Investigation of thermochemical boriding effect on wear behavior of a GGG 50 quality as-cast ductile iron

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Abstract

Purpose – This study aims to investigate the microstructure and the abrasive wear features of the untreated and pack borided GGG 50 quality ductile iron under various working temperatures.

Design/methodology/approach – GGG 50 quality as-cast ductile iron samples were pack borided in Ekabor II powder at 900°C for 3 h, followed by furnace cooling. Structural characterization was made by optical microscopy. Mechanical characterization was made by hardness and pin-on-disc wear test. Pin-on-disc test was conducted on a 240-mesh Al_2O_3 abrasive paper at various temperatures in between 25 and 450°C.

Findings – Room temperature abrasive wear resistance of the borided ductile iron increased with an increase in its surface hardness. High-temperature abrasive wear resistances of the borided ductile iron linearly decreased with an increase in test temperature. However, the untreated ductile iron exhibited relatively high resistance to abrasion at a temperature of 150°C.

Originality/value – This study can be a practical reference and offers insight into the effects of boriding process on the increase of room temperature wear resistance. However, above 150°C, the untreated ductile iron exhibited similar abrasive wear performance as compared to the borided ductile iron.

Keywords Wear, High temperature, Boriding, Ductile iron

Paper type Research paper

1. Introduction

Ductile iron (DI), which has excellent mechanical properties, machinability and low production costs, has been used widely in various industrial fields, such as in automotive and machine parts, tubes and drawing moulds (Sahin *et al.*, 2010; Abedi *et al.*, 2010). However, the main restriction in the application of DI has always been related to the low abrasive wear resistance. To improve its wear performance, suitable hard diffusion processes, such as carburizing, nitriding and boriding, are gaining importance. With a finger-like structure, borided ferrous and non-ferrous alloy components are characterized by their enhanced surface hardness and wear resistance under a variety of wear environment (Li *et al.*, 2008; Béjar and Henríquez, 2009). Therefore, boriding is now used as a successful surface hardening technology in many sectors of manufacturing. Among the various boriding processes, pack boriding, which uses solid precursors in the form of powder or paste, has some important advantages in terms of easy handling, the flexibility with respect to the composition of the powder, minimal equipment and low cost (Li *et al.*, 2008).

The boriding process used to form a range of metal boride phases is carried out at temperatures between 700 and 1,000°C in solid, liquid, gaseous or plasma medium (Fichtl, 1981). At this temperature range, boron atoms (their relatively small size and very mobile nature features) can penetrate easily into the surface of ferrous alloys forming compounds (FeB and Fe_2B) with the host metal. These compounds usually have satisfactory mechanical (tribological and fatigue) properties of the superficial layer. Boride layers are biphasic, as a rule, and comprise the borides FeB and Fe_2B. The resultant diffusion zone is known for its low coefficient of friction and high surface hardness, which may reach values of 2000 HV (Yoon *et al.*, 1999; Sen *et al.*, 2004a; Garcia-Bustos *et al.*, 2013).

Resistance to softening at elevated temperatures is another important property of borided surfaces (Li *et al.*, 2008; Sen *et al.*, 2004b). In a recent study, the effect of volume fraction of FeB (V_{FeB}) on the wear resistance of dual-phase (consisted of FeB layer on Fe_2B layer) boride layers formed on 31CrMoV9 and X40CrMoV5-1 quality steels have been examined at room and elevated temperatures (Motallebzadeh *et al.*, 2015). Although the examined borided steels exhibited superior wear resistance and identical friction characteristics at room temperature, their wear resistances decreased at 500°C in association with cracking at the contact region. The

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Table I Chemical composition (Wt.%)

