Dry sliding wear of 332.0 unaged Al-Si alloys at elevated temperatures

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Received 4 October 2005, received in revised form 4 May 2006, accepted 4 May 2006

Abstract

In this study, the effect of elevated temperatures on dry sliding wear and the coefficient of friction of cast 332.0 Al-Si alloys has been investigated. Block on disc type of wear and friction testing machine was used. Dry sliding wear tests were performed at elevated temperatures and a contact load of 55 N against hardened steel disc. The mass loss of test material during dry sliding wear test was determined gravimetrically. The results for the 332.0 Al-Si alloys show that there are two temperature zones, whose boundary is determined by the critical temperature ($T_c = 127\,^{\circ}\text{C}$), for wear rate or specific wear resistance at elevated temperatures.

The empirical wear rate or specific wear resistance expressions as a function of elevated temperature are derived using the data from experiments. Additionally, a Boltzmann-type approximation is formulated empirically for the coefficient of friction of these Al-Si alloys as a function of elevated temperature using a relation between the adhesion and friction coefficients.

Key words: 332.0 Al-Si alloys, dry sliding wear, elevated temperatures, mild and severe wear, adhesion and friction coefficients

1. Introduction

In recent years, cast Al-Si alloys have been widely used in automotive industry because of their high strength to weight ratio, and good cast ability. The applications of these cast Al-Si alloys can be found in the manufacture of various automotive engine components such as cylinder blocks, pistons and piston insert rings that are used in the tribological system [1, 2]. These components must have a dimensional stability in high temperature applications, as the high temperature sliding wear is a predominant process. For these reasons, properties of components must be improved. The sliding wear behaviour of these cast alloys depends on many different parameters of a tribosystem in which the influence of applied load, sliding speed, temperature, wearing surface hardness, reinforcement fracture toughness and morphology are critical parameters in relation with the wear regiment encountered [3–5].

Many authors report on sliding wear of cast Al-Si alloys in the literature. For example, Dwivedi [6] examined sliding wear temperature and wear behaviour of cast Al-Si-Mg alloys. Critical temperature was found to be a function of alloy composition, i.e. silicon content. Li et al. [7] studied mechanical mixing induced by sliding wear of an Al-Si alloy against M2 steel. Their results show that the mixed layers and wear debris have similar microstructural features, and are comprised of mixtures of ultra fine-grained structures, in which the constituents vary depending on the sliding loads. Dwivedi et al. [8] studied sliding wear and friction behaviour of Al-18%Si-0.5%Mg alloy. Their results suggest that the wear rate is a function of contact load, sliding speed, composition and thermal softening characteristics of sliding metal. Xian-Qing et al. [9] examined dry sliding friction and found that wear behaviour of wood ceramics/Al-Si composites has a topologically uniform interconnected network microstructure. Their tribological properties

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are improved dramatically compared to those of the matrix Al-Si alloy due to the formation of wide, compacted surface carbon films.

Lancaster [10] investigated the influence of temperature in the range from 20 to 600 ℃ on the wear rate of particular combination of metals, 60/40 brass in tool steel. He found two regimes of wear. At low temperatures, extensive intermetallic contact and welding occur, and the wear rate increases with increasing temperature. At high temperatures, however, the wear rate decreases by several orders of magnitude and protective surface films are generated during sliding.

While a number of researchers have reported on sliding wear of cast Al-Si alloys [1–4, 6–9], little is known about the effects of elevated temperatures on sliding wear of cast Al-Si alloys.

The focus of this study is to investigate the dry sliding wear and the coefficient of friction of 332.0 unaged Al-Si alloys at elevated temperatures. Additionally, empirical equations for the coefficient of friction of these 332.0 Al-Si alloys as a function of elevated temperature are formulated.

2. Experimental procedure

332.0 Al-Si alloy was used in the study. The chemical compositions of these samples are given in Table 1. The samples were in the form of 10 × 10 × 10 mm^3 cubic blocks. The curved surfaces were polished with 0.5 μm alumina to eliminate any damage, which may occur during the machining operation. The microhardness tests were carried out using Vickers indentation test at 25 g load (HV 0.25). The details of physical and mechanical properties are listed in Table 2. Wear tests were carried out under dry sliding conditions against a rotating steel disc using a block-on-disc apparatus equipped with a heating unit. The test sample and configuration used in the dry sliding wear test are given in Fig. 1. The counterface disc having an outer diameter of 30 mm, an inner diameter of 20 mm and a thickness of 13 mm was prepared using AISI 52100 bearing steel. The counterface rotating steel disc was hardened to Rockwell C 63±3.

