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Estimation of FeB layer's yield strength by comparison of finite element modeling with experimental data

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ABSTRACT

In this study, low alloy steel substrates were borided by pack boriding process, for 2, 4 and 6 h at 900 °C. Microstructural observations were conducted by using SEM. The structural composition of layers consists of boron rich phase (FeB) and iron rich phase (Fe_2B). First, experimental indentation studies were carried out to determine the load–unload curves of FeB layers at different peak loads. Important parameters such as hardness and Young's modulus of FeB layers, and contact area were obtained from experimental indentation test sample data. After the mechanical characterization of samples, finite element modeling was applied to simulate the mechanical response of FeB layer on low alloy steel substrate by using ABAQUS software package program. The unique contribution of this study different from previous methods is the estimation of the yield strength of FeB layer by combining the experimental indentation works and finite element modeling (FEM).

1. Introduction

Surface treatments of engineering materials are important for serviceable engineering components. Most techniques, including thermal and thermo-chemical surface treatments have been used in applications to give specific surface characteristics to materials. One of the thermo-chemical surface treatments of steel based materials is the boriding process. Boriding (or boronizing) is an important thermo-chemical treatment applied to ferrous and non-ferrous alloy components to enhance the surface hardness and wear resistance [1–3]. In the boriding processes, boron atoms diffuse into the surface of a workpiece and form borides with the base metal. Boriding can be carried out in solid, liquid or gaseous media [4]. Among various gaseous boriding processes is the most frequently used one whereas industrial boriding is predominantly applied to steel and ferrous alloys. The pack boriding processes have relatively high processing temperatures (800–1000 °C) and long process durations (3–16 h) to obtain an effective boride layer thickness [5,6]. The powder-pack boriding has the advantages of simplicity and cost-effectiveness over other boriding processes. In this technique, the boriding agent, which is in powder form, is placed into a heat resistant box and samples are embedded into this powder under inert gas atmosphere. At the end of boriding time, the box is cooled at room temperature and then, dust is removed over the samples [7].

Generally, for practical applications, the formation of a mono-phase (Fe_2B) with saw-tooth morphology is more desirable than a dual-phase layer comprising of FeB and Fe_2B [1–3,8–12]. Although the boron rich FeB phase is decidedly harder, it is more brittle than the iron sub-boride, Fe_2B phase. Furthermore, crack formation is often observed at the FeB/Fe_2B interface of a dual-phase layer, as FeB and Fe_2B phase's have different thermal expansion coefficients. These cracks often lead to flaking and spalling when a mechanical load is applied. By controlling the boronizing process parameters, especially limiting the boron potential of the boriding media, the Fe_2B phase can be consistently achieved during pack boriding [8,12]. However, lowering the boron concentration inevitably slows down the boron diffusion process. In return, longer boriding duration is necessary for a desired boride layer thickness [1].

On the other hand, an obvious drawback is the very complicated mechanical problems arising due to inelastic and/or inhomogeneous deformation in the indented coatings [13]. Therefore, until recently the interpretations of indentation tests have relied heavily on semi-empirical formulae. The development of indentation methodologies for the micro mechanical characterization of coatings requires a precise understanding of the correlation between uniaxial mechanical properties and hardness. One of such fundamental correlations was found by Tabor [14] for pyramidal (Vickers) indenters. The work of Tabor is one of the best examples in this area. However, owing to modern computers and advanced numerical methods the understanding of the mechanics in ball indentation [15–17], cone indentation [18] and Vickers Indentation [19] has increased rapidly in recent years. Fig. 1 illustrates the theoretical loading–unloading scheme and the estimation with the use of the measured parameters. According to the known

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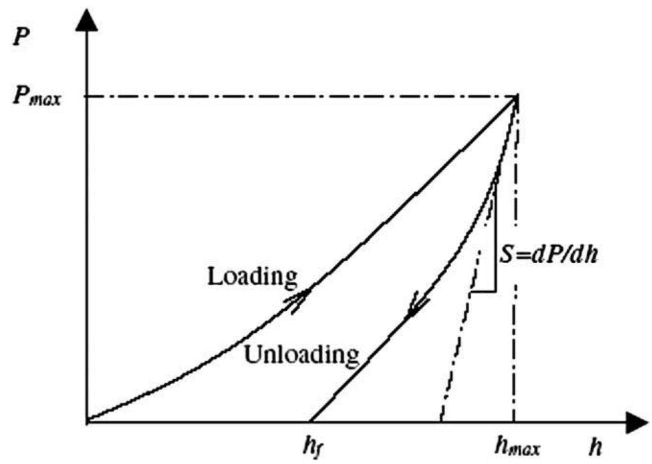

Fig. 1. Schematic diagram of a typical force versus displacement curve, where h is the indenter displacement, h_f the final penetration depth; h_{max} the maximum displacement (i.e., penetration depth of indenter), P the force applied to indenter; P_{max} the maximum force applied to indenter and S is the contact stiffness.

