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An investigation into the friction and wear mechanisms of aluminium high silicon alloy under contact sliding

M.L. Rahaman, Liangchi Zhang*

Laboratory for Precision and Nano Processing Technologies, School of Mechanical and Manufacturing Engineering, The University of New South Wales, NSW 2052, Australia

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ABSTRACT

This paper investigates the friction and wear of aluminium high silicon alloy Al-60Si against EN26 steel. The sliding tests were conducted on a pin-on-disk tribometer and the mechanisms of deformation induced by contact sliding were analysed by SEM and EDS. It was found that subsurface deformation and cracks in silicon particles play a central role in the mechanism variation of friction and wear. Under a low load, cracks appeared beneath the wear track. Matrix extrusion over the wear track took place, resulting in ductile abrasive wear. With increasing the applied load, the matrix material was sheared more, which reduced the extrusion and changed the wear mode to brittle delamination. When the load reached a critical value, deformation and severe cracking appeared in the deeper subsurface and the matrix softened due to frictional heating, leading to accelerated wear. Upon a further increase of the applied load, mechanical mixing of finely fragmented silicon particles took place, and the wear mode experienced a number of changes from "ductile delamination + abrasive", "brittle delamination/ploughed + abrasive" to "abrasive + ductile delamination".

1. Introduction

Due to their lightweight, high specific strength, good thermal conductivity and low coefficient of thermal expansion, aluminium–silicon alloys have been widely used in electronic packaging, aerospace and automotive industries [1,2]. The wear behaviour of different Al-Si alloys (e.g. hypoeutectic, eutectic and hypereutectic) has been carried out by a number of studies. For instance, it has been reported [3–6] that the wear resistance of Al-Si alloys increased up to eutectic composition, and that the minimum wear at the eutectic point was the result of balance between two opposing factors, the increased hardness and decreased aluminium matrix [7]. Unstable subsurface due to the formation of shear bands and cracks was considered to be culpable for increased wear in hypereutectic alloys [8]. In contrast, the wear resistance of Al-Si alloys was found to increase continuously with the increase of the silicon content under a variety of experimental conditions [9–11]. More silicon content in alloys increased the load-bearing capacity of the material [10], decreased the matrix deformation [11], and in turn enhanced the wear resistance. However, it has also been reported [12] that silicon content increase did not change the wear rate notably but lifted the transition load up. The size and shape of silicon particles were considered to have a significant effect on the wear of Al-Si alloys.

The silicon content and alloying/modifying elements could significantly alter the size, shape and distribution of silicon particles in Al-Si alloys. A few studies [6,10] showed that wear resistance of Al-Si alloys were not reliant on the size, shape and distribution of silicon particles, but depended on the total amount of silicon content in the alloy [10] as well as on the formation of a composite layer [6]. On the other hand, some other studies [4,12–16] claimed that fine, spheroidal and uniformly distributed primary silicon could enhance the wear resistance. In this context, many attempts have been taken to refine the primary silicon. For example, addition/increase of alloying element/modifier [9,17] and heat treatment [9,12,17] can convert the coarse primary silicon particles to fine intermetallic particles which bond strongly with matrix and result in lower wear. Modification of coarse needle-shaped eutectic silicon to finer, rounder and acicular structure by rear earth element can also improve the wear resistance [18]. Different processing techniques such as hot extrusion [19], selective laser melting [20] and high-pressure torsion [21] can be used to refine and homogenize the structure leading to a better wear resistance. Two main wear regimes (mild and severe) of Al-Si alloys have been reported in the dry wear studies mentioned above. The mild wear was caused by mechanical mixing and surface oxidation under low load, and the severe wear was triggered by direct metallic contact at high load [5,6,10,12,22]. An ultra-mild wear (UMW) regime has also been reported under lubricated

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* Corresponding author.
E-mail address: Liangchi.Zhang@unsw.edu.au (L. Zhang).

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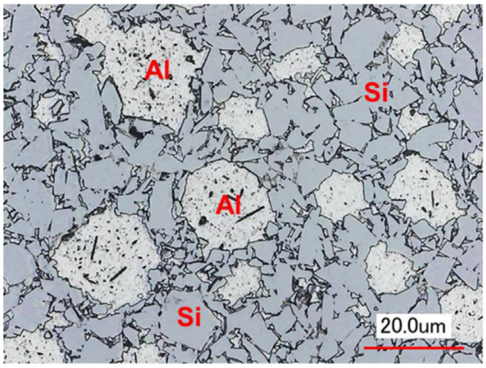

Fig. 1. A laser microscopy image of the as received Al-60Si alloy. A few Al and Si particles have been marked.

Table 1
Density, hardness, and chemical compositions of the aluminium high silicon alloy.

Density	Hardness, HV2	Chemical composition in wt.%			
(kg/m^3)	(kgf/mm^2)	Al	Si	Cu	Mg
2530 ($\pm$20)	265 ($\pm$10)	40.0	57.5	1.5	1.0

conditions where no measurable mass loss could be detected after a sliding of over 10^5 cycles [23,24].