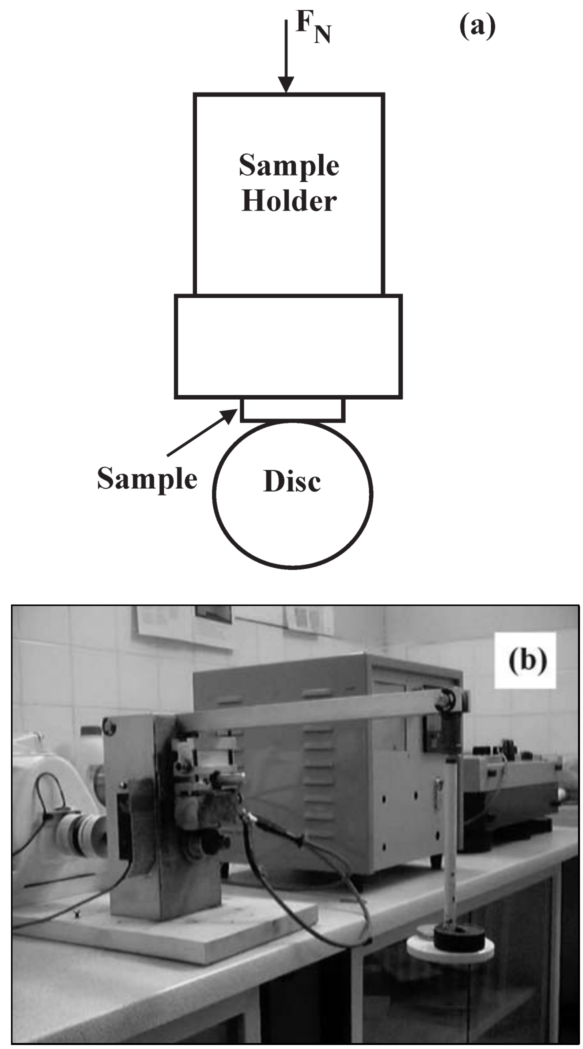

Fig. 1. The test sample and configuration used in dry wear test: (a) the test sample, (b) configuration.

Prior to testing, test samples were ground using 800 grit SiC paper, and then cleaned in acetone, dried and then weighed using an electronic balance. Samples were then placed on to the wear machine and the sliding wear tests were carried out. After each increment, the specimen was removed, ultrasonically cleaned in acetone and weighed with a balance to an accuracy of 0.1 mg and then remounted in the wear tester at the same location. Three test specimens of the same test material and new steel ring were used during each test. A constant force of 55 N was applied during the tests. The speed and duration of the test was 1.0 m·s^{-1} and 600 s, respectively, under the test conditions. The test blocks were capable of be-

Table 1. Chemical compositions of 332.0 (wt.%)

Material	Si	Fe	Cu	Mn	Mg	Zn	Ni	Bal
332.0	11.88	0.42	1.090	0.01	1.03	0.02	0.96	Al

Table 2. The physical and mechanical properties of 332.0

Properties	Material 332.0
Vickers hardness (kg/mm^2)	75 ± 3
Density (g/cm^3)	2.7

T a b l e 3. Numerical results obtained in experimental work of 332.0

Temperature T (°C)	Wear rate $W_{V/L}$ $(m^3/m) \times 10^{-12}$	Specific wear resistance $W^{-1}_{V/L,FN}$ $(N \cdot m/m^3) \times 10^{12}$	Coefficient of friction μ	Coefficient of adhesion σ For $\alpha = 0.3$	Coefficient of adhesion σ For $\alpha = 1.0$
50	1.23	44.71545	0.2	1.06458	1.0198
100	1.23	44.71545	0.25	1.09924	1.03078
150	1.35	42.30769	0.35	1.18673	1.05948
200	3.22	17.08075	0.45	1.29422	1.09659
250	9.15	6.01093	0.5	1.35401	1.11803
300	10.44	5.2682	0.52	1.37889	1.12712

