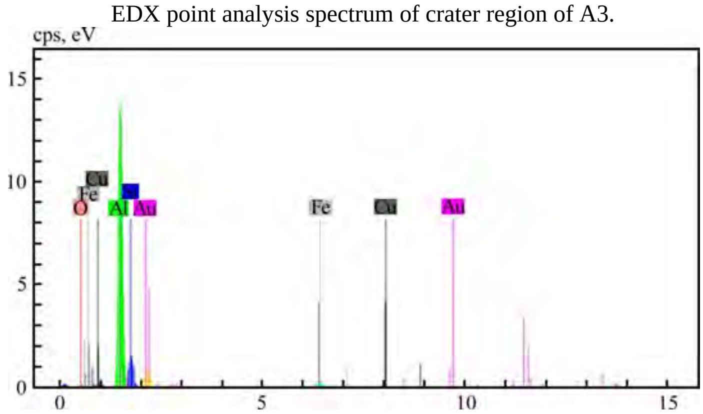
	Element (at%)			
	Al	Si	O	Fe
Smooth region	70.30	17.15	0.82	5.08
Crater region	68.73	8.37	10.24	8.94
Wear debris	79.16	10.08	2.72	3.66



EDX point analysis spectrum of smooth region of A3.



EDX point analysis spectrum of crater region of A3.



EDX point analysis spectrum of wear debris of A3.

sented on the surface are the same in both A1 and A2 modes. Also, oxide particles, predominantly existing on the worn surface, play a significant role in the formation of a tribolayer. Similar circumstances in the subsurface micrograph and morphology of wear debris of A1 and A2 modes indicate that wear mechanisms of both are the same (Fig. 4b, Fig. 4c).

Studies of wear in A3 mode

According to Fig. 5a, both crater and smooth regions were observed in A3 mode. In general, crater regions are one of the main illustrations of the delamination mechanism. Examination of smooth regions by SEM and EDS (Fig. 5a, Table 4) revealed that a great number of worn particles have been removed from the smooth regions; and, in comparison with A1 and A2 modes, a number of these particles on the surface has decreased. However, some worn particles have been trapped in grooves (Fig. 5b).

Because of the removal of wear particles and a gradual decrease in surface roughness, the possibility of a direct contact in A3 mode is higher than in A1 and A2, so that wear damages extensively extend. The EDS analysis of crater regions (Table 4) shows that oxide particles cannot be removed by ultrasonic cleaning.

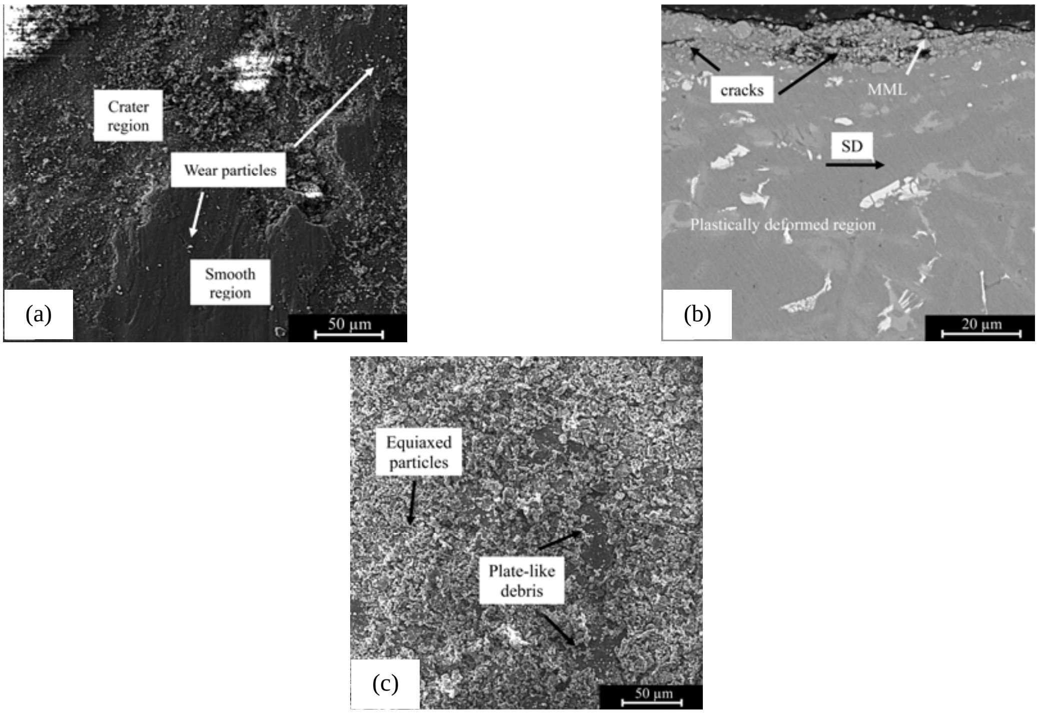


Fig. 4. In A2 mode: (a) SEM micrograph of worn surfaces; (b) longitudinal cross-section of the worn surface; (c) SEM micrograph of wear debris.

