16th International Research/Expert Conference
"Trends in the Development of Machinery and Associated Technology"
TMT 2012, Dubai, UAE, 10-12 September 2012

AN INVESTIGATION OF BORIDE LAYERS GROWTH KINETICS ON C15 STEEL

Andrijana Milinović
Mechanical Engineering Faculty in Slavonski Brod
Trg I.B. Mažuranić 2, 35000 Slavonski Brod, Croatia

Dragomir Krumes
Mechanical Engineering Faculty in Slavonski Brod
Trg I.B. Mažuranić 2, 35000 Slavonski Brod, Croatia

Ivica Kladarić
Mechanical Engineering Faculty in Slavonski Brod
Trg I.B. Mažuranić 2, 35000 Slavonski Brod, Croatia

Štefanija Klarić
Mechanical Engineering Faculty in Slavonski Brod
Trg I.B. Mažuranić 2, 35000 Slavonski Brod, Croatia

Stjepan Aračić
Mechanical Engineering Faculty in Slavonski Brod
Gundulićeva 20A, 35000 Slavonski Brod
Croatia

ABSTRACT
This study reports an evaluation of borides formed on C15 steel. Pack boronizing has been carried out in temperature range 870 – 970 °C with durations 4 – 8 h. Average thickness of obtained boride layers ranges from 69,9 to 239,2 µm. Microhardness of boride layers has been estimated by means of Vickers HV 0,1 method. Based on the average thickness of boride layers and through application of statistic methods the influence of temperature and duration of boronizing is analyzed. Analysis showed existence of influence of mentioned parameters upon observed properties of boride layer, and as a result, mathematical model showing their functional correlation have been obtained.
Keywords: boride layer, boronizing, kinetics

1. INTRODUCTION
Tools and the majority of machine parts are commonly exposed to wear during their use. In such working conditions, surface properties are often most important for their reliable and long service life. In order to improve wear resistance, a number of surface hardening treatments are developed within surface engineering, and one of them is boronizing. Boronizing is thermo-diffusion process in which boron atoms diffuse into a metal surface and form intermetallic compounds with atoms of base metal. Resulting boride layer is extremely hard and increases abrasive wear resistance of the surface. Moreover, boronizing also improves resistance to adhesion wear and corrosion. With proper selection of boronizing parameters and materials, machine parts lifetime can be extended 3 - 10 times [1]. Although boronizing is most suitable for carbon and low alloyed steels, it can also be applied on Ni, Co, Ti, W and Mo based alloys and sintered hard materials. Boronizing of carbon steels is usually carried out at temperatures 800 - 1050 ºC and treatment times 1 - 12 h. Obtained surface layer, with characteristic saw-tooth morphology, may consist of one iron boride phase (Fe_2B) or can be dual-phased ($FeB+ Fe_2B$). Although FeB is harder (1800 – 2100 HV) than Fe_2B (1400 – 1600 HV), it is

considered as an undesirable due to its brittleness. Furthermore, since FeB and Fe_2B borides have different coefficients of thermal expansion, crack formation on FeB / Fe_2B interface can often be observed. When high loads are applied, presence of these cracks and high internal stresses can often lead to spalling. [2-9]. Boronizing can be carried out in solid, liquid or gaseous media, and the most frequently used is pack boronizing. Many of process parameters (i.e. boronizing temperature and time, boron potential, substrate material) affect boronizing. In order to obtain desired properties of boride layer, it is very important is to establish the process parameters. The main objective of the present study is to investigate boronizing kinetics on C15 steel during pack boronizing.

2. EXPERIMENTAL INVESTIGATIONS

In order to ensure diffusion in austenite, boronizing process is carried out at 870, 920 and 970 ºC for durations of 4, 6 and 8 h. According to selected parameters, 3^2 factorial design with 3 repeating of each case is defined and 27 specimens with nominal dimensions Ø 16 x 7 mm have been cut. Before boronizing, surfaces of specimens were cleaned and ground using 600 grid emery paper. Pack boronizing is carried out in Durborid 3 powder (solid medium for boronizing temperatures 800 - 1000 ºC) in electric furnace without protective atmospheres. After boronizing, all specimens were longitudinally cross-section cut with use of electrical discharge machining and prepared for metallographic examinations (ground using 1000 grid emery paper, alumina polished and etched with 3 % nital). The morphology and types of borides formed on the surface of treated steels were confirmed by means of optical microscopy and scanning electron microscopy (SEM). Average boride layers thicknesses were determined using metallographic line method and digital Leica MW software [10]. The microhardness of boride layers were measured using a Vickers microhardness tester under test load of 0,981 N (HV 0,1).

