Comparison of mechanical properties of boronized and vanadium carbide coated AISI 1040 steels

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Comparison of mechanical properties of medium carbon steel AISI 1040 for vanadium carbide coated (VCC) and boronized conditions has been studied by means of microhardness, tensile and impact tests. For the treated steels, the boriding and vanadizing processes have been carried out in the same conditions, i.e., at a temperature of 1210 K for 4 h. The thickness of diffusion layer has been measured as 5 µm and 100 µm for the VCC and the boronized steels, respectively. In laboratory conditions, the VCC steels show considerably higher strength and surface hardening with respect to the untreated and the boronized steels. At the same time, Charpy V-notch impact tests have also been carried out for the steels with and without surface hardening. It is concluded that coating is effective in improving the mechanical performance of AISI 1040 steels.

Keywords: Vanadium carbide coating, Boronizing, Impact toughness, Borides, Notch

AISI 1040 steels are medium carbon steels and cheap materials that are widely used in manufacturing of simple constructions and machine elements. The main limitations of these materials are their low hardness and poor friction and wear properties. For that reason, many attempts have been made to improve their hardness and tribological properties. Boronizing treatment has been generally applied to improve the surface properties of these materials in utility industries. Indeed, the obtained hardness on the boronized steels is greater than 1600 HV and remains constant at high temperature, whereas it does not exceed 1000 HV in the best conditions, when using conventional means. Boride layer and formed hard boride phases such as FeB and Fe$_2$B in the boride layer on materials are known to be formed by the thermal diffusion of boron into the surface of materials improving hardness. The possibility of the formation FeB or FeB and Fe$_2$B phases depends on the boron chemical activity and the boron content as well as on the substrate temperature of the treatment. On the other hand, since fatigue is the primary failure mechanism of machine parts such as gears and shafts, the various mechanical and thermochemical surface treatment processes have been applied to improve their resistance. Nitriding, carburizing and vanadizing with vanadium carbide (VC) are considered one of the most widely used techniques to enhance resistance to wear at the surface of highly stressed machine parts. Among these processes, vanadizing is a surface deposition treatment carried out at 1123-1373 K in a molten salt or a packed medium or a vapour phase in which vanadium atoms deposit onto the surface of steels to form VC. Hard coatings of VC have been obtained on a number of steels by these processes and used for a variety of dies and machine components to improve the wear resistance.

The engineering systems are often set by the intended or unintended stress concentrators, including cracks, notches, bends or holes due to manufacturing process, service applications or damaged developed during service. V-notches are one of the simplest and most frequent geometries that appear in the test samples and the notched structural components. In considering the deformation of steels, the absorbed energy versus temperature in the Charpy V-notch test has been used to characterize the ductile to brittle transition. The aim of the present study is to investigate mechanical properties such as hardness, tensile behaviour and impact toughness of the VCC and the boronized AISI 1040 steels.

