In this study, case properties and diffusion kinetics of the AISI H10 steel borided in Ekabor-II powder were investigated by conducting a series of experiments at temperatures of (1123, 1173 and 1223) K for (2, 4 and 6) h. The boride layer was characterized with light microscopy, X-ray diffraction technique and micro-Vickers hardness tester. The X-ray diffraction analysis of the boride layers on the surfaces of the steels revealed the existence of FeB, Fe₂B, CrB, Cr₂B and MoB compounds. Depending on the chemical compositions of the substrates and boriding time, the boride-layer thickness on the surface of the steel ranged from 12.86 μm to 63.72 μm. The hardness of the boride compounds formed on the surfaces of the steels ranged from 1648 HV₀.⁰⁵ to 1964 HV₀.⁰⁵, whereas the Vickers-hardness value of the untreated steel was 306 HV₀.⁰⁵. The activation energy (Q) of the borided steel was 160.594 kJ/mol. The growth kinetics of the boride layer formed on the AISI H10 steel and its thickness were also investigated.

Keywords: AISI H10, boride layer, microhardness, kinetics, activation energy
taining an Ekabor-II powder mixture placed in an electrical-resistance furnace operating at temperatures of (1123, 1173 and 1223) K for (2, 4 and 6) h under atmospheric pressure. The microstructures of the polished and etched cross-sections of the specimens were observed under a Nikon MA100 light microscope. The presence of borides formed in the coating layer was confirmed with X-ray diffraction equipment (Shimadzu XRD 6000) using Cu-Kα radiation. The thickness of borides was measured with a digital thickness-measuring instrument attached to the light microscope (Nikon MA100). The hardness measurements of the boride layer on each steel and of the untreated steel substrate were made on the cross-sections using a Shimadzu HMV-2 Vickers indenter with a 50 g load.

2.2 Evaluation of the activation energy of boron diffusion

In order to study the diffusion mechanism, borided AISI H10 steel was used for this purpose. It is assumed that boride layers grow parabolically in the direction of the diffusion flux and perpendicular to the substrate surface. So, the time dependence of the boride-layer thickness can be described with Equation (1):

\[ x^2 = Dt \]  

where \( x \) is the depth of the boride layer (mm), \( t \) is the boriding time (s) and \( D \) is the boron diffusion coefficient through the boride layer. It is a well-known fact that the main factor limiting the growth of a layer is the diffusion of boron into the substrate. It is possible to argue that the relationship between the growth-rate constant \( D \), the activation energy \( Q \), and the temperature \( T \) in Kelvin, can be expressed as an Arrhenius equation (Equation (2)):

\[ D = D_0 \exp \left( \frac{-Q}{RT} \right) \]  

where \( D_0 \) is a pre-exponential constant, \( Q \) is the activation energy (J/mol), \( T \) is the absolute temperature in Kelvin and \( R \) is the ideal gas constant (J/(mol K)).

The activation energy for the boron diffusion in a boride layer is determined with the slope obtained in the plot of \( \ln D \) vs. \( 1/T \), using Equation (3):

\[ \ln D = \ln D_0 - \frac{Q}{RT} \]  

3 RESULTS AND DISCUSSION

3.1 Characterization of boride coatings

Light micrographs of the cross-sections of the borided AISI H10 steel at the temperatures of 1123 K and 1223 K for 2 h and 6 h are shown in Figure 1. As can be seen the borides formed on the AISI H10 substrate have a saw-tooth morphology. It was found that the coating/matrix interface and the matrix can be significantly distinguished and the boride layer has a columnar structure. Depending on the chemical compositions of the substrates, the boriding time and temperature, the boride-layer thickness on the surface of the AISI H10 steel ranged from 12.86 μm to 63.72 μm in Figure 2.

Figure 3 gives the XRD patterns obtained at the surface of the borided AISI H10 steel at 1123 K and 1223 K for the treatment times of 2 h and 6 h. The XRD patterns show that the boride layer consists of borides such as MB and M2B (M = metal: Fe, Cr). The XRD results showed that the boride layers formed on the H10 steel contained FeB, Fe2B, CrB, Cr2B and MoB phases (Figures 3a to 3d.)

Microhardness measurements were carried out along a line from the surface to the interior in order to see the variations in the hardness of the boride layer, the transition zone and the matrix, respectively. The microhardness of the boride layers was measured at 10 different locations at the same distance from the surface and the
The average value was taken as the hardness. The results of the microhardness measurements carried out on the cross-sections, along the line from the surface to the interior are presented in Figure 4. The hardness of the boride layer formed on the AISI H10 steel varied between 1648 HV0.05 and 1964 HV0.05. On the other hand, the Vickers hardness value for the untreated AISI H10 steel was 306 HV0.05. When the hardness of the boride layer is compared with the matrix, the boride-layer hardness is approximately five times larger than that of the matrix.