3. RESULTS AND DISCUSSION

3.1. Boride layer properties

Characteristic microstructure of boride layers obtained on steel surface is shown in Figure 1.

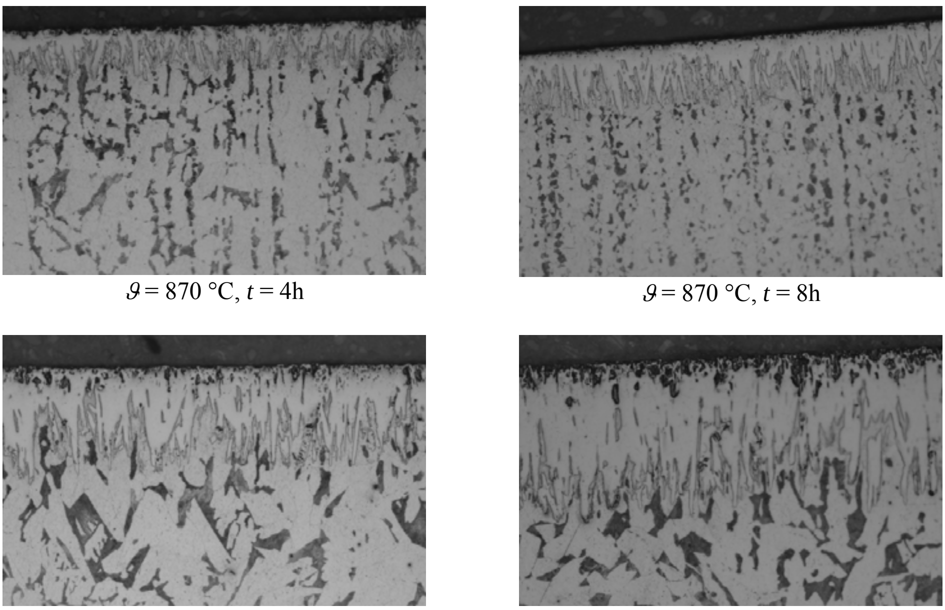

Figure 1. Microstructure of boride layers, magnification 200:1

Optical microscopy and SEM examinations revealed that borides formed on steels surface are compact and have characteristic saw-tooth morphology. Higher share of pearlite that are apparent in diffusion zone, were created due to increased content of carbon suppressed from the surface inward. It can be observed that at lower boronizing temperatures and times, borides grow in a more columnar nature. Increasing the time and temperature, saw-tooth morphology is less pronounced. It is possible to claim that saw-tooth morphology depends on boronizing temperature and time. Microstructure of specimens boronized at higher temperatures (920 and 970 ºC) indicates the presence of another phase in boride layer. Since XRD was not conducted, it can not be held for certain which phase is present, but its morphology indicates FeB phase [11]. Boride layer thicknesses, given in Table 1, are calculated as a mean of 20 measurements conducted on each sample according to design of experiment (3 samples for each of boronizing times and temperatures).

Table 1. Boride layer thickness

Boride layer thickness, µm								
ϑ = 870 ºC			ϑ = 920 ºC			ϑ = 970 ºC		
t = 4 h	t = 6 h	t = 8 h	t = 4 h	t = 6 h	t = 8 h	t = 4 h	t = 6 h	t = 8 h
69,9	98,4	103,9	117,9	156,7	158,3	172,7	210,6	239,2

Table 1 clearly shows that boride layer thickness increases with increasing boronizing time and temperature. Microhardness of Fe_2B iron boride has been estimated by means of Vickers method. Average values of measured hardness are given in Table 2. Results indicate that boronizing temperature and time does not significantly affect Fe_2B hardness.

Table 2 Microhardness of Fe_2B iron boride

Microhardness of Fe_2B, HV 0,1									
ϑ = 870 ºC			ϑ = 920 ºC			ϑ = 970 ºC			Average hardness
t = 4 h	t = 6 h	t = 8 h	t = 4 h	t = 6 h	t = 8 h	t = 4 h	t = 6 h	t = 8 h	
1527	1544	1479	1443	1562	1555	1545	1570	1645	1541

3.2. Kinetic study

The influence of boronizing temperature and duration with respect to average boride layer thickness is analyzed through application of statistic methods. Analysis of variance is conducted in order to test for significant differences between means of boride layer thickness (95 % confidence limit, significance level α = 0,095).