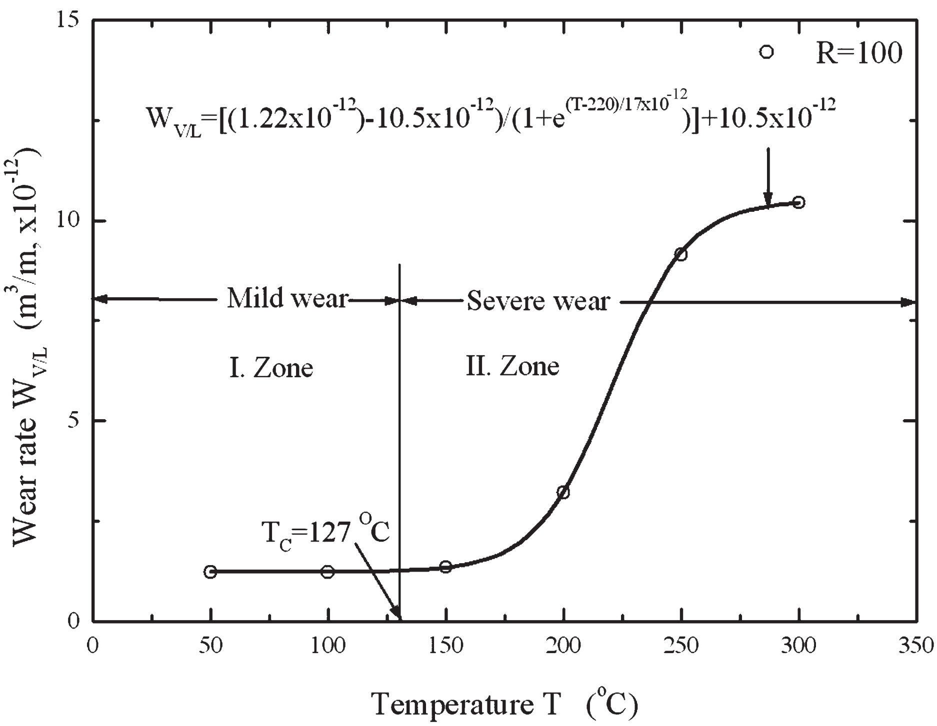

Fig. 2. Variations of wear rate versus temperature.

ing indexed in two positions. The test blocks were static under test loads while the disc was rotating during the tests. Wear tests at six different temperatures of 50, 100, 150, 200, 250 and 300 °C were carried out to observe the effect of heating. The temperatures of specimen were controlled by a thermos tactical system that was assembled to the wear test setup. The tangential force (frictional force) during sliding was measured by a force transducer attached to the wear machine and was continuously recorded on a chart recorder. The ratio of the tangential to the normal force gives the friction coefficient of all tests.

The weight losses were calculated by using the weight loss method [11, 12]. The wear volume V was determined from the measured mass losses using the density of the samples. The linear wear rates $W_{V/L}$ were computed using the following equation:

$$W_{V/L} = \frac{V}{L} = \frac{G}{\rho L}, \qquad (1)$$

where L is the sliding distance of the experiment sample, ρ is the density of the wearing material and G is the mass loss due to wear of the sample.

In particular, we define the specific wear resistance, $W^{-1}_{V/L,F_N}$

$$W^{-1}_{V/L,F_N} = \frac{F_N}{W_V}, \qquad (2)$$

where F_N is the applied normal force to the experiment sample. W_V is the volumetric wear rate defined in (1).

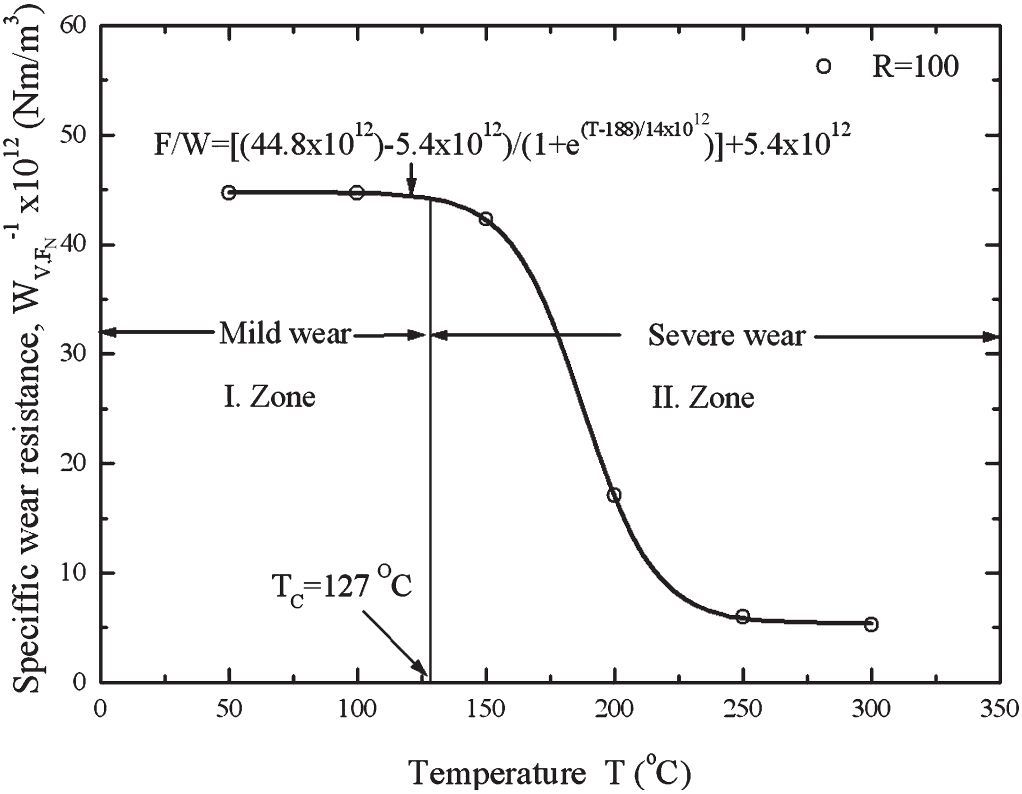

Fig. 3. Variations of specific wear resistance versus temperature.

