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Effect of Boriding on the Mechanical Properties of AISI 1045 Steel

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Abstract. Some mechanical properties of AISI 1045 borided steels were estimated in the present work. The boriding process was carried out by the powder pack method at 950°C with 8 h of treatment. The fatigue strength on borided notched specimens was evaluated with rotating bending tests (R=1) considering a stress concentration factor (*Kt*) of 2.53. Likewise, the presence of residual stresses in boride layers was established by the XRD technique. The Daimler-Benz Rockwell C test was used, also, to estimate the strength adhesion of the coated system. The results show a decrease in the fatigue strength of AISI borided steels due to the presence of high porosity in the layers. Finally, the Rockwell-C adhesion test showed no coating failure for the boride layer.

1 Introduction

Boriding is a thermo chemical surface hardening process that involves diffusion of boron into a well-cleaned base metal (steel) surface at high temperature. The boriding process takes place at temperatures between 850 and 1000°C. The resulting metallic boride provides high hardness and wear resistance, high-temperature resistance and corrosion resistance [1]. The boriding of steel alloys results in the formation of either a single-phase or double-phase layer with definite compositions. Depending upon boron potential, the chemical composition of the substrate, temperature and treatment time, two phases can be identified on the layer: the outer, FeB (orthorhombic crystalline structure), with a boron content of ~ 16 wt.%, and an inner phase with tetragonal crystalline structure, Fe_2B, with a boron content of ~ 9 wt.% [2].
A diffusion zone exists below these layers, because of the massive precipitation of iron borides without coalescence, essentially small precipitates of the Fe_2B phase, forming a dark colour interface with the inner part of the material. The morphology of the layers depends fundamentally on the chemical composition of the substrate. In low-alloy steels, saw-toothed layers are obtained whereas in high-alloy steels these layers tend to be flat [3].
Due to essential difference between mechanical and physical properties of coating and substrate, different methods are applied to study the effect of boriding on ferrous and non-ferrous alloys [4]. The objective of this work is to investigate the mechanical properties such as fatigue strength, adherence of the coated system and residual stresses on AISI 1045 borided steel.

2 Experimental procedures

2.1 Boriding process

All the samples were borided at 950°C with 8 h of exposure time. A stainless steel AISI 304 L container was used to carry out the conventional pack powder boriding treatment. At the end of the process, the container was removed from the furnace and slowly cooled until room temperature. The borided samples were prepared metallographically for its characterization. On the other hand, the concentration profile of the alloying elements across the borided phase was estimated by the GDOES technique using a Horiba Jobin Yvon RF GD equipment, operating at a typical radio frequency discharge pressure of 650 Pa and power of 40 W.

2.2 Fatigue strength on borided notched specimens

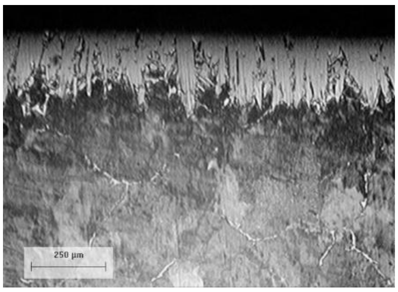
Fatigue tests were carried out on both borided and non-borided notched specimens. First, the presence of the boride layer on the notch area was confirmed by optical microscopy as shown in Figure 1. Also, Figure 1 depicts the configuration of specimens exposed to the boriding treatment. The mechanical tests were performed using cantilever type-rotary bending testing machine (RBF 200) under a frequency of 66 Hz, considering a stress concentration factor (*Kt*) of 2.53. The borided and non-borided samples were exposed to stress levels between 158 to 655 MPa; where these values are obtained by the staircase method [5].

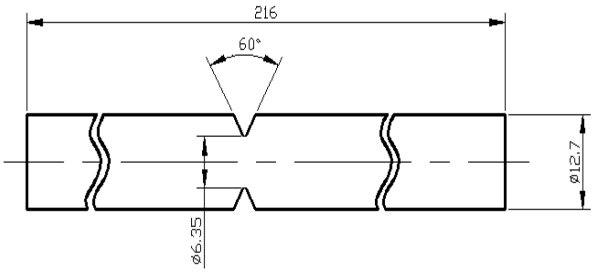
2.3 Depth profile of residual stresses in AISI 1045 borided steel

Cylindrical samples of borided AISI 1045 were used to evaluate the profile of residual stresses along the boride layer. The tests were carried out using XSTRESS3000 X-ray equipment with a CrK_α radiation with a diffraction angle of $2\theta = 156.4°$ (wavelength $\lambda = 2.28$ A) operating at 30 KV. The ψ tilt angles are fixed between -45° to +45° and the φ angles were established in 0, 45 and 90°. In each rotation angle, eight measurements on different ψ angles were done. In order to obtain a residual stress profile vs. boride layer thickness, the surface of the borided steels was removed by electrolytic polishing each 10 μm. The reference values of Young's modulus and Poisson´s ratio used in the calculations were taken from [6].

