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Analysis of the micro-abrasive wear behavior of an iron aluminide alloy under ambient and high-temperature conditions

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A B S T R A C T

This study examines the micro-abrasive wear behavior of an iron aluminide alloy to determine correlations between the abrasive wear modes, volume of wear (V), and coefficient of friction (μ). Experiments were conducted with a specimen of Fe–30Al–6Cr (at.%) iron aluminide alloy, a sphere of AISI 52100 bearing steel and abrasive slurries prepared with black silicon carbide (SiC) particles and glycerin. Different levels of sliding distance (S), normal force (N), abrasive slurry concentration (C), and temperature of test (Te) were used for the micro-abrasive wear tests by rotative ball; during the experiments, the abrasive slurry was continuously agitated and fed between the sphere and the specimen, and, in parallel, the normal (N) and the tangential (T) forces were simultaneously monitored. Subsequently, the volume of the craters and the coefficient of friction acting in the tribological system "*sphere–abrasive particles–specimen*" were calculated. The results showed that *i*) the abrasive wear mode reported for all wear craters was rolling abrasion, independent of the temperature; *ii*) the temperature has an important effect on the behavior of the volume of wear and the coefficient of friction; and *iii*) with an increase in the temperature, a decrease in the volume of wear and the coefficient of friction was observed.

1. Introduction

Aluminides as a material class have been investigated since the historical discovery of Ni_3Al ductilization through boron doping by Aoki and coworkers in the late 1970s [1]. Since then, engineers and scientists have observed the advantages of the use of the aluminide alloys (intermetallics) in mechanical and metallurgical applications; consequently, in the past decades, aluminide alloys of cobalt (Co), iron (Fe), nickel (Ni), niobium (Nb), and titanium (Ti) have been thoroughly studied due to their potential for adoption as structural materials subjected to high temperature works [2].

These aluminide alloys present a high concentration of aluminum (Al) [2] that is able to form a continuous and adherent layer of alumina (Al_2O_3) on a surface exposed to air or to atmospheres containing oxygen. Beyond the advantage of this layer of alumina in protecting the material against corrosion and high temperatures of oxidation [2–4], the aluminide alloys have smaller densities (due to greater thermodynamic stability) than the chromium oxide (Cr_2O_3) scale characteristic of stainless steels [2], high fusion points, and show considerable mechanical and metallurgical properties [3,5–7] because of their crystalline structure.

In particular, the mechanical properties of steels containing iron aluminides can be handled by variations in the percentage of aluminum, type of heat treatment, and grain size [8,9], causing certain materials to be directed to specific mechanical–metallurgical requirements as a function of these parameters.

The insertion of iron aluminides (Fe_3Al) allows the yield strength stress of a material to reach a limit of approximately 500 °C while the ultimate stress remains constant or increases [10–13]. This phenomenon, known as the Flow Stress Anomaly (*FSA*), is an important effect observed in iron aluminide alloys that can benefit many engineering applications, such as the hot portion of internal combustion motors, which usually works at temperatures at which *FSA* is observed in iron aluminide alloys. In particular, iron aluminide alloys show *FSA* from room temperature up to approximately 550 °C [6,14].

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Nomenclature

b	Diameter of the wear crater [mm]
C	Abrasive slurry concentration [% SiC+% glycerin] (volumetric value)
D	Diameter of the sphere [mm]
E	Young's Modulus [GPa]
h	Depth of the wear crater [mm]
H	Hardness of the material [GPa] [HV]
n	Sphere rotational speed [rpm]
N	Normal force [N]
R	Radius of the sphere [mm]
S	Sliding distance [m]
t	Test time [s]
T	Tangential force [N]
Te	Temperature of test [°C]
v	Tangential sliding velocity at the external diameter of the sphere [m/s]
V	Volume of wear (volume of the wear crater) [mm^3]

Greek letters

α	Significance level (ANOVA–Analysis of variance)
μ	Coefficient of friction
ν	Poisson's coefficient

These advantageous properties can also be amplified by another particularity of iron aluminide alloys: their potentially low material and processing costs [15,16], which are necessary to qualify and quantify their tribologic properties and behavior. Contemplating the need to research the wear behavior of intermetallics, the scientific community has investigated different types of wear tests. For example, Guan et al. [17] analyzed the wear behavior of an Fe–28Al–10Ti alloy in a ball-on-disc tribometer using alumina as the counterbody material; following this same type of wear experiment, Zhang et al. [18] tested a sintered specimen of Fe–28Al–5Cr alloy against a Si_4N_3 sphere as the counterbody. Moreover, Sharma et al. [19] studied the tribological behavior of a Fe–28Al–3Cr alloy using a ball-on-plate equipment configuration with a tungsten carbide sphere as the counterbody material, and Kim and Kim [20] reported results of the sliding wear behavior of Fe–25Al, Fe–28Al and Fe–30Al specimens materials in a pin-on-disc wear test method, using AISI 52100 bearing steel as the counterbody material.