Wear rate, the specific wear resistance, the coefficient of friction and the adhesion coefficient of the studied materials are given in Table 3.

3. Results and discussion

The plots of wear rates and specific wear resistance as functions of temperature for 332.0 Al-Si alloys are shown in Figs. 2 and 3. As can be seen the figures display a correlation for wear rate and specific wear resistance as a function of temperature as follows:

$$W_{\mathrm{V/L}} = \frac{1.22 \times 10^{-12} - 10.5 \times 10^{-12}}{1 + \mathrm{e}^{(T-220)/17\times 10^{-12}}} + + 10.5 \times 10^{-12}, \qquad (3)$$

$$W^{-1}_{\mathrm{V/L,F_N}} = \frac{44.8 \times 10^{12} - 5.4 \times 10^{12}}{1 + \mathrm{e}^{(T-188)/14\times 10^{12}}} + 5.4 \times 10^{12}, \quad (4)$$

where $W_{\mathrm{V/L}}$ is wear rate (Zone I and Zone II) and $W^{-1}_{\mathrm{V/L,F_N}}$ is the specific wear resistance (Zone I and Zone II).

The results also suggest that 332.0 Al-Si alloys have the following two zones under a constant load and at varying temperature conditions (Figs. 2, 3):

Zone I is called "mild wear zone". It is the zone between the initial temperature and the critical temperature $T_c \cong 127$ °C. Zhang and Alpas [13] and Wilson and Alpas [14] found that the critical temperatures were $T_c = 123$ °C and $T_c = 125$ °C, for 6061 and A356 Al-Si alloys, respectively. Wilson and Alpas [14] developed the following formula for T_c:

$$T_c = 0.4T_m, \qquad (5)$$

where T_m is the melting point of the test specimen. Our results show that T_c is higher than the value obtained from Eq. (5). We think that the reason for this discrepancy is due to the different rates of the elements forming the alloy specimen.

Zone II is called "severe wear zone". Different definitions for severe wear zone can be found in the literature. For example, Zhang and Alpas [13] and Wilson and Alpas [14] found that the start of delamination wear is a highly localized form of seizure or galling occurring in the sliding contact zone. This phenomenon is different from the isothermal sliding delamination mechanism. Isothermal delamination occurs under isothermal sliding conditions at low frictional heating, and most of the wear debris consists of plate-like particles [13, 14]. Mild wear zone and severe wear zones are shown on Figs. 4a,b,c and 5a,b,c.

