1. INTRODUCTION

Boronizing refers to a surface diffusion treatment by which a boride coating is formed on the component surfaces. Formation of iron borides on steel surfaces is a well-known example of boronizing [1, 2]. It is a thermal diffusion treatment of boron compounds used to form iron borides which typically require process temperatures ranging from 833 to 1273 K in solid, salt, gaseous, paste, spark plasma sintering (SPS), electrochemical and plasma media [3–8]. The boronizing methods stated above have certain disadvantages. In gaseous boronizing, boron sources such as BCl₃, TMB (trimethyl borate), TEB (triethyl boron) and BF₃ along with H₂ and Ar gases are used [9–11]. In the case of liquid boronizing, formation of a firmly adhesive salt layer on the workpieces constitutes one of its advantages; however this can be quite costly to remove after boronizing has been completed. Pack boronizing is used commercially by Ekabor®. Although pack boronizing is more widely applied for commercial purposes than other methods, higher treatment temperatures and longer periods of time constitute its drawbacks [12–14].

Plasma boronizing has many advantages over the conventional boronizing process. For example, high energy efficiency is expected as a high energy of source of plasma is utilized in the plasma boronizing process, and distortion can be minimized after the process since the processing temperature is relatively lower than that in the conventional processes. However, the plasma boronizing process also has its limitations. B₂H₆ and BCl₃ gases have been used as boron source gases but these gases are relatively expensive, toxic and explosive. Corrosion in the vacuum chamber by boron chloride is another serious problem in plasma boronizing [10].

The characterization of boronized steels by using various boronizing processes has been evaluated by a number of investigators [12, 15–17]. However, the literature on kinetic and characterization of paste boronized steels in a plasma environment is scarce. In this study, low alloyed AISI 8620 steel was plasma paste boronized. The removal of the borax paste remaining on the surface of the specimen boronized with 100% borax paste is difficult and the process is time-consuming, therefore, SiC and B₄C were added to the borax paste. In addition, the ways in which SiC and B₄C provide a contribution to the formation of phases FeB and Fe₂B were investigated. This occurs by a decrease or an increase of the boron concentration with SiC and B₄C in the environment. The main objective of this study is to characterize plasma paste boronized AISI 8620 steel using borax pastes. The phase structure, microhardness and kinetics of the boride layers were investigated using X-ray diffraction (XRD), microhardness tester. In addition, the present study provides a good comparison between plasma paste boronizing and conventional boronizing.

2. EXPERIMENTAL DETAILS

AISI 8620 steel which contained 0.19% C, 0.4% Cr, 0.7% Mn and 0.4% Ni was used for the investigations. The samples had a cylindrical shape and were 18 mm in diameter and 6 mm in length. AISI 8620 steel samples were ground using 800 mesh SiC paper and polished with 0.1 alumina suspension to obtain a smooth surface. In this study, borax, SiC and B₄C powder mixtures (each of 150 μm) with various per-

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centages were used as a paste. Figure 1 shows a flow chart of the preparation of borax based pastes on the sample steels for plasma paste boronizing. The powder mixtures were accumulated on the steel that was immersed in a powder-alcohol suspension. Percentages of paste mixtures used in this study are shown in Table 1.

A plasma paste boronizing treatment was performed in a dc plasma system, which is described in [12]. The prepared samples were placed in the vacuum container and the container pressure was set to $2 \times 10^{-2}$ mbar of vacuum. The samples were plasma paste boronized at 973, 1023 and 1073 K for 2, 5 and 7 h in a gas mixture of 70% H$_2$–30% Ar under a constant pressure of 10 mbar. The temperature of the samples was measured by using a chromel-alumel thermocouple that was placed at the bottom of the treated samples.

Cross-sections of plasma paste boronized steels were prepared metallographically to observe morphological details using the BX60 Olympus microscope. The X-ray diffractograms were obtained by using a copper tube source as dictated by the conventional bragg-brentano ($\theta$–2$\theta$) technique having symmetric geometry with monochromatized radiation (Cu K$\alpha$, $\lambda = 0.15418$ nm). The thickness of the layers formed on the steels was measured by an optical micrometer attached to the optical microscope.

The hardness of the boride layers was measured on the cross-sections using the Micro-Vickers indenter (Shimadzu HMV-2) with 50 g loads.

### 3. RESULTS AND DISCUSSION

#### 3.1. Surface Characterization

Figure 2 shows optical microstructures of plasma paste boronized steel at 1023 K for 5 h for 100% borax, 70% borax + 30% SiC, 70% borax + 30% B$_4$C, 30% borax + 70% SiC, 30% borax + 70% B$_4$C paste mixtures. The morphology of borides formed on the surface of the substrate has a columnar nature.

The thickness of the boride layers formed on the steels ranged from 14 to 91 $\mu$m. The thickness of boride layer increased with the increase in boronizing temperature and time [18–20] in all paste mixtures. While the maximum boride layer thickness value was obtained for 100% borax, the minimum boride layer thickness value was obtained for 70% borax + 30% B$_4$C paste mixture. Since the plasma activates the chemical reaction to a higher extent, a thicker boride layer is formed than when using conventional boronizing.

### Table 1. Ratios of borax, SiC and B$_4$C paste mixtures used for plasma paste boronizing treatment

<table>
<thead>
<tr>
<th>Borax</th>
<th>SiC</th>
<th>B$_4$C</th>
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<tbody>
<tr>
<td>100%</td>
<td>-</td>
<td>-</td>
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<tr>
<td>70%</td>
<td>30%</td>
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<td>70%</td>
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<tr>
<td>30%</td>
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</tr>
<tr>
<td>30%</td>
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<td>70%</td>
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**Fig. 1.** Flow chart of preparing of borax based pastes on the samples steel for plasma paste boronizing.

**Fig. 2.** Optical cross-section microstructure of plasma paste boronized steel in different % borax paste mixtures for 5 h at 1023 K, (a) 100% borax, (b) 70% borax + 30% SiC, (c) 70% borax + 30% B$_4$C, (d) 30% borax + 70% SiC, (e) 30% borax + 70% B$_4$C.