Generally, there are several types of wear experiments that can be used to evaluate the abrasive wear behavior of intermetallics, for example, the pin-on-disc [21,22] and dry sand rubber wheel (DSRW) tests [23,24], abrasive wear tests often used by researchers interested in the abrasive wear of materials [21–28], and, principally, the pin-on-drum abrasive wear test method, which is well accepted for studying the abrasive wear of intermetallics [29–33]. Since 1997, however, when the “ball-cratering wear test” was introduced [34] to tribologists, this type of micro-abrasive wear test has been used in premier universities and research centers by many researchers, as is referenced below.

Essentially, “micro-abrasive wear testing by rotating ball” or the “ball-cratering wear test” is designed to evaluate the abrasion resistance of surfaces on a small scale, allowing the precise control of tribosystem variables [35]. The aim of this type of micro-abrasive wear test is to generate “wear craters” on the specimen. It differs from conventional wear tests (which affect the entire surface) in the sense that the damage is constrained to a definite geometry (the crater) that can be reproduced in many places on the same surface, allowing for multiple tests on the same specimen. In addition, the localized damage allows the study of small-scale systems such as coatings [36–50], which are difficult to handle in conventional wear tests [35].

Fig. 1 shows a schematic diagram of the ball-cratering wear test: a rotating ball is forced against the surface of the specimen being tested under a normal force (N), while an abrasive slurry is introduced between the sphere and the specimen during the experiments; “h” represents the depth of the wear crater. This same figure shows an optical microscope image of such a wear crater in which the test evaluation is made by measuring the diameter of the wear crater (b) by optical microscopy, scanning electron microscopy (SEM), or any CAD software [51–54] and deriving the volume of wear (V) [34].

Fig. 2 shows the two mechanical configurations of ball-cratering equipment, namely *i*) the “fixed-ball” mechanical configuration (Fig. 2a and b) and *ii*) “free-ball” mechanical configuration (Fig. 2c), both of which are commonly found in the literature [55–59]. Alternatively, Cozza et al. [36,53,54,60,61] have proposed “fixed-ball” equipment configurations with some differences in terms of the translation movement of the specimen and fixation of the sphere, principal proponents of the mechanical system of the ball-cratering equipment [53,60] (please see “Supplementary content” [60]) in which the eccentricity of the sphere was completely nulled (initially, the nulling of the eccentricity of the sphere was discussed by Gee and Wicks [42]). Furthermore, using proper instrumentation, the tangential force (T) acting on the tribological system may be measured simultaneously with the normal force (N), allowing an effective coefficient of friction (μ) to be determined [36,51–53,60].

Upon analyzing the surface of each wear crater following the experiments, two abrasive wear modes can be observed: “grooving abrasion” (Fig. 3a [52]), which results when the abrasive particles slide on the specimen [62,63], and “rolling abrasion” (Fig. 3b), which results

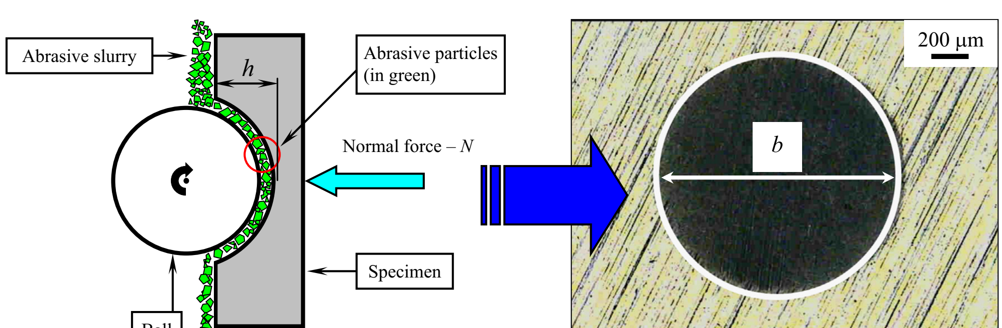

Fig. 1. Micro-abrasive wear test by rotating ball: a representative figure showing the operating principle and the abrasive particles between the ball and the specimen. In the example wear crater, “h” is the depth and “b” is the diameter of the wear crater.