### 3.2 Kinetics

In this study, the effects of the processing temperature and boriding time on the growth kinetics of a boride layer were also investigated. The kinetic parameters such as the processing temperature and time must be known for the control of the boriding treatment. Figure 5 shows the time dependence of the squared value of the boride-layer thickness at increasing temperatures. This evolution followed the parabolic growth law where the diffusion of boron atoms is a thermally activated phenomenon. The growth-rate constant $D$ at each boriding temperature can be easily calculated with Equation (1).
As a result, the calculated growth-rate constants at three temperatures, (1123, 1173 and 1223) K, are (5.58 × 10⁻¹⁰, 9.67 × 10⁻¹⁰, and 1.18 × 10⁻⁹) cm² s⁻¹ for the borided AISI H10 steel. 

Table 1 lists the calculated values of the growth constant for each boriding temperature. 

Figure 6 describes the temperature dependence of the growth-rate constant according to the Arrhenius equation. The boron activation energy can be easily obtained from the slope of the straight line presented in Figure 6. The value of the boron activation energy was then determined as 160.594 kJ/mol for the borided AISI H10 steel. 

Table 2 compares the obtained value of energy (160.594 kJ/mol) with the data found in the literature. It is seen that the reported values of the boron activation energy depended on the chemical composition of the substrate and the used boriding method. The calculated value in this study is comparable with the values reported in the literature as seen in Table 2.

### Table 2: Comparison of the Activation-Energy Values for Diffusion of Boron with Respect to Different Boriding Media and Substrates

<table>
<thead>
<tr>
<th>Steel</th>
<th>Temperature range (K)</th>
<th>Boriding medium</th>
<th>Activation energy (kJ/mol)</th>
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</thead>
<tbody>
<tr>
<td>AISI 8620</td>
<td>973–1073</td>
<td>Plasma paste</td>
<td>99.77</td>
<td>16</td>
</tr>
<tr>
<td>AISI W1</td>
<td>1123–1233</td>
<td>Pack</td>
<td>177.8</td>
<td>17</td>
</tr>
<tr>
<td>AISI 52100</td>
<td>1123–1233</td>
<td>Pack</td>
<td>269</td>
<td>18</td>
</tr>
<tr>
<td>AISI 1035</td>
<td>1073–1273</td>
<td>Salt bath</td>
<td>227.5</td>
<td>19</td>
</tr>
<tr>
<td>AISI H13</td>
<td>1073–1223</td>
<td>Powder</td>
<td>186.2</td>
<td>20</td>
</tr>
<tr>
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<td>244</td>
<td>21</td>
</tr>
<tr>
<td>AISI H10</td>
<td>1123–1223</td>
<td>Pack</td>
<td>160.594</td>
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Figure 6 describes the temperature dependence of the growth-rate constant. The plot of ln D as a function of the reciprocal temperature exhibits a linear relationship according to the Arrhenius equation. The boron activation energy can be easily obtained from the slope of the straight line presented in Figure 6. The value of the boron activation energy was then determined as 160.594 kJ/mol for the borided AISI H10 steel.

Table 2 compares the obtained value of energy (160.594 kJ/mol) with the data found in the literature. It is seen that the reported values of the boron activation energy depended on the chemical composition of the substrate and the used boriding method. The calculated value in this study is comparable with the values reported in the literature as seen in Table 2.

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A contour diagram describing the evolution of the boride-layer thickness as a function of the boriding parameters (the time and the temperature) is shown in Figure 7. This contour diagram can be used for two purposes: (1) to predict the coating-layer thickness with respect to the processing parameters, namely, the time and temperature; (2) to determine the value of the processing time and temperature for obtaining a predetermined coating-layer thickness. The boride layer increased with an increase in the boriding time and temperature for the borided AISI H10 steel.

### 4 Conclusions

The following conclusions may be derived from the present study.

- The boride types formed on the surface of the hot-work tool steel have columnar structures.
- The boride-layer thickness obtained on the surface of the AISI H10 steel was 12.86–63.72 μm, depending on the chemical compositions of the substrates.
- The multiphase boride coatings that were thermally grown on the AISI H10 steel consisted of the FeB, Fe₃B, CrB, Cr₂B and MoB phases.
- The surface hardness of the borided steel was in the range of 1648–1964 HV₀.05, while for the untreated steel it was 306 HV₀.05.
The boron activation energy was estimated to be 160.594 kJ/mol for the borided AISI H10 steel.

A contour diagram relating the boride-layer thickness to the boriding parameters (the time and the temperature) was proposed. It can be used as a simple tool to select the optimum boride layer for a practical utilization of this kind of material.

5 REFERENCES