Effect	SS	DF	MS	*F*	*p*
Intercept	191630,4	1	191630,4	7160,390	0,000000
Temperature ϑ, °C	18811,5	2	9405,8	351,452	0,000032
Duration t, h	3064,5	2	1532,2	57,253	0,001139
Error	107,1	4	26,8		

Test result (*F* and *p* values) for both factors (temperature and duration) indicates their influence upon boride layer thickness. It is also determined that temperature affects boride layer thickness, more than duration. As a result of regression analysis, regression parameters are determined, and the fitted regression model (second-order polynomial) is given by:

$$d = -811{,}53 + 0{,}845 \times \vartheta + 10{,}398 \times t - 3{,}489 \times t^2 + 0{,}046 \times \vartheta \times t \qquad \ldots(1)$$

where: d – is boride layer thickness, µm; ϑ – is boronizing temperature, °C and t – is boronizing duration, h.

Graphical representation of model (1) is a three dimensional plot shown in Figure 2. The model (1) describes functional relationship between boride layer thickness and temperature and duration for boronizing of C15 steel, and it can be used either for:

- prediction of boride layer thickness with respect to boronizing time and temperature
- selection of boronizing time or temperature for obtaining desired boride layer thickness.

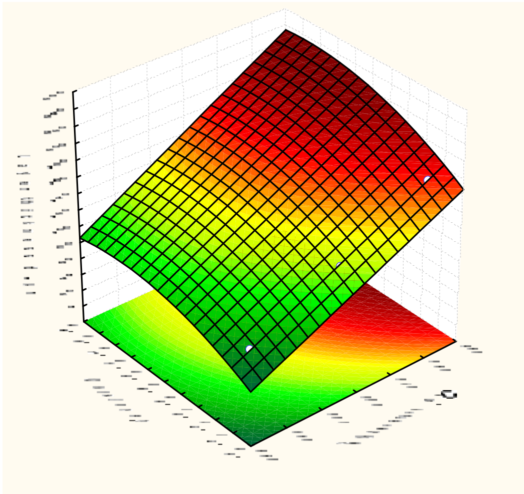

Figure 2. Graphical representation of functional correlation between boride layer thickness and temperature and duration for boronizing of C15 steel

4. CONCLUSION

Taking into consideration all results of this study, following conclusions can be established:

- Obtained boride layers are compact with pronounced saw-tooth morphology.
- Thickness of boride layer strongly depends on boronizing temperature and time.
- Microhardness of Fe_2B iron boride varies in the range of 1443 - 1645 HV 0,1. Almost equal hardness values indicate that, in the case of C15 carbon steel, boronizing temperature and time does not affect significantly the Fe_2B hardness.
- Empirical expression for boronizing of C15 steel has been derived through usage of statistic methods. This expression is convenient for technological and industrial application, and could be used for estimation of boride layer thickness in dependence on boronizing parameters (temperature and time).

5. REFERENCES

[1] Stewart K.: Boronizing protects metals against wear, Advanced Materials & Processes, 151, 3(1997), 23-25.

[2] Sen S., Sen U., Bindal C.: An approach to kinetic study of borided steels, Surface and Coatings Technology, 191, 2-3(2005), 274-285.

[3] Krumes D.: Površinske toplinske obrade i inženjerstvo površina, Strojarski fakultet u Slavonskom Brodu, Slavonski Brod, 2004.

[4] Matijević B.: Toplinsko difuzijski proces boriranja čelika, Magistarski rad, Fakultet strojarstva i brodogradnje, Zagreb, 1992.

[5] Milinović A.: Istraživanje kinetike nastanka boridnih slojeva na nelegiranim čelicima, Doktorski rad, Strojarski fakultet u Slavonskom Brodu, Slavonski Brod, 2010.

[6] ASM Handbook: Volume 4: Heat Treating, Sinha A. K.: Boriding (Boronizing) of Steels, Ohio: ASM International, 1991., 437-447.

[7] Genel K.: Boriding kinetics of H13 steel, Vacuum, 80, 5(2006), 451-457.

[8] Yu L.G., Chen X. J. Khor K. A., Sundararajan G.: FeB/Fe_2B phase transformation during SPS pack-boriding: Boride layer growth kinetics, Acta Materialia, 53, 8(2005), 2361-2368.

[9] Von Matuschka A. G.: Borieren, Carl Hanser Verlag München, Wien, 1977.

[10] Leica Materials Workstation v.3.6.1, software for microstructure analysis, 2005.

[11] Milinović A., Krumes D., Marković R.: An investigation of boride layers growth kinetics on carbon steels, Technical Gazette, 19, 1(2012), 27-31.