Roganti et al. [15] suggested that shear stresses on

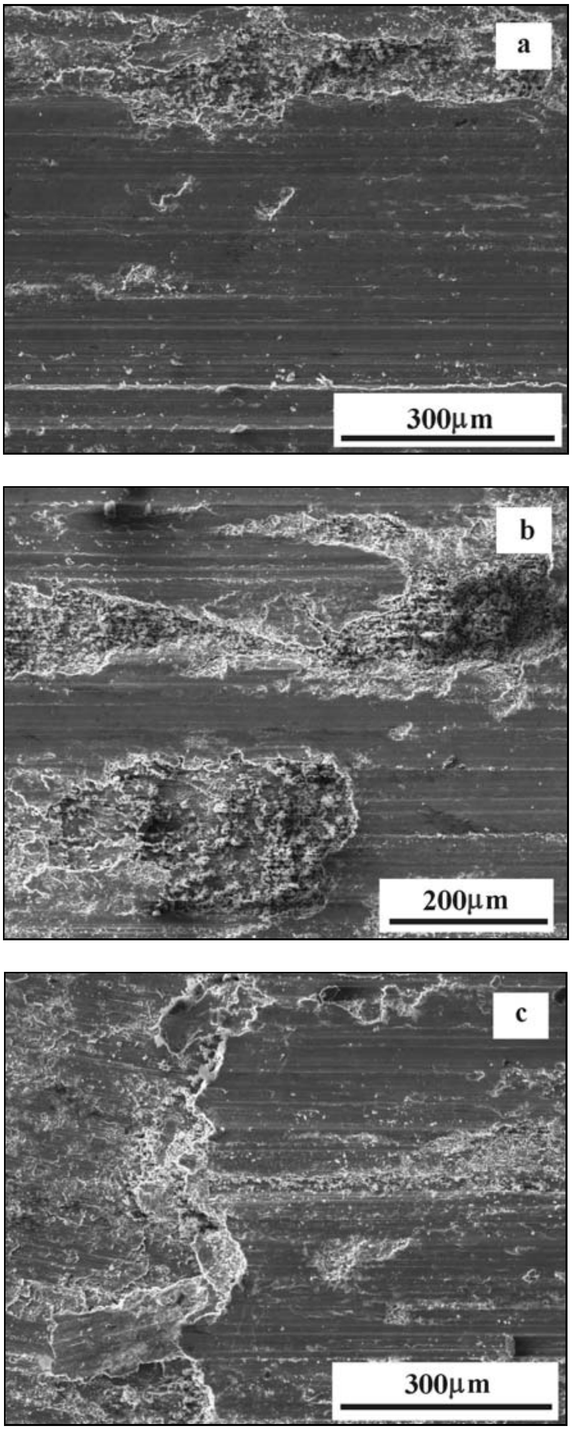

Fig. 4. SEM micrographs of the worn surface at: 50 ℃ (a), 100 ℃ (b), 150 ℃ (c).

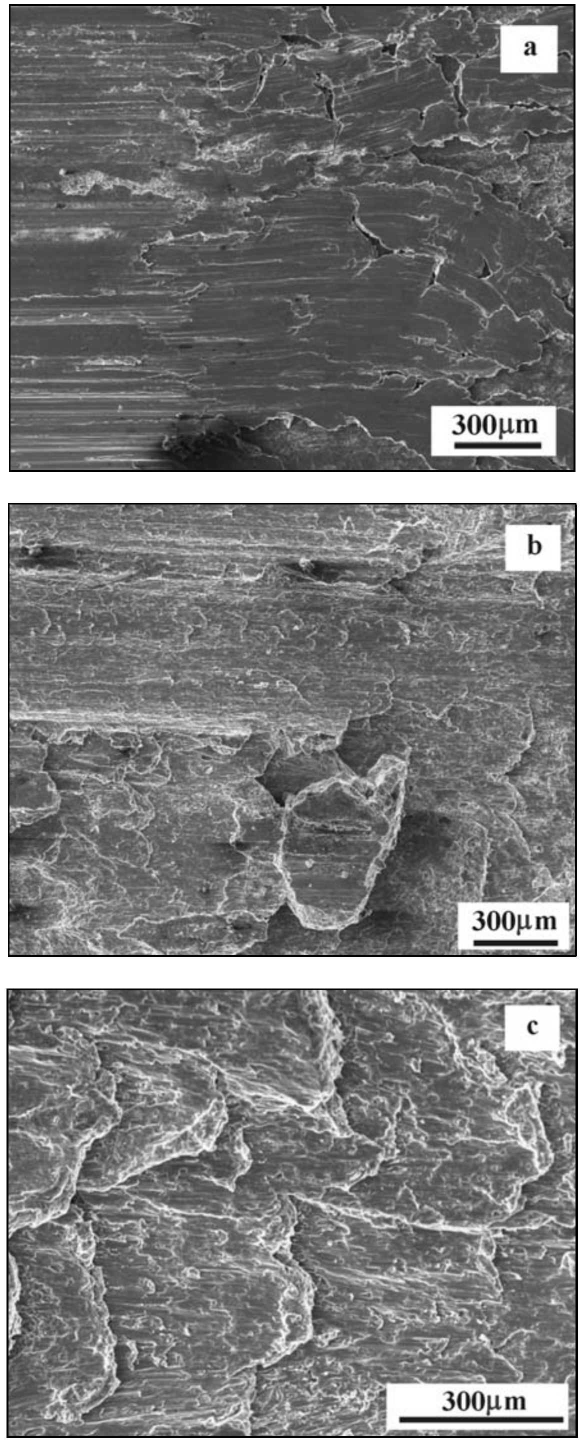

Fig. 5. SEM micrographs of the worn surface at: 200 ℃ (a), 250 ℃ (b), 300 ℃ (c).

and under the surface of the sample occur as a result of sliding the disc on the sample (Fig. 6). According to these researchers, dry sliding wear in Al-Si alloys can be explained through delamination theory (Fig. 6):

I. The brittle Si phase is the basic reason for under surface deformation. This kind of delamination occurs due to the fracture of Si phases caused by the under surface shear stresses created by the sliding disc (Fig. 6a).