Experimental Procedure

The substrates used for this study are AISI 1040 medium carbon steels. Chemical composition of the
test materials are given in Table 1. The test pieces used in tensile and microhardness tests were cut from a bar 2 mm in diameter and 30 mm in length and annealed at 900 K for 10 h to remove potential residual stresses before machining the specimens. They were treated by two treatment methods which are boronizing and vanadizing. The boronizing of the steels was achieved in a solid medium using the powder pack method. In this method, commercial Ekabor-II boron source and activator (ferro-silicon) were thoroughly mixed to form the boriding medium. The test samples and packet were heated in an electrical resistance furnace for 4 h at 1210 K under the atmospheric pressure. The vanadizing process was carried out in the molten borax bath (% 55 Fe-V + % 45 borax) at the same conditions. After the furnace process, the boronized and the VCC samples were removed from the furnace, cooled in air, sectioned from one side, prepared metallographically up to 1200-grid emery paper, and polished using 3µm alumina pastes. The polished samples were etched by 4% Nital before the test. The morphology and the thickness of the VC and the boride layer were observed by using an optical microscope (Fig. 1). The presence of carbides and borides on the surface of the VCC and the boronized steels was determined by using the X-ray diffractometer (Rigaku D-MAX 2200) with a CuKα radiation of 0.15418 nm wavelength (Fig. 2). The hardness of the VCC and the boronized AISI 1040 steels was determined by using a Vickers microhardness tester with a load of 100 g. Many indentations were made on each coating film under each experimental condition to check reproducibility of the hardness data. On the other hand, the VCC and the boronized AISI 1040 steels were pulled at $10^{-6}$ s$^{-1}$ strain rate and 20 mm gauge length in the room temperature with an Instron type machine, full automatic and having 5 kN capacity. Load and elongation curves were recorded during the tensile tests and converted into stress-strain curves (Fig. 3). Ultimate tensile stress (maximum stress on the stress-strain curve, $\sigma_{UTS}$), yield stress (stress at 0.2% offset strain, $\sigma_y$) and elongation were determined from these curves. In addition, Charpy impact tests were performed using an instrumented Charpy impact testing machine with an energy capacity of 300 J and tests were conducted using the 10×10×55 mm$^3$ size of standard V notched untreated, the VCC and the boronized specimens at the room temperature. Notch of 2 mm depth were worked by milling with a 45º double angle cutter. Further experimental details were described elsewhere. 

<table>
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<tr>
<th>Table 1 — The chemical composition of AISI 1040 steels</th>
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<td>Steel type</td>
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<tr>
<td>----------------</td>
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<tr>
<td>AISI 1040</td>
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Fig. 1 — The optical microscope cross-sectional view of (a) borided and (b) VCC AISI 1040 steels

Fig. 2 — XRD pattern of AISI 1040 steels (a) borided and (b) VCC
Results and Discussion

The cross-section morphology of the VCC and the boronized AISI 1040 steels has been examined by using an optical microscopy and given in Figs 1a and 1b. As can be seen from Fig. 1a, three distinct regions have been identified on the surface of the borided steels (i) boride layer including borides, (ii) transition zone and (iii) matrix that is not affected by boron. By comparing the substrate morphology of the treated and the untreated samples, the homogeneous grain structure is seen due to the temperature process at the treated samples. The boride layer formed on the surface of steels has a sawtooth morphology due to the growth morphology and the chemical composition. The VCC steels have also smooth morphology and three distinct regions, whereas the transition region is very thin (Fig. 1b). In literature, the borided carbon steels usually lead to the formation of two borides. In the present study, the prominent phases formed in the boride layer of AISI 1040 steels are FeB near the surface and Fe₂B in vicinity of the steel matrix, while the vanadized steels have VC phases (Figs 1a and 1b) where their presence has been detected by XRD analysis (Figs 2a and 2b). The transition zone of the boronized steels has a grain growth structure which is not very clear in the Fig 1a, whereas the transition zone of the vanadized steels has a grain refinement structure. As can be seen in Fig. 1, the effective thickness of the diffusion layer of the boronized and the VCC samples are about 100 µm and 5 µm, respectively. In earlier studies, it has been pointed out that the thickness of the diffusion layer changes with steel type, treatment time, alloying elements and carbon or boron content. Depending on boronizing time and chemical compositions of AISI 316L steel substrates, the depth of the borides is ranged from 10 to 40 µm. In this study, the thickness of the boride layer and the VCC are in the range of 10 to 200 µm and 3 to 10 µm, respectively. The present results are in good agreement with the previously published results. The difference of the thicknesses of the modified layers in the boronized and vanadized AISI 1040 steels is due to the different diffusion mechanisms, activation energy, and atomic radius of boron, carbon, and vanadium atoms.