In all of the above studies, the silicon content in Al-Si alloys is around 30 percent, except Ref. [1] which reported that the wear resistance of Al-50Si (wt.%) alloy was better than that of the Al-18Si (wt.%) alloy. It was considered that silicon addition the hardness increase of Al-Si alloys was almost four times when silicon content increased from 27% to 60%. However, to the best of the authors' knowledge, no study has been done on the friction and wear behaviour of Al-Si alloys with over 50% silicon.

This paper aims to reveal the friction and wear mechanisms of Al-60Si alloy, with the aid of the pin-on-disk tests and electron microscopy analyses.

2. Experiment

The ingot of the Al-high Si alloy Al-60Si (wt.%) used in this study was fabricated by a series of powder metallurgy processes, in which the aluminium and silicon powders of 99.9% purity were mixed and cold pressed under a pressure of 100 MPa for 30 minutes. The mixture was then hot pressed under 50 MPa pressure at 600 °C for three hours in vacuum ($<10^{-2}$ Pa).The ingot was cut and machined to a cylinder of 5 mm in diameter to be used as a pin. The surface roughness (R_a) of the polished pin and disk before testing was 0.12 and 0.30 μm, respectively. The pin-on-disk test was carried out on a CETR tribometer, using an Al-60Si pin sliding against an EN26 steel disk. The sliding conditions were: load =5 to 20 N, sliding speed =0.5 m/s, and sliding duration =1 hour. The microhardness of the samples was measured using a DuraScan 80 hardness tester. The microstructural analyses were carried out with the aid of scanning electron microscopes Hitachi3400I, FEI Nova NanoSEM 230/450 and laser microscope, Keyence VK-X200 series. To examine the subsurface microstructure, a small sample piece was cut from a worn pin using a Linear Precision Saw (Buehler Isomet 5000). The piece was then mounted on a fixture with its side surface polished on a TegraPol 15 system to expose the cross-section of the wear track. The cross-sectional samples were etched in 10% NaOH solution for 3 minutes. The wear of the pin was quantified by its weight loss, measured on a high-precision digital scale, Semi MicroAnalytical GH252 (resolution: 0.01 mg).

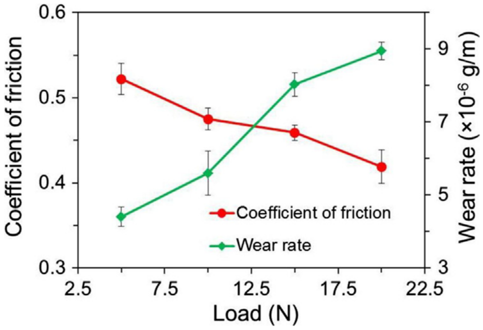

Fig. 3. Variations of friction coefficient and wear rate of the Al-60Si alloy when sliding against an EN26 steel disk.

3. Results and discussion

3.1. Microstructure of the as-received Al-60Si

Fig. 1 shows the laser microscopy image of the as-received Al-60Si alloy. The weight percentage of the alloy is shown in Table 1. The material's Vickers hardness (HV2) and density were measured to be 265 ± 10 kgf/mm^2 and 2530 ± 20 kg/m^3, respectively. The aspect ratio of a particle is defined as the longest-to-shortest length ratio of a particle. The average size (longest length) and aspect ratio of the silicon particles were measured to be 4.81 μm (standard deviations =2.58 μm) and 1.78 (standard deviations =0.8), respectively. The size and aspect ratio distributions of the silicon particles are shown in Fig. 2.

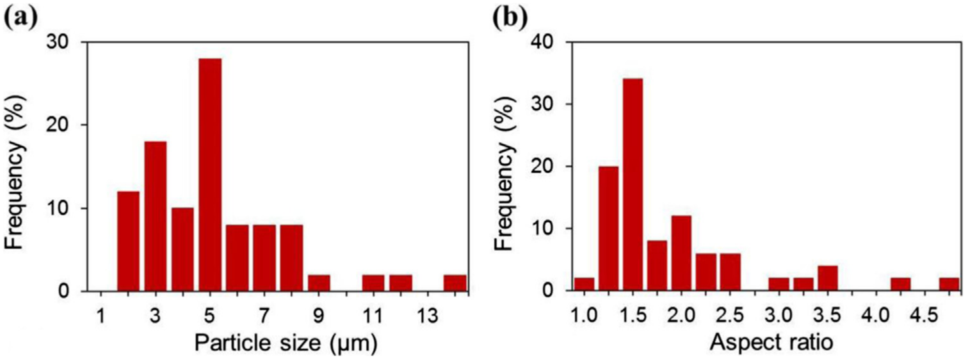

Fig. 2. (a) Size distribution, and (b) aspect ratio of silicon particles.