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LETTER

Effect of sliding environment on dry sliding wear of as-cast eutectic Al–Si

**M. Gwaze · I. Baker · F. E. Kennedy ·
P. R. Munroe**

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Wear resistance has been found to improve for Al–Si alloys with increasing silicon content up to the eutectic composition (12.6 at.% Si), after which it deteriorates [1–3]. Wear in Al–Si alloys has been characterized into mild and severe wear regimes. Mild wear occurs under conditions of low normal loads, and an oxide layer that forms on the wear surface usually slows down the wear process. Severe wear occurs under high normal loads and is often characterized by inclusions of the worn counterface, along with oxides, in the mechanically mixed surface tribolayers [4, 5]. The results of Razavizadeh and Eyre [6] suggest that there is generally insufficient frictional heating on the wear surface for general oxide formation. Instead, a mechanism of oxidation of asperities followed by fracture and compaction of these oxidized asperities into the valleys on the metal wear surface has been suggested [7, 8]. During mild wear of Al–Si alloys, a smooth surface is generally observed with interspaced wear scar areas [1]. The presence of material from the worn counterface embedded in the wear pin has been observed on both smooth and scarred areas [7, 9, 10].

Lower wear rates may be observed when harder counterfaces, such as diamond-like carbon (DLC) or yttria-stabilized zirconia, are used instead of the hardened steel surfaces traditionally employed in wear tests, particularly if the hard counterface has a smooth surface [11]. Also, argon test environments have shown reduced wear rates as compared to tests performed in air, with the wear rates under argon being as much as ten times lower in some cases [11, 12]. The increase in wear rates in atmospheres with higher oxygen content has been attributed to the presence of abrasive wear debris on the surface [12].

In a recent paper [12], we studied the wear of as-cast eutectic Al–Si against a yttria-stabilized zirconia counterface using pin-on-disk tribotests in two different environments, air and dry argon. The wear rate of the pins tested in air was more than twice that of those tested under argon. Similarly, the zirconia counterface showed much more wear for tests conducted in air. There was substantial subsurface cracking in the pins during wear testing in air, but none was observed in pins tested under argon. Scanning transmission electron microscope (STEM) examination of the near-surface region of the pins that had been worn in air showed mechanically mixed regions with considerable amounts of both aluminum oxide and zirconium oxide—the aluminum oxide particles had evidently acted as abrasive particles to remove material from the zirconia counterface. In contrast, the pins tested in argon showed little zirconium oxide in the near-surface regions.

In that study [12], it was unclear whether the moisture present in air made a significant contribution to the wear rate. Thus, the objective of the present study was to clarify the influence of moisture in the wear environment and its effects on the proposed wear mechanism of crack formation and debris accumulation on wear surfaces. To that end, pin-on-disc wear tests were performed in a flowing dry oxygen environment using the same materials and conditions as in our previous study, and the resulting wear surfaces were characterized in the same fashion [12]. The results, described below, are compared with those from previous tests conducted in air and in dry argon. It is possible that the size of the Si particles may affect the wear

M. Gwaze · I. Baker (✉) · F. E. Kennedy
Thayer School of Engineering, Dartmouth College, Hanover, NH 03755-8000, USA
e-mail: ian.baker@dartmouth.edu

P. R. Munroe
Electron Microscope Unit, University of New South Wales, Sydney, NSW 2052, Australia

rate, but that was not the focus of this investigation. It has been observed that during wear tests the Si particles near the wear tip readily fracture to very fine particles, of often only a few tens of nanometers in size [12].

The average weight loss results for the pin-on-disc wear tests with a 23-N load run for 1 km run in oxygen are compared with previous tests run in air and argon (three tests under each condition) in Fig. 1. Mass loss, measured by weighing the wear pins before and after the wear test, shows a small increase in the amount of wear when there is oxygen present in the atmosphere and a further increase when both oxygen and moisture are present, indicating that both influence the wear processes.

Measured humidity levels in the test chamber showed relative humidity levels of 5.7% when argon or oxygen was flowing through the chamber. In comparison, the tests conducted in air had the same relative humidity levels as the rest of the room, i.e., a relative humidity of ∼52%.

Using a scanning electron microscope (SEM), the formation of oxide tribolayers was observed on the worn pins, with some compacted debris left on the surface after the tests conducted under oxygen, see Fig. 2. By comparison, the worn pin surface was mostly smooth with distributed wear scars for tests conducted under argon, while the surfaces of the pins worn in air showed strong signs of exfoliation and delamination with some cracks on the surface [12].

STEM specimens were extracted from the worn pin surfaces using a focused ion beam (FIB) microscope and the resulting pits examined using SEM. Secondary electron images of the pits worn in oxygen showed clear evidence of subsurface cracking, see Fig. 3. This feature had also been noted in tests performed in air, but was absent in tests performed in argon [12]. A bright field STEM image and accompanying EDS X-ray elemental maps of a subsurface region are shown in Fig. 4. The X-ray maps show inclusion of zirconium oxide in the subsurface of the wear pin. Again, this feature was prominent in tests performed previously in air, but was not present in tests performed in argon [12].