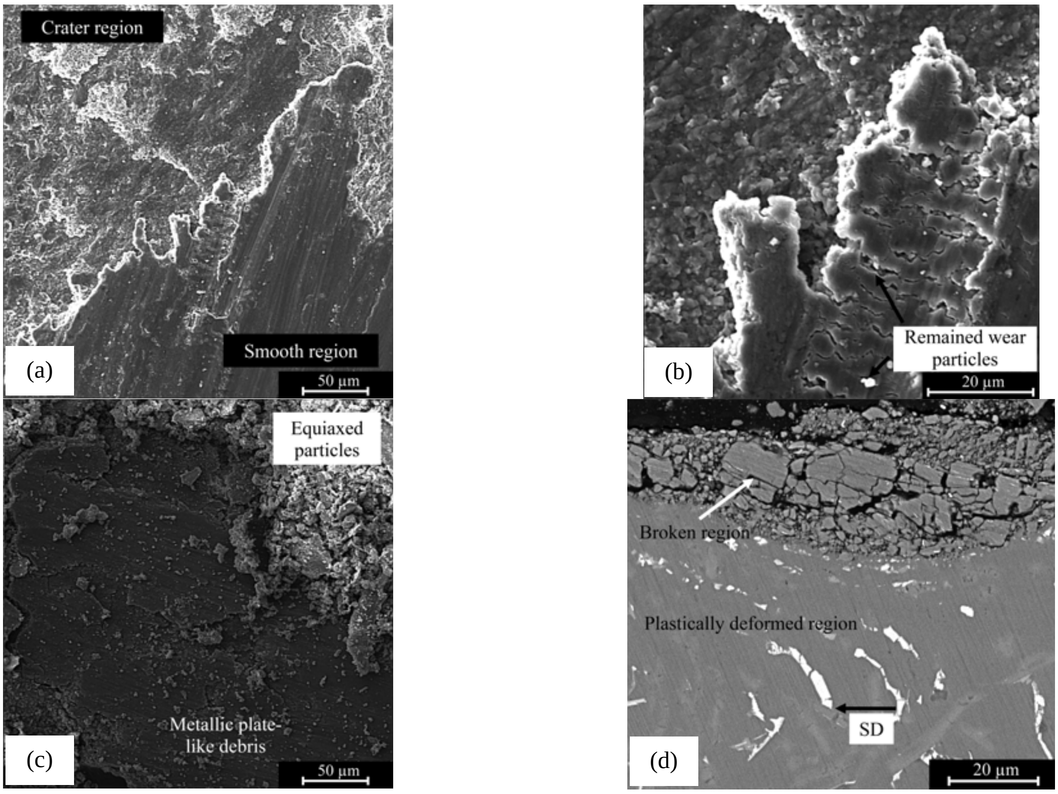


Fig. 5. In A3 mode: (a) SEM micrograph of worn surfaces; (b) enlarged view of worn surface; (c) SEM micrograph of wear debris; (d) longitudinal cross-section of the worn surface.

The debris made up a mixture of fine equiaxed particles and plate-like flakes with metallic features (Fig. 5c). Table 4 shows that plate-like particles in A3 mode were removed monolithically from the alloy because of the similarity between the chemical analysis of the pin (Table 1) and wear debris. In general, metallic wear particles were formed by plastic delamination and/or gross material transfer by seizure [11].

Fig. 5d shows that the subsurface of A3 mode consists of broken plastically deformed regions and bulk undeformed regions. The presence of these regions in the subsurface micrograph can be the sign of the occurrence of the severe regime. It is well known that the severe regime is initiated when the subsurface undergoes plastic yielding [16]. In this case, softening material appears near the surface due to a direct contact between metals, and a high temperature of the interface results in expansion of plastic regions [12]. When the whole apparent contact surface is covered with the plastic region, the plastic deformation level changes from the order of asperity of roughness to the order of apparent contact area and thus, the wear mode would become severe and seizure occurs [12]. Furthermore, the near surface temperature may be sufficiently high to decrease the shear strength substantially in a subsurface. This promotes extensive shear in planes parallel to the sliding surface and as a result (at a certain depth), the shear take place across the whole surface and then macro-displacement occurs [4].

Investigation of wear mechanisms of A1, A2, and A3 modes

Mechanisms of the tribolayer formation are shown in Fig. 6 in three modes determined by measuring the mean weight loss and studying worn particles.

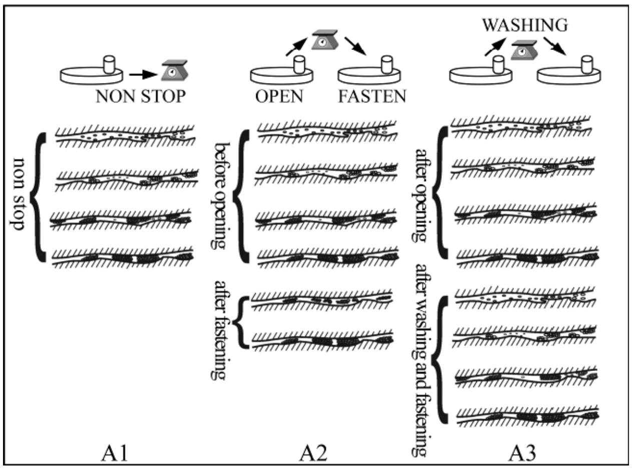


Fig. 6. Scheme of tribolayer formation mechanisms in A1, A2, and A3.