2.4 Adhesion of the coated system

This method uses a standard Rockwell-C hardness tester causing layer damage adjacent to the boundary of the indentation. After indentation, an optical microscope was utilized to evaluate the test at a magnification of 100X. The damage to the coating was compared with a defined adhesion strength quality as shown in Figure 2. HF1 to HF4 define a sufficient adhesion whereas HF 5 and HF 6 represent insufficient adhesion (HF is the German short form of adhesion strength).





(a) **(b)**

Figure 1 (a) Cross sectional view of AISI 1045 borided steel at 950°C with 8 h of treatment, (b) Configuration of notched specimen, scale in mm.

3. Results and discussions

The characteristic of Fe_2B and some of its properties, such as high melting point and stability, are similar to those of other compounds which are known to be effective diffusion barriers [7]. The morphology of the boride layer is saw-toothed, due to the tendency of Fe_2B crystals to grow along a direction of minimum resistance, perpendicular to the external surface. The mean value of Fe_2B boride layer thickness is approximately 200 μm based on 50 measurements in different sections of the borided steel. Furthermore, borided phases are formed according to the chemical composition of the material. It is more likely to observe only Fe_2B growth in low carbon and low alloy steels, with a saw-toothed morphology. By contrast, flat growth fronts of a bilayer FeB/Fe_2B are formed when the substrate has more carbon and alloying elements such as: molybdenum, tungsten, vanadium and chromium [8]. Likewise, compact and continuous hard layers are created when the temperature and time increase. Furthermore, GDOES analysis (Figure 3) provides a boron surface value close to 11.5 wt. % B. Moreover, the carbon does not dissolve significantly at the boride layer during the boron diffusion; consequently, the carbon is displaced to the diffusion zone (below the layer/substrate interface). At this zone, both the boron and the carbon form boroncementite ($Fe_3B_{0.67}C_{0.33}$) which contains about 4% wt. B approximately [9].

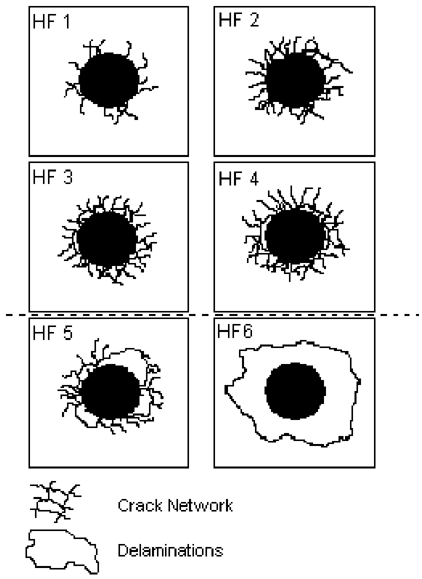


Figure 2 Adhesion strength quality HF1 to HF6

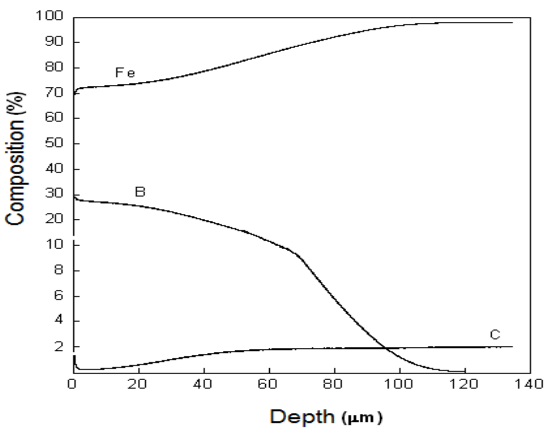


Figure 3 GDOES analysis on the surface of AISI 1045 borided steel.

Figure 4 shows the results of the fatigue test on samples exposed to the boriding process and unborided steels. It is visible that on borided samples, the fatigue strength decrease compared with untreated specimens.

To explain this behavior, Figure 5 depicts the residual stress profile of the Fe2B boride layer. The decrease in fatigue strength after boronizing is due to the boronizing-induced compressive stresses in the boronized layer; these are balanced by high tensile stresses which are chiefly located in an extremely thin layer directly underneath the boronized layer (this thin layer is denominated diffusion zone).

