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Evaluation of the effect of boride layer structure on the high temperature wear behavior of borided steels

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A B S T R A C T

The present study evaluates the high temperature sliding wear characteristics of the paste borided 31CrMoV9 and X40CrMoV5-1 steels with respect to the phase structure of the boride layers. Boride layers formed on the surfaces of the examined steels were about 65 µm in thickness and consisted of FeB and Fe_2B phases. The volume fraction of FeB (V_{FeB}) in the boride layers were 31% and 47% for 31CrMoV9 and X40CrMoV5-1 steels, respectively. The testing temperature of 500 °C caused an increment in the wear loss and the friction coefficient for both of the borided steels while their tribological performances were almost similar at room temperature (RT). In association with the presence of low amount of V_{FeB} in its boride layer, borided 31CrMoV9 steel underwent severe wear at 500 °C as the result of heavy cracking on the worn surface when compared to the borided X40CrMoV5-1 steel.

1. Introduction

Surface modification processes, which are based on covering the bulk materials with a protective surface layers via deposition or thermo-chemical processes, offer attractive technical solutions to enhance the performance of the engineering components utilized in wear and /or corrosion related applications [1]. In spite of their superior performance at RT, there is a risk of cracking and/or degradation for the surface layers at elevated temperatures arising from generated thermal stress which is in addition to the external working stress [2]. Generally thermal stress develops as the result of the mismatch in the thermal expansion coefficients between surface layer and the substrate [3–5]. If the thermal expansion coefficient of the substrate is larger than that of the surface layer, it expands more than the surface layer during heating and therefore leads to generation of tensile type thermal stress at elevated temperatures. When tensile thermal stress exceeds surface layer strength, vertical channel cracks form on the surface [6]. Unlike tensile thermal stress, compressive thermal stress is beneficial in retardation of crack initiation and/or propagation at surface layer [3,7]. In this respect, a number of scientific investigations have been made to control the thermal stress by altering the structure of the surface layers (multilayered, gradient and composite nature) formed by deposition techniques [4–6,8–13]. When thermo-chemical diffusion processes are of concern, boriding results in the formation of single (Fe_2B) or dual-phase (Fe_2B+FeB) surface layers on ferrous alloys depending on the process parameters [14,15]. In a recent study, tribological performances of single-phase (consisting of 35 µm thick Fe_2B layer) and dual-phase (consisting of 118 µm thick Fe_2B and 52 µm thick FeB layers) boride layers formed on 4140 quality steel have been examined at room and elevated temperatures [16]. Although similar tribological behavior was observed at RT, dual-phase boride layer exhibited superior wear resistance to single-phase boride layer especially at 500 °C. Being motivated by the results of Ref. 16, this study was initiated with the aim to determine the impact of V_{FeB} on high temperature wear resistance of dual-phase boride layers. More specifically, boride layers formed on two different steels with identical total thicknesses were subjected to wear tests at RT and 500 °C.

2. Materials and methods

In the present study, disc-shaped samples (35 mm in diameter and 6 mm in height) machined from 31CrMoV9 steel (0.32 wt% C, 2.52 wt% Cr, 0.67 wt% Mn, 0.22 wt% Mo, 0.15 wt% V, 0.27 wt% Si,

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0.025 wt% P, 0.012 wt% S) and X40CrMoV5-1 steel (0.42 wt% C, 5.19 wt% Cr, 0.36 wt% Mn, 1.33 wt% Mo, 0.96 wt% V, 1.07 wt% Si, 0.01 wt% P, 0.01 wt% S) were exposed to the paste boriding process. The boriding process was carried out in a conventional furnace under argon atmosphere after covering the surfaces of samples with 5 mm thick Ekabor®-Paste. Before boriding, the samples were ground and polished using 2500 grit SiC paper and 0.25 μm alumina powders, respectively and washed in distilled water and ultrasonically degreased in acetone. Taking into consideration the finding of Dilektasli [17], 31CrMoV9 and X40CrMoV5-1 steels were borided at 900 °C for 4 h and 950 °C for 6 h, respectively in order to develop boride layers on their surfaces with almost identical thickness (about 65 μm). At the end of the boriding process, samples were left in furnace to cool to room temperature slowly.

Characterization studies of the borided samples were carried out by structural investigations and hardness measurements. The structural surveys consisted of light optical microscope (LOM-Leica-CTR6000, Germany) examinations and X-ray diffraction (XRD, GBC, Australia) analysis. LOM examinations were conducted on the cross-sections of the samples which were prepared using standard metallographic procedures and etching with 2% Nital solution. XRD measurements were carried out by utilizing CuK_α radiation. The surface hardness of borided steels were measured by using a Vickers microhardness tester (Shimadzu, HMV2, Japan) under indentation load of 100 g. The hardness of the borided surfaces was quantified in $HV_{0.1}$ scale after averaging five subsequent measurements.