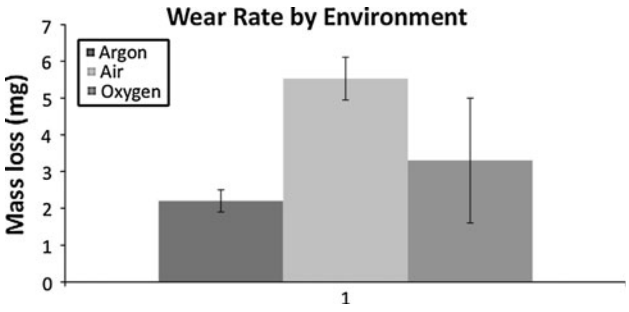

Fig. 1 Total mass loss of wear pins run for 1 km with a 23-N load in different test environments. Three tests were performed in each environment. *Error bars* signify standard deviations

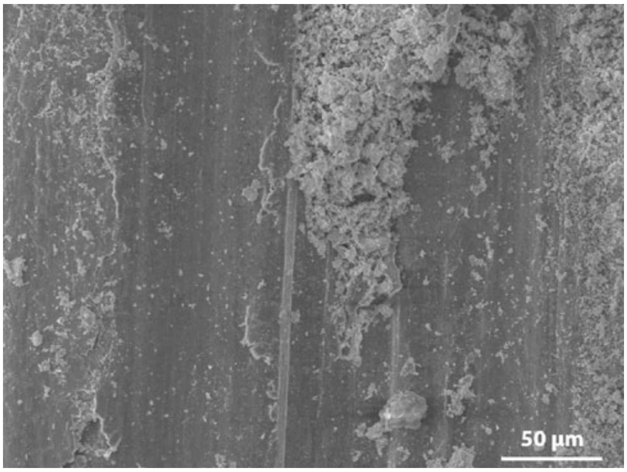

Fig. 2 Secondary electron image of a pin worn in oxygen showing the presence of compacted wear debris

Pins that were tested in oxygen exhibited properties mostly similar to those of the pins tested in air but the features were more exaggerated. An oxide-rich tribolayer with zirconia inclusions was present on the surface of the wear pin. The small reduction in wear rate that was observed upon going from air to oxygen environments may be attributed to the absence of moisture in the oxygen test environment.

Figure 5 shows the change in average friction coefficient for the samples tested in the three environments as a function of time and, hence, distance. It can be seen that in the environments containing oxygen friction gradually decreases as wear progresses and oxides are formed on the

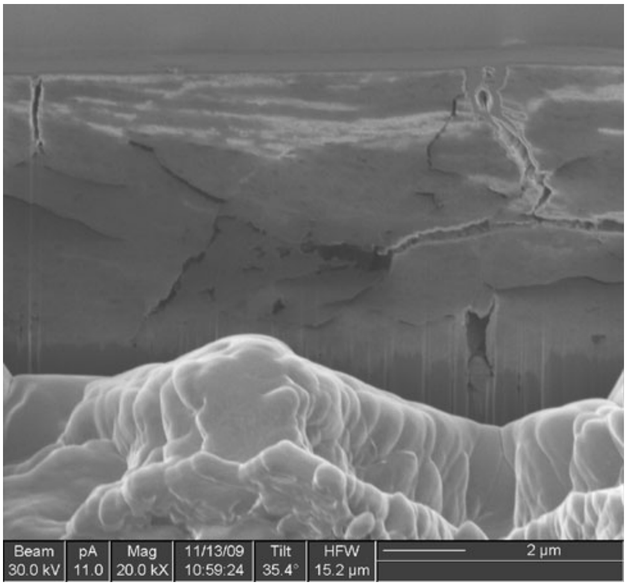

Fig. 3 Secondary electron FIB cross-sectional image from a pit produced using the FIB from a pin worn under oxygen. Note the subsurface cracks