C	Si	Mn	P	S	Mg
3.77	2.45	0.33	0.038	0.067	0.05

Figure 1 General appearance of abrasive wear tester used in this study

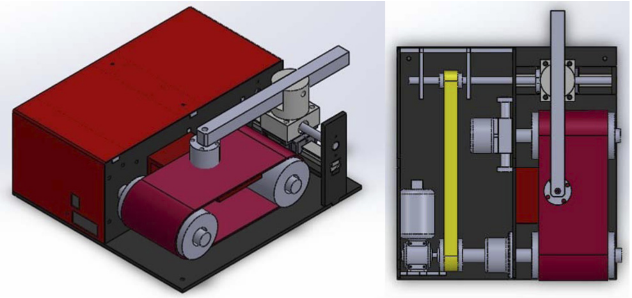
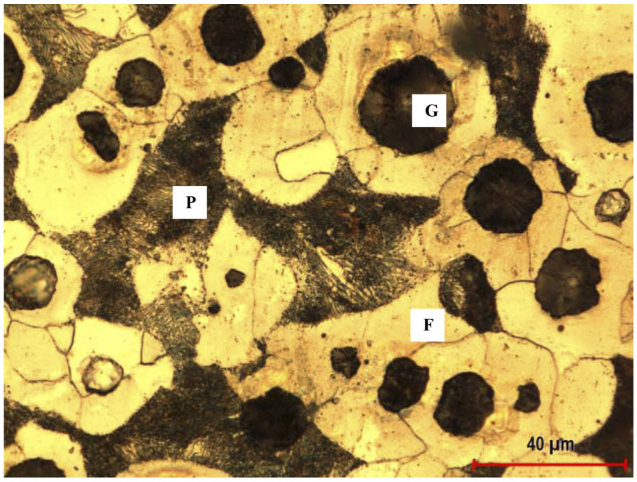
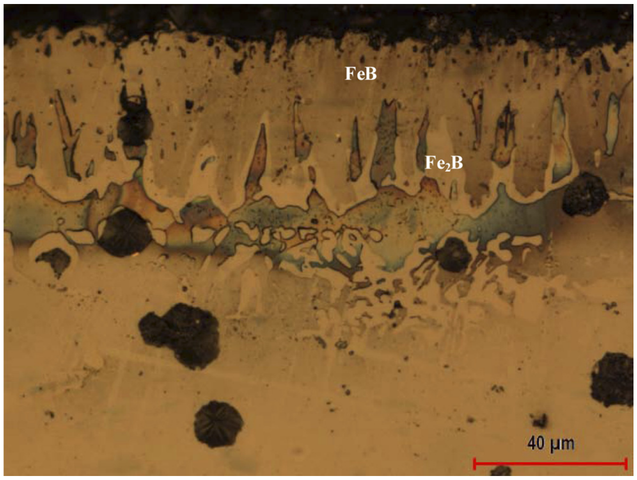


Figure 2 Microstructure of as-received DI



Notes: F = ferrite; G = graphite; P = pearlite

Figure 3 Cross-sectional OM micrograph of the borided DI at 900°C for 3 h



borided 31CrMoV9 steel (V_{FeB} = 31 per cent) underwent severe wear at 500°C under dry sliding conditions against an alumina ball when compared to the borided X40CrMoV5-1 steel (V_{FeB} = 47 per cent). As the dry sliding wear response of the boride layer at high temperatures is related to the control of thermal stress by altering the structure of the surface layers (Motallebzadeh *et al.*, 2015), it is necessary to study the wear behavior of boride layer identified for components exposed to abrasive elements and high operating temperatures. In the present work, the focus is on the characterization of the microstructure and the study of abrasive wear features of

