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Numerical evaluation of scratch tests on boride layers

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ABSTRACT

An experimental and numerical study of the scratch test on FeB/Fe_2B bilayers is presented. The boride layers were formed at the surface of AISI 304 steels by developing the powder-pack boriding process at temperatures of 1223 K for 2, 6 and 10 h of exposure times. From the set of experimental conditions of the boriding process, scratch tests were performed with a linearly-increasing load mode of 1 to 90 N on 7 mm in length to determinate the most effective and informative testing conditions and to estimate the critical load (L_c) at which the boride layer fails. The damage in the boride layer was examined by high resolution SEM. Experiments tests indicated that at a critical load the boride layer fails through brittle fracture. Numerical calculations considering the residual stress field generated by the scratch load showed that at this load the tensile stresses inside the boride layer become large enough to cause brittle failure. The residual stress fields generated by the scratch load were analyzed and related with the failure mechanisms observed by the experimental tests.

1. Introduction

One of the most important functional requirements in the manufacturing process is the adhesive strength of the coating with the substrate because the performance and life of the coating are limited by the adhesion strength [1]. Scratch testing is a characteristic technique for systems with hard coatings [2]. The test consists of drawing a hard stylus along the material surface under an increasing normal load, until coating failure. The induced normal and tangential forces as well as the resulting scratch morphology are analyzed. The load at which at least one of certain failure modes occurs at the coating and/or substrate is referred to as the critical load. Material with uniform cross-sectional hardness shows a lineal relationship between the critical load of hard coating obtained by the scratch test and the substrate hardness [3].

The properties of both substrate and coating, the metallurgical bonding between coating and substrate, the thickness of the coating and the geometry of the indenter determine the type of failure. If during a scratch test the coating is very soft compared to the substrate the coating is scraped off exposing the substrate and if indeed the coating is harder than the substrate the failure modes result in spallation and buckling, finally when both the coating and the substrate are hard the failure mode is observed to be chipping [4–6].

Furthermore, among the processes for modifying the surface of mechanical components is the boriding in which the surface of a specimen is saturated by boron [7]. The boriding can be applied to a wide range of steel including carbon steel, low alloy steel, tool steel and stainless steel. Borided steel components display excellent performance in several tribological applications in mechanical engineering and automotive industries. Borided steels exhibit high hardness (about 2000 HV), high wear resistance, and improved corrosion resistance [8–10].

Scratch tests have been carried out to evaluate the coating–substrate system of boriding processes by different techniques [11–14]. The scratch test was applied to evaluate TiB_2/TiB coatings on high speed steel produced by physical vapor deposition (PVD) where experimental results showed that the failure mechanisms observed were spalling at the scratch flank for a critical load of 35 N [15]. On the other hand in [16] a scratch test was developed on XC38 borided steels which were exposed to molten borax salts. The type of coating formed at the surface of the steel was a single (Fe_2B) or duplex (FeB + Fe_2B) boride layer according to different agents used (B_4C, Al and SiC). Three different types of damage were observed: cracks that propagated in depth along the scratch trails (Hertzian fracture), cracks that developed on the scratch side and propagated away from the scratching zone, and cohesive scaling that appeared on the sides at the extreme end of the scratch zone when the applied load becomes relatively high.

Because of the high number of parameter involved in the experimental test, the scratch test becomes a complex system. In practice the results of the scratch test are only used to rank different layer/substrate system. However the finite element method can be used to extend the knowledge of the failure mechanisms that occurred on the coating during the scratch test, based on the study of the influence of each parameter separately [17–20]. The aim of this study is to analyze by the finite element method the failure mechanisms through the stress

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distribution in the boride layer from borided AISI 304 steels during the scratch test.

2. Experimental procedure

2.1. The powder-pack boriding process

The powder-pack boriding process was carried out on commercial square samples of AISI 304 stainless steel at a temperature of 1223 K, and 2, 6 and 10 h of exposure times. The thermochemical treatment was developed by embedding the samples in a closed-container containing B_4C Ekabor II powder mixture. The container was placed into a furnace in the absence of inert gases. After the furnace process, the container was removed from the furnace, and slowly cooled to room temperature.

Metallographic sections were prepared to observe morphological details by the use of optical microscopy with a GX51 Olympus instrument. Fifty measurements were performed from a fixed reference on different sections of the borided samples to determine the thickness of the boride layer. The layer thickness measurements were obtained by selecting the needles that reached the deepest into the substrate. Fig. 1 depicts the growth of the FeB and Fe_2B layers at the surface of the borided AISI 304 steel for a treatment temperature of 1223 K. The thickness of the boride layer for each treatment condition is shown in Table 1.