Wear performance of the borided steels was examined under dry sliding conditions against an alumina ball (6 mm diameter) under normal load of 3 N on a high temperature ball-on-disc type wear tester (CSM High temperature Tribotester, Switzerland). Wear tests were performed at RT and 500 °C with a sliding speed of 5 cm/s along a circular path of 5.5 mm in radius for a total of 250 m sliding distance. For high temperature wear tests, samples were heated in the normal atmospheric condition and the test was started when the desired temperature was reached. At least three tests were run under the same condition for each borided steel to ensure the reproducibility of data. The frictional force data was continuously recorded during the wear tests. By the end of the tests, wear tracks developed on the surfaces of the samples were monitored using a 2-D contact surface profilometer (Dektak-6M, Veeco, USA) and examined by a scanning electron microscope (SFEG SEM, Philips, Holland). Profilometric measurements were made at eight different locations of each wear track to determine the average depth and the width of the wear track. Wear loss of the samples were quantified by multiplying the average cross-sectional area of wear track with its circular length.

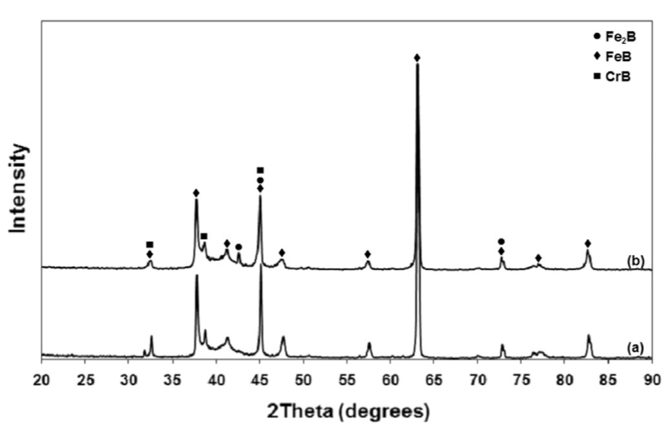

Fig. 1. XRD patterns of borided (a) 31CrMoV9 and (b) X40CrMoV5-1 steels.

3. Results

The XRD patterns of the borided steels are displayed in Fig. 1. Boride layers formed on 31CrMoV9 and X40CrMoV5-1 steels consisted mainly of iron borides (in the form of FeB and Fe_2B) and chromium boride (CrB). When the peak intensity of the CrB is of concern, it is evident that the amount of CrB phase present in the boride layers is very limited as compared to FeB and Fe_2B phases.

Cross-section LOM micrographs of the borided steels are shown in Fig. 2. Boride layers exhibited dual-layered structure, so that FeB layer appeared as darkly etched zone at the outermost sections whereas Fe_2B layer appeared as brightly etched zone in the inner sections. The average thicknesses of the FeB and Fe_2B layers are given in Table 1. Hardness measurements revealed the hardness of the borided surfaces as 2000 ± 20 $HV_{0.1}$ and 2185 ± 15 $HV_{0.1}$ for the 31CrMoV9 and X40CrMoV5-1 steels, respectively.

The friction curves of the examined steels tested at RT and 500 °C are presented in Fig. 3. At RT, the friction coefficient of both samples reached a steady state regime at about 0.8. Unlike RT, they exhibited different friction characteristics at 500 °C. The testing temperature of 500 °C imposed heavy fluctuations on the friction curve of the borided 31CrMoV9 steel in comparison to the borided X40CrMoV5-1 steel. The friction curve of the borided 31CrMoV9 steel decreased up to sliding distance of about 40 m after the running in period, then increased and reached to the steady state regime at sliding distance of about 80 m. In the case of the borided X40CrMoV5-1 steel, a steady state regime was reached immediately after the running in period. In steady state regimes, friction coefficient fluctuated in between 0.9 and 1.2 for the borided 31CrMoV9 steel where it varied in between 1.0 and 1.1 for the borided X40CrMoV5-1 steel.

The worn surface SEM micrographs of the examined steels are presented in Fig. 4. The sliding of the alumina ball on the borided surfaces at RT generated shallow wear tracks (about 0.4 μm in depth) with smooth morphology as the result of removing of the

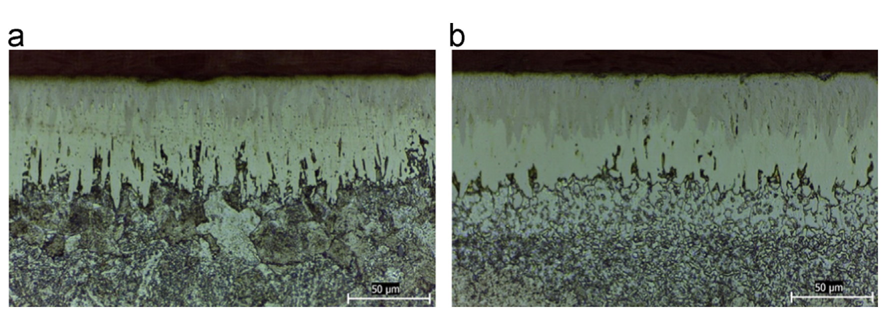

Fig. 2. Cross-sectional view of borided (a) 31CrMoV9 and (b) X40CrMoV5-1 steels.