technique [20], these parameters were used to evaluate H (hardness), stiffness ($S = dP/dh$), the Young's modulus of the "layer + indenter" system; E^* $(S/2(\pi/A)^{0.5})$, and the so-called elastic recovery $R = ((h_{max} - h_f)/h_{max})$, where A is the indenter projection area determined from the maximum depth of indenter penetration h_{max}. In turn, the Young's modulus of the layer, E_{layer}, was calculated from the formula $1/E^* = (1 - \upsilon_{ind}^2/E_{ind}) + \left(1 - \upsilon_{layer}^2/E_{layer}\right)$, where E_{ind} is the Young's modulus of the indenter, υ_{ind} and υ_{layer} are the Poisson's ratio of the indenter and the layer ($\upsilon_{layer} = 0.2$), respectively [20].

Additionally, load–unload curves characteristics and P–h relationships of a power law material from its given experimental indentation were investigated in a previous study [21]. In that study, a novel optimization approach was proposed to extract mechanical properties of a power law material whose stress–strain relationship may be expressed as a power law from its given experimental indentation P–h curve. A set of equations have been established to relate the P–h curve to mechanical properties; E, σ_y and n of the material.

In particular, in the previous studies about borides [22–24] hardness and fracture toughness values of FeB layers formed on

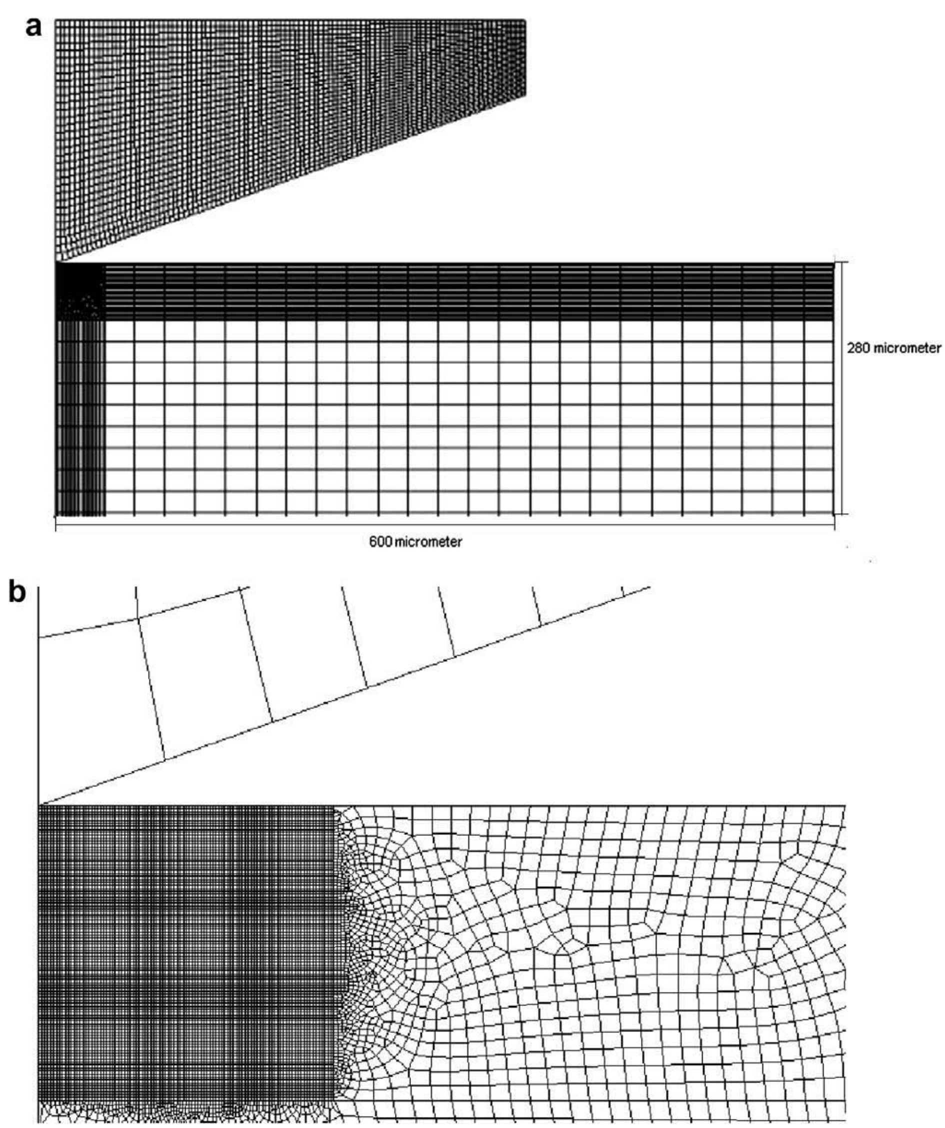

Fig. 2. (a) Schematic of the finite element model used in this work. (b) Magnification of contact area of the model.