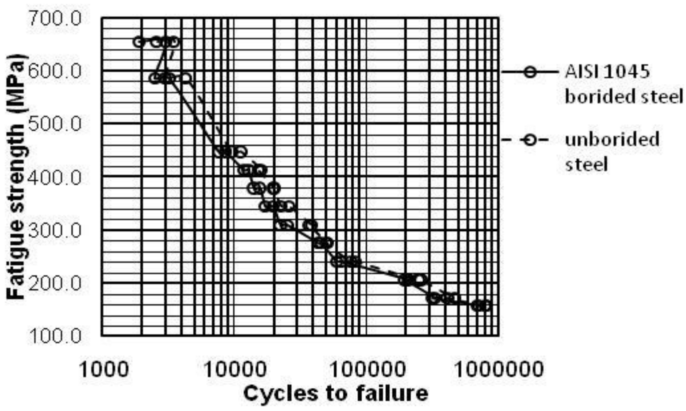


Figure 4 *S-N* diagrams for unborided and borided AISI 1045 steels

The residual stresses obtained at the surface of the borided samples are in function of the rotation angle in three different directions of the boride growth. In the layer of continuous Fe_2B, the compressive stresses decrease, and toward the boride-substrate interface, they change to tensile stresses corresponding to the steel substrate. Also, as stated by Babushkin et al. [10], the magnitude and distribution of residual stresses depend to a considerable extent on the phase composition of the boride coating. Likewise, the influence of the porosity that exhibits the boride layer can affect the fatigue strength of the borided samples. The % of porosity obtained by the grid method (Figure 6) in different areas of the boride coating indicates a mean value of 20% approximately.

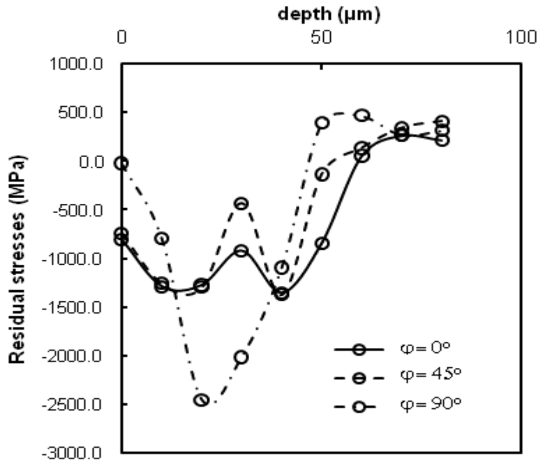


Figure 5 Distribution of residual stresses along the boride layer formed at the surface of AISI 1045 steel.

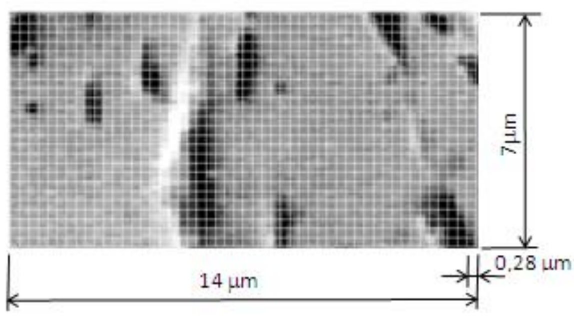
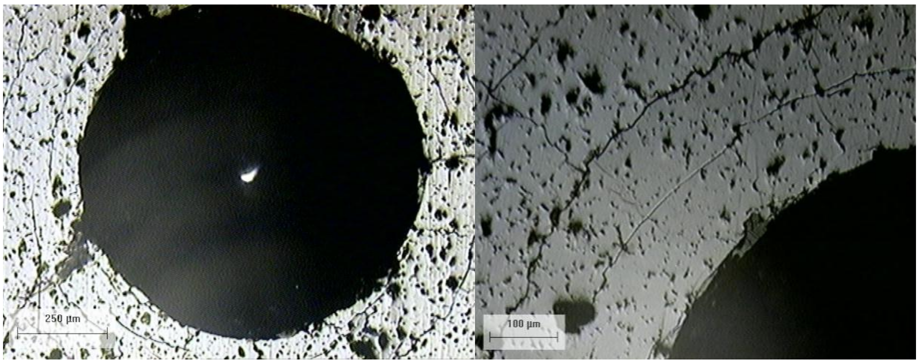


Figure 6 Porosity determined by the grid method for the AISI 1045 borided steel.

The adhesion of the coated system was evaluated with the Daimler-Benz Rockwell-C test as shown in Figure 7. The jagged Fe_2B/substrate interface increases the adhesion of the system. The indentation impact shows radial cracks at the perimeter of the indentation craters without delamination, which denotes sufficient adhesion with a HF3 quality value.



(a) (b)

Figure 7 (a) Optical micrograph of adhesion test of AISI 1045 borided steel at 950°C with 8 h of treatment (5X), (b) magnified area that denotes radial cracks around the indentation crater (10X).

4. Conclusions

The effect of boriding on the mechanical properties at the surface of AISI 1045 steels was evaluated in this work. The presence of Fe_2B layer with a surface concentration of 11.5 wt. % B is detected by the GDOES technique at the temperature of 950°C with 8 h of exposure time. The cantilever type-rotary bending tests with notched samples (*Kt* of 2.53), denote that the fatigue strength of borided steels decrease compared with non-borided samples, due to the presence of high compressive residual stresses at the surface of borided steels, which are balanced by tensile residual stresses located underneath the boride layer. On the other hand, the presence of high porosity in the layers can affect the fatigue strength of borided samples. Finally, the coated-system shows sufficient adhesion due to the saw-toothed morphology of the layer/substrate interface.

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