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The influence of applied load, sliding velocity and martensitic transformation on the unlubricated sliding wear of austenitic stainless steels

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Abstract

In this work, the sliding wear of AISI 304 and AISI 316 austenitic stainless steels was studied as a function of applied load (from 6 to 20 N) and tangential velocity (from 0.07 to 0.81 m s^{-1}). Wear experiments were conducted in a commercial pin-on-disc equipment and were designed with response surface methodology. Worn surfaces and wear debris were analyzed through scanning electron microscopy, X-ray diffraction, Mössbauer spectroscopy, surface temperature and instrumented indentation. Results indicated plasticity-dominated wear (metallic particle oxidation, adhesive wear and mixed wear) as the sliding wear mechanisms. The wear rate was dependent on the interaction between applied load and tangential velocity, and an empirical model of wear rate as a function of applied load and tangential velocity was proposed by means of central composite design. The change in the wear mechanism was associated with the subsurface plastic deformation and surface temperature, which were strongly affected by sliding speed. In addition, strain-induced martensitic transformation was observed on the sliding surface of the austenitic stainless steels.

Keywords: Sliding wear; Austenitic stainless steels; Strain-induced martensitic transformation

1. Introduction

Austenitic stainless steels are extensively used in nuclear reactors, biomedical implants, as well as in components for chemical and food industries. They are widely used because of their high resistance to oxidation and corrosion resistance. However, austenitic stainless steels exhibit poor wear resistance and their use may result in material transfer between sliding bodies, mechanical mixing, oxidation and strain-induced martensitic transformation [1–6].

These studies [1–6] present experiments conducted at different load levels, sliding distances and sliding velocities, usually varying one-factor-at-a-time. However, if these factors were varied in an orderly way, even over a narrow range, as in this work, a more complete picture of the wear behavior of the austenitic stainless steel could be obtained [7].

In this work, the response surface methodology was used to obtain empirical expressions for the wear rates of AISI 304 and AISI 316 steels as a function of applied load and sliding speed. A wear map was obtained with fewer experimental data, compared to the one-factor-at-a-time procedure. Correlations between wear rate models and the characteristics of worn surfaces, debris and subsurface hardness were also depicted.

2. Experimental procedure

The specimens consisted of AISI 304 and AISI 316 austenitic stainless steel pins sliding against discs of the same material. The chemical composition of the AISI 304 steel pins was 0.07% C, 18.48% Cr, 9.04% Ni, 1.85% Mn, 0.36% Mo, and that of the AISI 316 steel pins was 0.08% C, 18.63% Cr, 9.78% Ni, 1.80% Mn, 2.04% Mo. The initial Vickers hardness of the AISI 304 and AISI 316 steel pins was 177 HV_{30}, and 181 HV_{30}, respectively. These hardness values were determined using a load of 30 kgf with a Buehler VMT-7 hardness tester. The pins were 8 mm in diameter and 21 mm long, with flat ends. Discs of 74 mm diameter and 8 mm thickness were used as the counterface. Before the tests, each pin was ground finished in a sliding test machine by successive use of abrasive papers with 320, 400 and 600 grit

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sizes, resulting in a surface roughness (arithmetic average, *Ra*) of 0.13 ± 0.01 μm. The discs were ground to a surface roughness of 0.40 ± 0.01 μm. The AISI 304 and AISI 316 alloys were selected due to their differences in friction and wear behavior under sliding conditions [1,3,8].

Sliding experiments were carried out with a conventional pin-on-disc test machine under unlubricated conditions. Tests were run at room temperature (23 ± 2 °C), at controlled humidity (55 ± 3%), with normal loads from 6 to 20 N, tangential velocities from 0.07 to 0.81 m s^{-1} and with a wear track radius of 22 mm. Based on load values and pin dimensions, nominal pressures ranged from 0.1 to 0.4 MPa. The experiments were interrupted after 3600 s. Before and after each test, pins and discs were ultrasonically cleaned, dried and weighed by analytical scales with 0.1 mg and 0.01 g resolution, respectively. Each test was repeated three times and performed in a random test condition sequence. In order to measure the surface temperature, a thermocouple was installed in a 1 mm hole, located at 2 mm from the pin contact surface. The flash temperature was calculated using equations developed by Lim and Ashby [9,10], derived from classical heat flow theory. The asperity contact radius was set at 10 μm, according to Asby et al. [10].