Microhardness measurements of the boronized and the VCC steels have been carried out from surface to interior along a line to see variation of the hardness of boride layer, VC layer, transition zone and matrix of steels. From these measurements, the hardnesses of the boride and VC layer have been found to be much higher than that of the matrix (Fig. 4). These are consequences of the presence of the hard phases such as FeB, Fe₂B and VC in the boride and VC layer. The hardness of the VCC steels is much higher than that of the borided steels due to residual stresses introduced phases (FeB, Fe₂B) and the matrix. The high hardness value of the VCC steels with respect to the boronized steels could also be attributed to the hard carbide layer adherent to the substrate and some excessive carbons (Fig. 2b). In earlier study in VCC steels, the high hardness value obtained from diffusion layer has been explained with presence of hard VC phase in the coating layer, which provides an

Fig. 3 — Stress-strain curves of untreated, boronized and vanadized AISI 1040 steels.

Fig. 4 — The hardness distribution of the vanadized and the boronized AISI 1040 steels.
Table 2—Tensile properties of AISI 1040 steels (a value in parentheses denotes the standard deviation of a single observation).

<table>
<thead>
<tr>
<th>Materials</th>
<th>Yield stress (MPa)</th>
<th>Ultimate tensile stress (MPa)</th>
<th>Fracture strain (%)</th>
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<tbody>
<tr>
<td>Untreated AISI 1040</td>
<td>380(11)</td>
<td>490(13)</td>
<td>36(1.13)</td>
</tr>
<tr>
<td>Boronized AISI 1040</td>
<td>650(14)</td>
<td>852(17)</td>
<td>21(0.08)</td>
</tr>
<tr>
<td>VCC AISI 1040</td>
<td>720(19)</td>
<td>960(21)</td>
<td>29(1.01)</td>
</tr>
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extremely hard surface compared to those of carburizing, carbonitriding and boronizing in AISI 1040 steels. These results showed that the VCC steels show the higher hardness value than that of the boronized ones.

Tensile properties of the VCC and the boronized AISI 1040 steels are given in Table 2. As can be seen from this table, the $\sigma_y$ and the $\sigma_{UTS}$ values of the boronized and the vanadized steels increase compared with the untreated steels. However, the elongation decreases in both the VCC and the boronized steels with the surface processes (Fig. 3). After the surface treatment, the values of $\sigma_y$ and $\sigma_{UTS}$ of vanadized steels and boronized steels are increased respectively by a factor close to 1.95, 1.73 and 1.89, 1.71. It is evident that the improvement in the $\sigma_y$ and the $\sigma_{UTS}$ values of the vanadized steels is more noticeable than that of the boronized steels. The differences in the tensile properties between the boronized and the VCC steels are due to different borided and coated layer thickness and phases formed with boronizing and vanadizing. It is noticed that VC phases belongs to a class of materials that possess high melting points, very high hardness and wear resistance.

The Charpy impact test, also known as the Charpy V-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is a measure of a given material toughness and acts as a tool to study temperature-dependent brittle-ductile transition. In this work, the impact properties of the VCC and the boronized notched AISI 1040 steels were also studied. After notched, the impact energy were obtained about 130±5.7 J, 145±6.2 J and 154±6.0 J for untreated, boronized and VCC steels, respectively, whereas this energy is 300±8.1 J for unnotched steels. From these results, the VCC steels have a higher impact toughness with respect to boronized steels. This is because the boronized steels have two phases in the diffusion region, although the coated steels have a single phase in the present work. These phases introduce residual stresses around the notch due to compressive and tensile stresses in the boronized steels. Finally, the residual stresses provide cracks during the impact tests.

Conclusions

Boride layers formed on the surface of steels have a sawtooth morphology and FeB, Fe$_3$B phases, while the VCC steels have smooth morphology and VC phases. The effective thickness of diffusion layer of the boronized and the VCC samples are about 100 µm and 5 µm. By comparing tensile and hardness results of vanadizing and boronizing process of AISI 1040 steels, vanadizing is a more effective process for surface hardening than boronizing. And also, the VCC steels have a high impact toughness with respect to the boronized steels.

References