II. Delamination can be considered as a surface deformation as given in Fig. 6b. In this deformation mechanism sliding is a function of normal pressure applied to the surface. In this case, delamination is not related with brittle Si phases. The main source

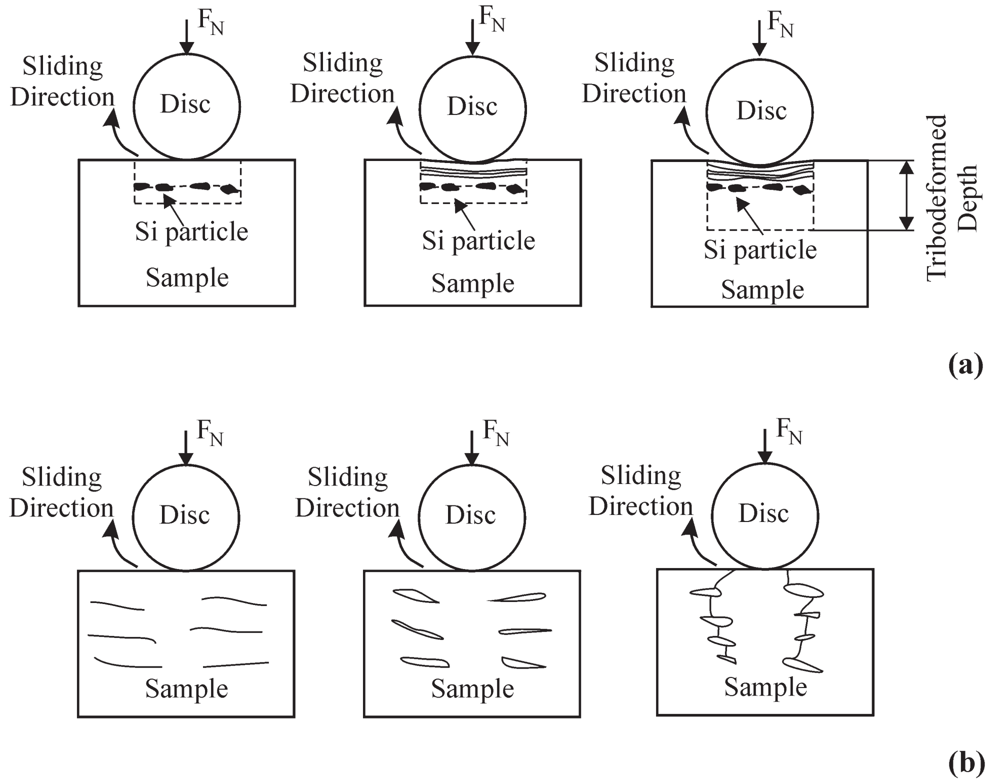

Fig. 6. Schematic representation of two mechanisms involved in sliding wear: (a) I. delamination, (b) II. delamination [15].

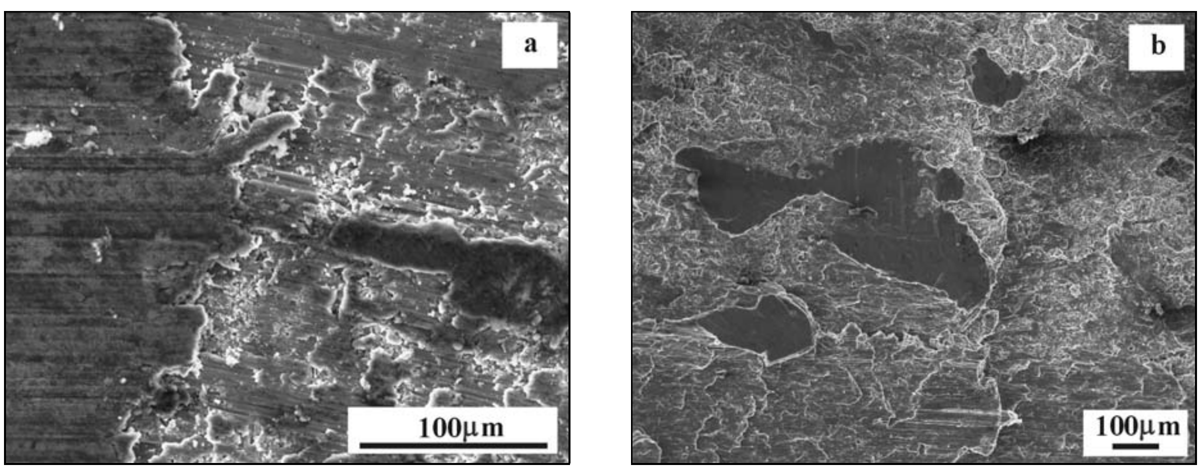

Fig. 7. SEM micrographs of the worn surface: (a) I. delamination mechanism, (b) II. delamination mechanism.

of this delamination is the creation excessive tribo-deformations due to contact fatigue on the sample surface. Contact fatigue creates under surface cracks in the metals sliding on each other. The expansion of these cracks causes deformations in the form of fractures. Due to continuous motion of the disc on the sample surface, these kinds of cracks are formed constantly and deform the neighbouring regions. Thus, more wear chip is removed from the sample surface.