Figure 4 Hardness profile of the DI borided at 900°C for 3 h

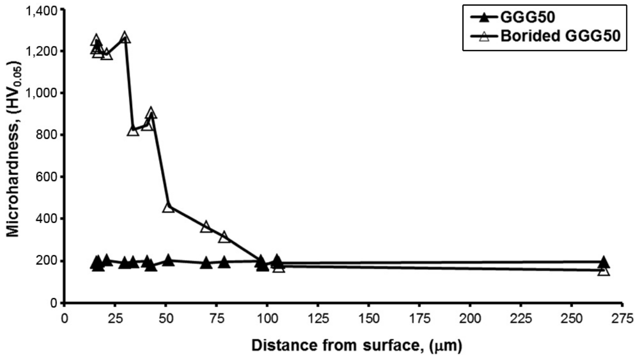


Figure 5 The effect of test temperature on the relative wear resistance of the untreated and borided DI abraded on a 240-mesh Al_2O_3 abrasive grains

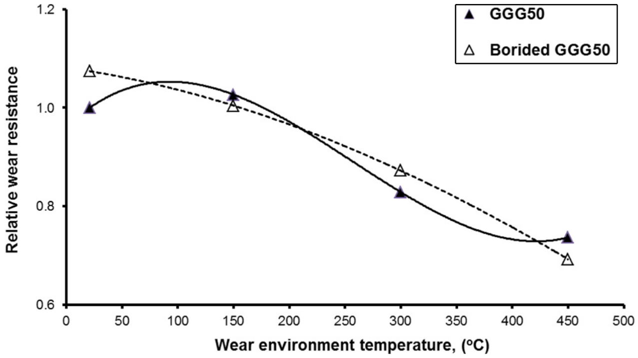
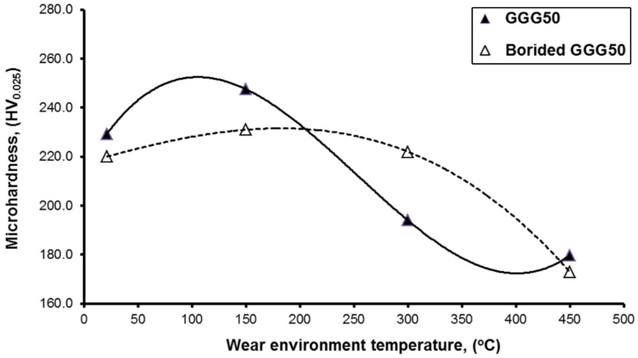


Figure 6 The effect of test temperature on subsurface hardness of the untreated and borided DI abraded on 240-mesh Al_2O_3 abrasive grains



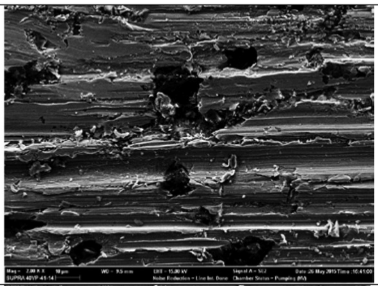
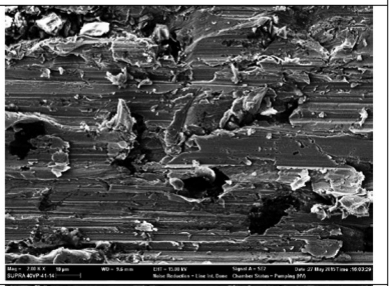
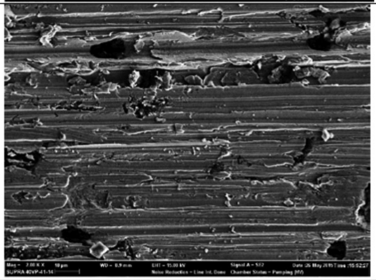
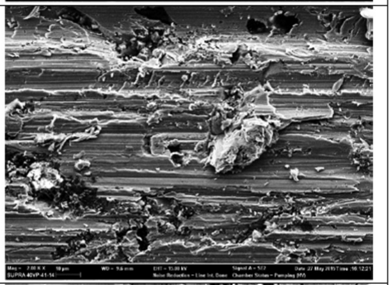
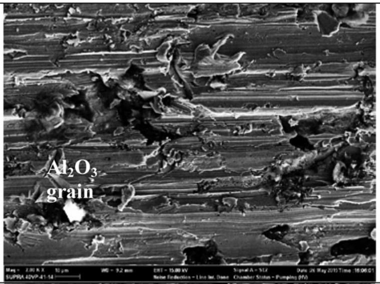
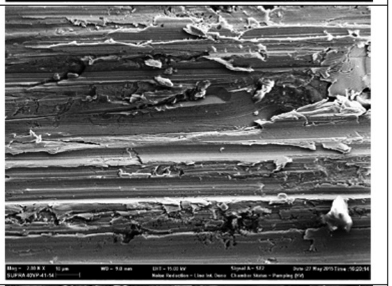
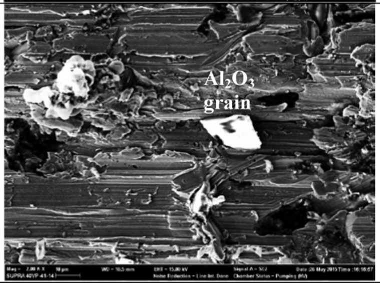
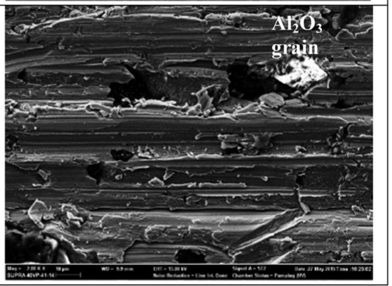
the untreated and pack borided DI under various working temperatures.