The presence of borides on the surface of the borided AISI 304 steel was verified by XRD technique (GBC MMA instrument) using CuKα radiation of $\lambda = 0.154$ nm wavelength. The XRD pattern, depicted in Fig. 2, confirmed that the boride layer formed with 10 h of exposure was composed of a FeB/Fe_2B bilayer.

Table 1
Thickness of FeB/Fe_2B layer obtained from the experimental conditions of borided AISI 304 steel.

Exposure time [h]	Thickness [μm]	
	FeB	FeB + Fe_2B
2	8.6 ± 0.9	13.4 ± 0.6
6	23.2 ± 2.3	30.3 ± 1.1
10	34.6 ± 1.9	44.4 ± 1.2

Because the thickness of the FeB phase is around 35 μm, the peaks determined of the Fe_2B phase in the diffractogram correspond to crystals dissolved in the FeB, since the FeB phase grows from the transformation of the Fe_2B. Even this coating is defined as a FeB-base phase since it generally contains high boron products in the outermost part [21].

2.2. Instrumented indentation testing

The borided AISI 304 steels were evaluated using a commercial nanoindenter (TTX-NHT, CSM Instruments) with a Berkovich diamond tip. The nanoindentations were performed with a constant applied load of 100 mN along the depth of the boride layer (FeB + Fe_2B) and

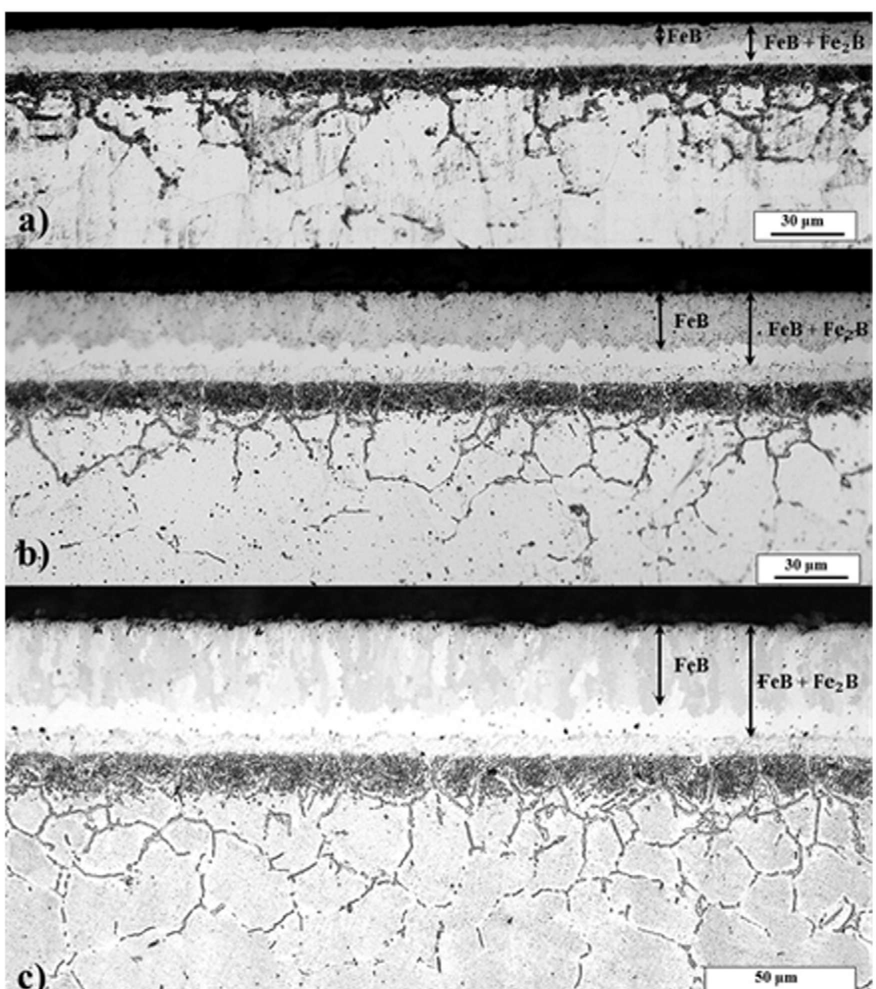

Fig. 1. Cross-sectional views of the borided AISI 304 steel for a boriding temperature of 1223 K and various exposure times: (a) 2 h, (b) 6 h and (c) 10 h.