We believe that the wear in severe wear zone starts with I. delamination mechanism (Fig. 6a) and continues as II. delamination mechanism (Fig. 6b) and "galling". These two mechanisms are shown in Figs. 7a,b.

Figure 8 suggests a correlation between the coefficient of friction μ and temperature T:

$$\mu = \frac{0.18 - 0.53}{1 + e^{(T-151)/39}} + 0.53. \qquad (6)$$

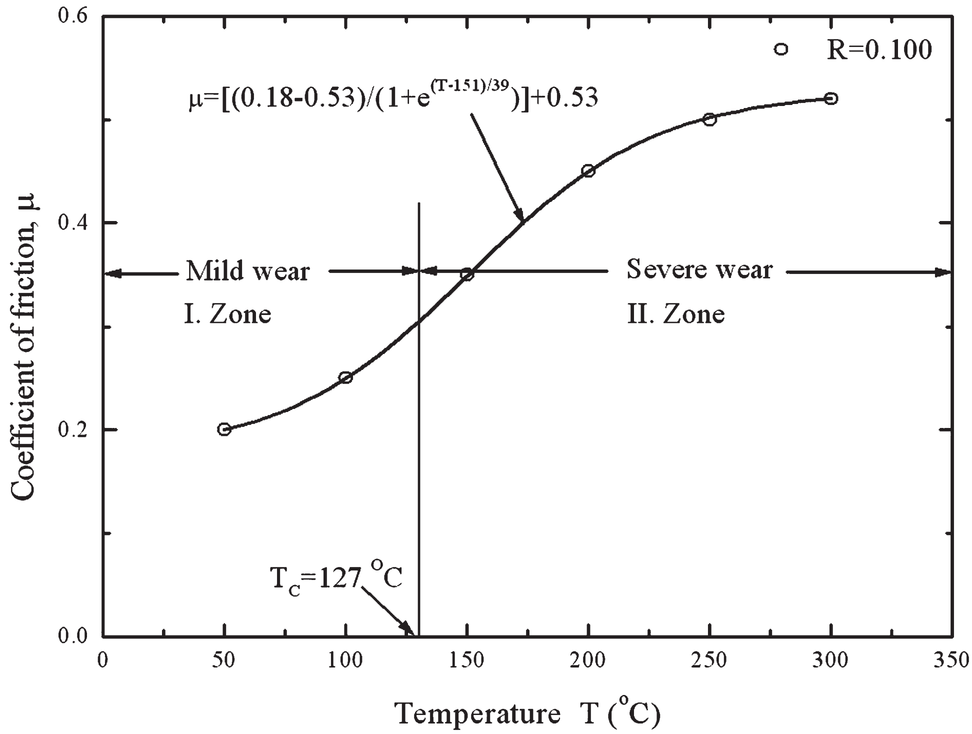

Fig. 8. Friction coefficient versus temperature at load 55 N.

