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Tribological behavior of borided AISI 1018 steel under linear reciprocating sliding conditions

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ABSTRACT

In this study, the wear behavior of AISI 1018 borided steel is characterized. The boriding thermochemical treatment was carried out at 1273 K for 6 h, and different thicknesses of the boriding agent surrounding the samples were examined. The layer structure was composed of FeB and Fe_2B layers.

The tribological properties at the surface of borided and unborided steel were evaluated employing the ball-on-flat method with sliding reciprocating wear tests, using an Al_2O_3 ball as the counterpart. The applied load and the sliding speed remained constant at 5 N and 5 mm/s, respectively, with sliding distances of 81 m, 108 m and 135 m.

The coefficients of friction (CoFs) on the boride layers from the sliding reciprocating wear tests for dry and lubricated conditions were evaluated. The CoFs are independent of the boriding potential expressed as the powder thickness. Surface wear for longer sliding distances in lubricated conditions was neglected; there was no difference between the wear track and the original surface roughness in the profilometer results. The wear scar diameter and the worn surfaces of borided and unborided steels in both experimental conditions were characterized by SEM to understand the wear mechanisms.

1. Introduction

Sliding wear of metals in machinery components is costly to industry and is often associated with adhesive contact [1,2]. Surface treatments, such as carburizing, nitriding and boriding, have been used to reduce adhesive wear, but boriding has advantages over the former two processes as it improves the surface hardness, adhesive wear and high-temperature resistance [3–5]. The combination of such surface properties makes this process an excellent candidate for specific industrial applications, such as gear boxes for turbines, cam-shafts, weapons, parts of agricultural machinery, etc., that require high tribological performance [6–10].

Boriding is a thermochemical treatment that involves the diffusion of boron atoms at the surface of different ferrous and non-ferrous materials at temperatures ranging from 1123 K to 1273 K and with exposure time ranging from 1 to 10 h or more [11–13]. The result of the treatment for an iron-based alloy consists of a single Fe_2B layer or a FeB/Fe_2B bilayer, with flat or saw-tooth morphology. The latter morphology is commonly formed on low-carbon and low-alloy steels. The former is mainly produced on high-carbon and highly alloyed steels. The development of one or another structure depends on different parameters such as the chemical composition of the substrate, temperature/time, the boron potential at the surface, the activator used in the boriding agent or media and the treatment method [14]. However, considering the mechanical properties, saw-toothed morphology is the preferred process, as its structure strongly adheres to the substrate [14,15].

Boride coatings can be produced by liquid, gaseous or solid procedures, which have their respective advantages. For industrial applications, boriding in solid state is more desirable than the other two methods due to its ease of treatment, simplicity of the required equipment and cost-effectiveness [16,17].

The superior contribution of the boride layer to the wear resistance of some materials under dry sliding conditions has been well-established. However, tribological research on borided surfaces under the lubricated condition has received less attention. Some of these studies were conducted on borided AISI 52100 steel and Ti6Al4V alloy under dry and lubricating conditions [18,19].

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The borided materials exhibited superior tribological performance in terms of remarkable wear resistance and low coefficients of friction compared to those without surface modification. The combination of surface roughness and high hardness could have contributed to decrease the coefficient of friction. Although the boride layers of 1018 steel are well-known to be compact, hard and adherent [20]. The present study was conducted to evaluate the tribological performance of boride and unborided low-carbon 1018 steel. On the sliding reciprocating wear method, especially the tribo-pair boriding steel and alumina ball under lubricated and dry sliding conditions. Thus, the boride layers formed on low-carbon steel under lubricated sliding conditions could be applied, for example, to the manufacture of bearings for universal joints and other automotive applications where sliding wear prevails.

2. Experimental procedure

2.1. Powder-pack boriding process

The boriding treatment was carried out at a temperature of 1273 K for 6 h on AISI 1018 low-carbon steel samples without using controlled atmosphere; a conventional furnace brand Lindberg that reaches a working temperature of 1273 K was used. The chemical composition of AISI 1018 steel is shown in Table 1. Work pieces 12.7 mm in diameter and 5 mm thick were employed. They were placed inside an AISI 304 stainless steel multicontainer; 6 samples can be included at the same temperature and time. The boron potential was varied through the different mixture thicknesses (from 5 to 30 mm). It was made with 70% SiC, 20% B_4C and 10% KBF_4.

2.2. Structural examinations

The presence of the FeB and Fe_2B layers was verified with X-ray diffraction (XRD). XRD patterns were obtained with a PANalytical diffractometer model X'PER PRO MRD equipped with CuKα radiation at $\lambda=0.154$ nm. The growth of the iron boride layers at the surface of the AISI 1018 steel sample was analyzed using a JEOL JSM-6360LV scanning electron microscope (SEM).