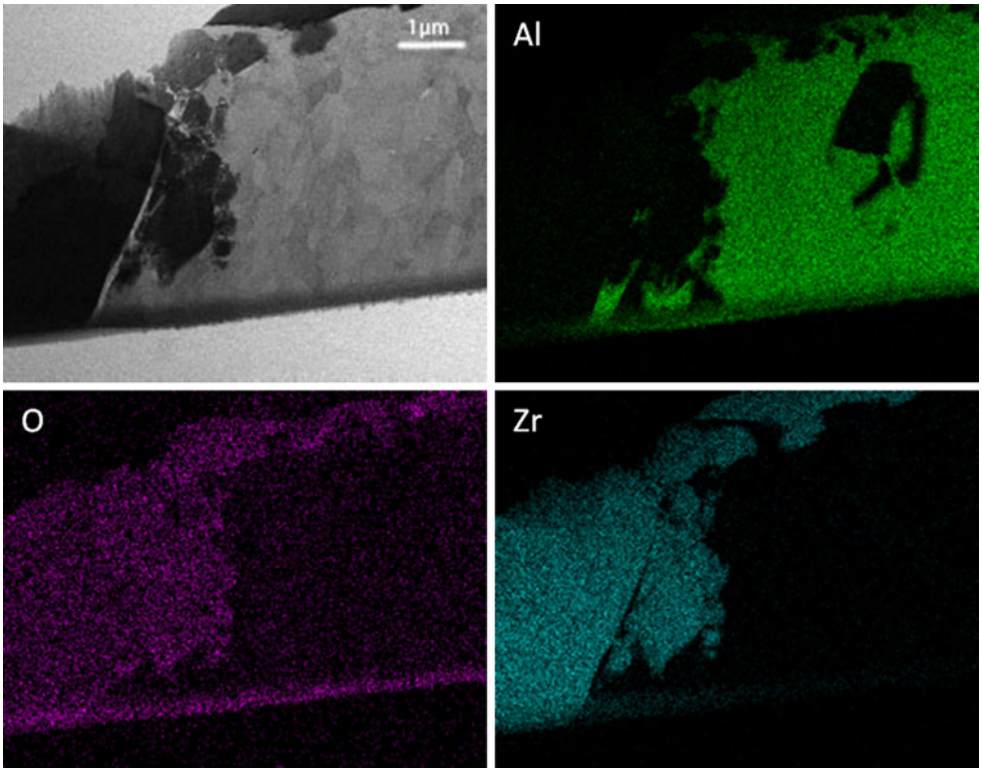

Fig. 4 A STEM image and corresponding EDS X-ray maps of a sample cut out from the surface of a pin worn in oxygen. The X-ray maps show the inclusion of zirconia in the subsurface of the wear pin. The dark feature in the aluminum map is a Si particle

wear surface, whereas in the argon environment the decrease in friction was considerably smaller. In general, the relative friction results correspond to the wear results, with tests conducted in argon showing the lowest friction and lowest wear, while the wear and friction were both highest in air. The greater standard deviation of wear results for the samples tested in oxygen may be related to the more variable friction noted in the oxygen environment (see Fig. 5), and both of those variations may be related to a less uniform surface oxide layer in that environment.

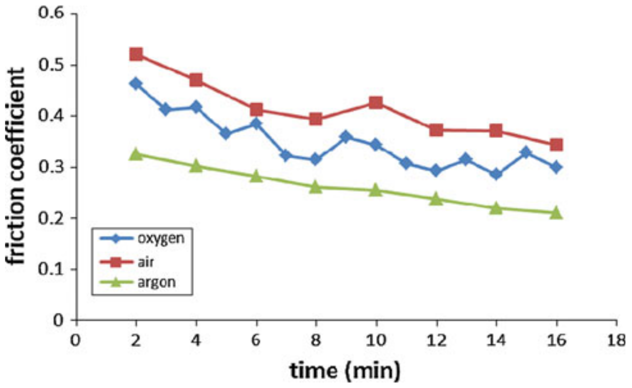

Fig. 5 Sliding friction as a function of time during wear tests run for 1 km under argon, air, and oxygen atmospheres

Combining the observations presented in this article with the prior results obtained by Baker et al. [12], it is evident that the wear rate and the dominant wear mechanisms are dependent on the testing environment. Different surface morphologies indicate different dominant wear mechanisms at play which would explain the different wear rates as the wear environment is changed between dry argon, dry oxygen, and moisture-containing environments. The results here for tests conducted in dry oxygen confirm the earlier observations by Baker et al. [12] showing transfer of material from the zirconia counterface to the Al–Si pin surface. In the absence of moisture, wear rates are lower as expected, as moisture acts to facilitate the oxide formation process. Intense surface and subsurface cracking were observed, suggesting that wear occurs through a process described by Shivanath et al. [7] where the formation of the tribolayers is said to occur through the oxidation of asperities on the surface, followed by the subsequent breaking-off of these structures and compaction into valleys created by wear from surface oxide layers. The presence of oxygen in the wear environment resulted in higher wear rates caused by brittle oxide layers that formed on the surface of wear pins.

Results presented in this article are in sharp contrast to those obtained by Yen et al. [13], who found a slow decrease in wear rate with increasing humidity from

3–70% and a rapid decrease at 100% humidity for eutectic Al–Si worn against a cast iron counterface. Overall, they observed a decrease in wear rate over the range 3–100% humidity of nearly two orders of magnitude. At low humidity, they observed that adhesive wear occurred, but that in the presence of significant moisture both the cast iron and Al–Si formed surface oxide layers that lead to a reduced wear rate by preventing direct metal-to-metal contact. It is known that cast iron or hardened steel counterfaces produce lower wear rates since FeO is formed during the wear process and acts as a solid lubricant [13]. Clearly, FeO was not present in the current study. In the present study, a zirconia counterface was used, on which moisture has no discernable effect [14]. Instead increased moisture levels led to greater oxidation of the Al–Si. This increased the wear of the zirconia counterface due to the increased number of aluminum oxide particles, and the wear rate of the Al–Si pin was increased due to both the greater amount of loose aluminum oxide and zirconia particles. In summary, the wear rate increased when oxygen was present and further increased when both water and oxygen were present, indicating that both influence the wear processes as shown by the different wear surface microstructures.

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