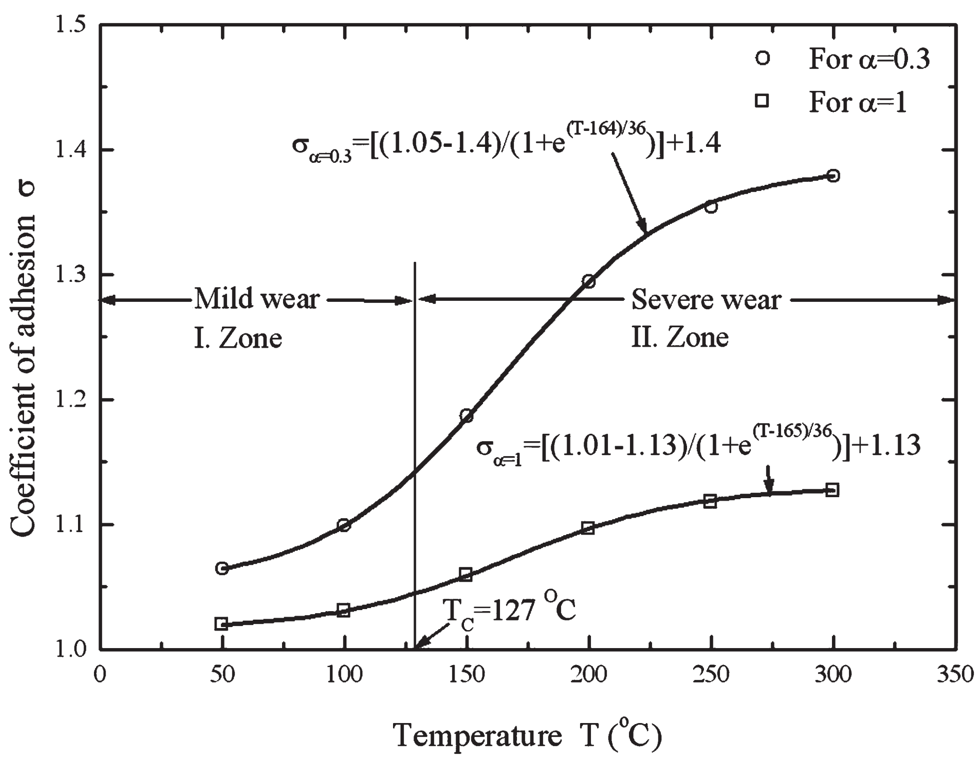

Fig. 9. Adhesion coefficient versus temperature at load 55 N.

It is clear that the friction coefficient increases with temperature.

McFarlane and Tabor [16] gave the following expression between the friction coefficient μ and adhesion coefficient σ for the relative motion of indium on steel:

$$\sigma = \left(\frac{\mu^2}{\alpha} + 1\right)^{0.5}, \tag{7}$$

where α is a constant. McFarlane and Tabor [16] estimated $\alpha = 0.3$ for indium on steel.

In our work, even though no experiments were performed for direct determination of adhesion coefficient, we estimated adhesion coefficient for Al-Si alloy using Eq. (7) at values of $\alpha = 0.3$ and $\alpha = 1.0$ using the friction coefficients determined in our experiments. Both data are plotted in Fig. 9 against temperature change. It can easily be seen that the two of the graphs can be fit to a Boltzmann approximation (Fig. 9). The curves are plotted using a curve-fitting algorithm. In fact, the use of Eq. (7) to calculate the adhesion coefficient may not give the actual values for adhesion coefficient of Al-Si alloys on steel because we have no data for adhesion coefficient for Al-Si alloys on steel. However, assuming a similar relationship as in Eq. (7), we expect a similar curve which is evident from the plots for $\alpha = 0.3$ and $\alpha = 1.0$. Therefore, the validity of Eq. (7) should be verified performing experiments for adhesion coefficient for Al-Si alloys on steel case. The actual values of the required parameters (such as α – Boltzmann parameters) can only be obtained through experiments.

4. Conclusion

An investigation onto the effect of elevated temperatures on dry sliding wear and the coefficient of friction of cast 332.0 Al-Si alloys has yielded the following:

– There are two temperature zones (Zone I and Zone II) for wear rate or specific wear resistance at elevated temperatures. These are severe and mild wear zones.

– The critical transition temperature from mild wear zone to the severe wear zone is 127 ℃. This is higher than the critical temperature estimated using Eq. (3). We believe that the discrepancy is due to the difference in the percentage of the alloy used in the experiment.

– It is observed that the variation of friction coefficient has similar two zones.

– If we assume that Eq. (7) is valid for Al-Si alloys on steel, then we can conclude that the relation between the adhesion and friction coefficients can be formulated using a Boltzmann-type approximation. The validity of Eq. (7) should be verified for this case by experiments. Then the actual α coefficient can be determined.

The relation between wear rate or specific wear resistance and temperature can be fit to a Boltzmann approximation.

Acknowledgements

The author thanks the Faculty of Engineering, Erciyes University for allowing him to use the Tool and Die Laboratory, the Engineering Workshop and Materials Testing Laboratory. The author also thanks Drs. Huseyin Canbolat and Cetin Kantar for their thoughtful comments and suggestions in preparing this manuscript.

Nomenclature

$W_{\mathrm{V/L}} = \frac{V}{L} = \frac{G}{\rho L}$ – volume wear rate ($\mathrm{m^3/m}$)

ρ – density of the wearing material ($\mathrm{g/cm^3}$)

G – mass loss due to wear (g)

$W_{\mathrm{V/L,F_N}} = \frac{G}{F_{\mathrm{N}}\rho L}$ – volume wear rate per pressure force ($\mathrm{m^3/N\cdot m}$)

$W^{-1}_{\mathrm{V/L,F_N}} = \frac{F_{\mathrm{N}}\rho L}{G}$ – specific wear resistance ($\mathrm{N\cdot m/m^3}$)

$\sigma = \left(\frac{\mu^2}{\alpha} + 1\right)^{0.5}$ – coefficient of adhesion

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