2.3. Hardness and surface roughness

Vickers microindentation tests were conducted at 50, 100, 150, 210, 260, 380 and 560 μm from the surface of the borided layers to the substrate using a Wolpert 402 MVD apparatus. The values are the average of five indentations with a constant indentation load of 100 g and a dwell time of 15 s according to the ASTM-E384 and ASTM C1327 procedures. In addition, the surface roughness (Ra) was measured on the borided and unborided samples by using a Veeco optical profilometer model DEKTAK 6M – STYLUS PROFILER and DEKTAK 32 software.

2.4. Reciprocating wear tests

Sliding friction and wear tests of the borided and unborided steel samples under dry and lubricated conditions were carried out on a ball-on-disk tribometer with reciprocating motion. Prior to the tribological experiments, the coated samples were slightly grounded with abrasive paper with a grit size of 2500 and then polished with 1 μm diamond paste for both conditions. A 6 mm diameter Al_2O_3 ball was utilized as the counterpart at ambient temperature (24 ± 2 °C and 36 ± 2% RH) under dry sliding for 81, 108 and 135 m sliding distances. Three wear tests were performed for each condition. Previous studies showed that the wear mechanism and the friction coefficient of such borided steels remain constant until the boride layer is removed [8,13]. Therefore, we chose a short sliding distance to be sure that we remained on the boride layer. In addition, in this reciprocating tribometer there is a limit on the wear test speed. To increase the sliding distance and conduct the wear test in short exposure times, we had to increase the sliding speed. However, increasing the sliding speed was beyond the tribometer's specifications. Steady-state friction values remain constant in short and long sliding distances until the boride layer is removed. Wear data for the treated surfaces could not be usefully compared in experiments during which the boride layer was removed. The stroke length and the sliding speed of the ball were 5 mm and 0.005 m/s, respectively. These parameters were chosen according to the limits of the tribometer and the size samples. A previous study showed that increasing the wear temperature to 500 °C (523 K) under dry sliding does not affect the tribological behavior of borided steel. During the wear testing, frictional force data were continuously recorded. The test load of dry and lubricated sliding wear was 5 N, which corresponded to maximum contact pressures of about 1.28 GPa and 1.45 GPa for the unborided and borided samples, respectively. However, when the wear tests were conducted under different loads (1, 3, 5, 6, 7 and 8 N), light loads such as 1 and 3 N did not form a clear and obvious wear track for wear loss measurements. In addition, at higher loads such as 6, 7 or 8 N under the dry sliding condition, the friction coefficient increased, and due to safety conditions, the tribometer stopped. Alumina is widely used as a counterpart because the system (alumina vs. hard coating) has already been proven to show higher wear resistance and significant differences in material behavior during sliding. This may be related to the high hardness, high oxidation resistance and high surface chemical inertness of the Al_2O_3 ball [21]. Sliding tests under lubrication were carried out using a fully formulated synthetic engine oil HX7 10W-40, which was smeared on the surface of the samples to simulate boundary lubrication [19]. The results of the wear tests were evaluated by calculating the area of the wear tracks formed on the surface of the samples. Width and depth measurements were taken using an optical profilometer. In addition, wear tracks were examined using a scanning electron microscope (SEM-HITACHI TM-100, Japan). Coated steels under lubricated conditions were sonically cleaned in acetone for 10 min before the microscope observations. This procedure was also utilized for cleaning the counterparts. The contact surfaces of the alumina ball were examined using a light optical microscope (LOM-Leica DM750M, Germany).

Table 1
Chemical composition of AISI 1018 steel (wt. %).

C	Si	Mn	S	P	Fe
0.15–0.20	0.15–0.35	0.60–0.90	0.050 (max)	0.040 (max)	Balance

3. Results

A cross-section SEM micrograph of the borided steel is shown in Fig. 1. Borided layers exhibited a dual-layer structure, the FeB and Fe_2B layer, as shown with XRD in Fig. 2. Saw-toothed morphology at the interfaces of the FeB/Fe_2B and Fe_2B/substrate was observed. This morphology has been verified and reported [11,12,16,22–25]. The average thickness of the total layer was about 215 μm. The measurement of individual layer thicknesses showed that the FeB layer thickness is a function of the boron potential, with values ranging from 80 to 108 μm.

Hardness on the cross section of the borided AISI 1018 steel samples with different boron potentials is shown in Fig. 3. The profiles show that the FeB phase the hardness is in the range of