In A1 mode, a non-stop test was carried out and ultrasonic washing was not applied. In this case, the formation of a tribolayer was accompanied with agglomeration and compaction of wear particles.

In A2 mode, the test was stopped and the sample was not washed. Before the sample is taken out of the test instrument, the mechanism of the tribolayer formation is similar to that of A1 and after placing the test and size of wear particles were reduced as a result of sliding motion. On the other hand, in each stop, heat which is generated during test can be decreased and ductility of underlayer can decline in comparison with A1. So, it cannot be expected that thickness of A2 tribolayer is the same.

In A3 mode, the sample has washed during each stop. Although A1 mechanism could be repeated at each cycle, after a while the ability of creation of worn particles reduced. Thus, a tribolayer cannot be formed again.

CONCLUSIONS

The effect of removing worn particles by ultrasonic cleaning on the wear characterization of LM13 alloy was investigated. The following conclusions can be made:

In A1 and A2 modes, the formation of a tribolayer is followed by agglomeration and compaction of wear particles. The wear behavior of A1 and A2 modes was approximately the same. Ultrasonic cleaning removed a great amount of wear particles from smooth regions. A3 mode had the highest wear rate due to a direct contact in the absence of wear particles and it experienced a severe regime.

REFERENCES

1. Elmadagli M., Perry T., Alpas A.T. A Parametric Study of the Relationship between Microstructure and Wear Resistance of Al-Si Alloys. *Wear*. 2007, **262**, 79–80.
2. Clarke J., Sarkar A.D. Wear Characteristics of As-cast Binary Aluminum-silicon Alloys. *Wear*. 1979, **54**, 7–16.
3. Das S., Prasad S.V., Ramachandran T.R. Tribology of Al-Si Alloy-graphite Composites: Tribo Induced Graphite Films and the Role of Silicon Morphology. *Mater Sci Eng A*. 1991, **138**, 123–132.
4. Somi Reddy A., Pramila Bai B.N., Murthy K.S.S., Biswas S.K. Wear and Seizure of Binary Al-Si Alloys. *Wear*. 1994, **171**, 115–127.
5. ASTM G99. *Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus*. ASTM International. United States. 2007.
6. Venkataraman B., Sundararajan G. Correlation between the Characteristics of the Mechanically Mixed Layer and Wear Behavior of Aluminium Al-7075 Alloy and Al-MMCs. *Wear*. 2000, **245**, 22–38.
7. Gohar R., Rahnejat H. Fundamental of Tribology. London: Imperial College Press, 2008. pp. 20–74.
8. Hiratsuka, Muramoto K. Role of Wear Particles in Sever-mild Wear Transition. Wear. 2005, **259**, 467–476.
9. Abouei V., Shabestari SG., Saghafian H. Effect of Fe-Rich Intermetallics on the Wear Behavior of Eutectic Al-Si Piston Alloy (LM13). *Mater Charact*. 2010, **61**, 1089–1096.
10. Abouei V., Saghafian H., Kheirandish Sh. Effect of Microstructure on the Oxidative Wear Behavior of Plain Carbon Steel. *Wear*. 2007, **262**, 1225–1231.
11. Deuis R.I., Subramanian C., Yellupb J.M. Role of A193 Fiber in Eutectic Al-Si Alloy. *Compos Sci Technol*. 1997, **57**, 415–435.
12. Nakahara T. A Model of Seizure Based on Burwell and Strang's Concept of Wear Mode Transition. *Tribology and Interface Engineering Series*. 2005, **880**, 547–553.

Received 19.09.14
Accepted 24.11.14

Реферат

В настоящей работе приведены результаты трех исследований трения скольжения в условиях сухого трения, которые были проведены с помощью аппарата шифт-диск при скорости скольжения 0,17 м/с и при нормальной нагрузке 30 Н. Эвтектический сплав алюминий-кремний (сплав LM13) и инструментальная сталь были выбраны в качестве образцов изнашиваемых поверхностей. Чтобы учесть влияние изношенных частиц, в течение одного испытания они удалялись периодически с помощью ультразвуковой очистки, в то время как в другом отбор частиц проводили без применения ультразвуковой очистки. Для изучения изменений в характере износа, еще один тест на износ проводился при непрерывной работе. При контроле износа – исследовании формирования и удаления изнашиваемого слоя в условиях без ультразвуковой очистки, наблюдался мягкий режим износ и низкая скорость износа. Что касается тяжелого режима, было замечено удаление некоторых частей изнашиваемого слоя, в случае, когда очистка была применена.

Ключевые слова: износ скольжения, ультразвуковая очистка, изнашиваемый слой, трибология, сплав LM13.