2.1. Experimental design

The response surface methodology (RSM) consists of a group of techniques used in the empirical study of relationships between one or more measured responses and a number of input factors. It comprises (1) designing a set of experiments, (2) determining a mathematical model and (3) determining the optimal value of the response, in such a manner that, at least, a better understanding of the overall system behavior is obtained. The empirical relationship is frequently obtained by fitting polynomial models. First-order and second-order experiment designs are set up with the purpose of collecting data for fitting such models [11,12].

The second-order polynomial can be expressed by the general equation:

$$Y = \beta_0 + \sum_{i=1}^{k}\beta_i X_i + \sum_{i=1}^{k}\beta_{ii} X_i^2 + \sum_{i=1}^{k-1}\sum_{j=2}^{k}\beta_{ij} X_i X_j + \varepsilon \qquad (1)$$

where X_1, X_2,..., X_k are the input factors which affect the response Y; k is the number of input factors; β_o, β_i ($i = 1, 2, \ldots, k$) and β_{ij} ($i = 1, 2, \ldots, k, j = 1, 2, \ldots, k$) are the unknown parameters (regression coefficients or parameters) and ε is random error. The second-order polynomial, Eq. (1), can be expressed in coded values using the following equation:

$$x_{ui} = \frac{X_{ui} - \bar{X}_i}{S_i}, \quad i = 1, 2, \ldots, k \qquad (2)$$

where X_{ui} is the actual level in the original units of the ith factor for the uth experimental run, $\bar{X}_i$ is the average of the low and high levels of the ith factor, and S_i is the range between the low and high levels divided by two. The use of coded factors instead of the original factors simplifies experimental designs, makes mathematical computation easier, increases the accuracy and enhances the interpretability of the coefficients estimated in the model [11]. The second-order polynomial equation, Eq. (1), can be represented by a contour plot, which consists of curves of constant response values. In these plots, coordinate axes represent the levels X_1 and X_2 of the factors, in original units, and/or x_1 and x_2, in coded units. Each contour corresponds to a specific value of the predicted response [11].

In this work, the response surface methodology was adopted to obtain an empirical model of wear rate (response) as a function of normal load and tangential velocity (input factors). A central composite design (CCD) [12] was used to describe the response surface of the wear rate and to estimate the parameters in the second-order model, Eq. (1). This design consists of a factorial portion, an axial portion and a center point. The factorial portion of such design is a complete 2^k factorial design with factor levels coded by −1 (for the low level) and +1 (high level). The axial portion ($2k$ star points) are points located on the coordinate axes of the factorial portion at a distance α from the design center. The name "center point" is given for a number, n_0, of repetition runs conducted for the condition in coded levels (0;0). The total number of design points is thus $N = 2^k + 2k + n_0$.

In this investigation, values $n_0 = 6$ and $\alpha = \sqrt{2}$ [12] were chosen for two factors: normal load and tangential velocity ($k = 2$, L and V), resulting in a total number of individual experiments (N) equal to 14. Thus the CCD is composed of four factorial settings $(x_1, x_2) = (\pm 1, \pm 1)$, four axial settings $(x_1, x_2) = (\pm\sqrt{2}, 0)$ and $(x_1, x_2) = (0, \pm\sqrt{2})$ and six repetitions at the center point. In Eq. (2), value $x_{ui} = -1$ was determined based $X_{ui} = 6$ (one of the load values), $\bar{X}_i = 13$ (average of the low and high levels of load) and $S_i = 7$ (range between the low and high levels of load divided by two).

The unknown parameters of the second-order model, Eq. (1), were estimated by the least squares method. The lack of fit and the degree of significance of the model were tested by analysis of variance (ANOVA) using the software Statistica® [11,13,14].

2.2. Wear analysis

The worn pin surfaces and the morphology of the wear debris were examined with a Philips XL30 scanning electron microscope (SEM). The chemical composition of the pin surface and wear debris was determined by X-ray energy dispersive spectroscopy (EDX). The wear debris phase constitution was determined with a Philips MPD 1880, X-ray diffractometer (XRD), using CuKα radiation and by Mössbauer spectroscopy, in transmission mode, using ^{57}Co γ-rays source, at room temperature. Values of Vickers microhardness of the cross-section of worn surfaces were obtained with a Fischercope H100V depth-sensing instrumented indentation apparatus using 80 mN load.

3. Results

3.1. Empirical wear rate model

Table 1 shows the wear rate values of AISI 304 and AISI 316 alloys obtained with the central composite design. Table 2 presents only the results of a factorial analysis, in which the