2. Experimental details

The material used in the present study was unalloyed DI (GGG 50) with a chemical composition shown in Table I. Boriding treatment was carried out in a sealed stainless steel container located in an electrical resistance furnace. The container was filled with commercial Ekabor II boriding powders that consisted of the boriding source B_4C, the activator KBF_4 and the diluent SiC. The test DI to be borided was placed in contact with the boriding medium. Then, boriding was performed at the constant atmosphere at 900°C for 3 h, followed by furnace cooling. The thickness of coating and its morphology were conducted on the cross-section of the borided DI after etching with 2 per cent nital by utilizing an optical microscope (OM). A Shimadzu microhardness tester was used to measure the hardness along the depth in the cross-section of the modified DI. Microhardness was measured at an indentation load of 50 g for 15 s.

Wear behavior of the boride layer and untreated DI was examined by using an abrasive wear tester, schematically shown in Figure 1. The tests were conducted at room (25°C) and at elevated temperatures (up to 450°C) by rubbing the samples on a 240-mesh Al_2O_3 abrasive paper. Test samples for wear studies were machined into cylinder, which was of 6 mm in diameter and 20 mm in length. Abrasion tests were carried out by applying a normal load of 10 N for a total sliding distance of 8.4 m at a sliding speed of 0.5 m/s. During the wear tests, it was ensured that the samples always

Figure 7 SEM micrographs showing the morphology of the worn surfaces of the untreated and borided DI abraded on 240-mesh Al_2O_3 abrasive grains at room (25°C) and at elevated temperatures (up to 450°C)

Test Temperature (°C)	Materials	
	Untreated DI	Borided DI
25		
150		
300		
450		

encountered fresh abrasive particles by allowing the abrasive papers to move perpendicular to the sliding direction. Wear loss of the samples was determined by measuring the weight of the samples before and after the tests, with 0.1-mg sensitivity. The effect of wear environment temperature on the abrasive wear behavior of the untreated and borided DI is analyzed on the basis of relative wear resistance (RWR):

$$\mathrm{RWR} = \frac{\text{total weight loss of untreated DI at room temperature}}{\text{total weight loss of other samples at other temperature}}$$

After the wear tests, worn surfaces of the untreated and borided DI were examined by a scanning electron microscope (SEM) and a stylus profilometer. The roughness-measurement length was 2 mm for average-surface-roughness (R_a) and maximum-roughness-depth (R_y) determinations, in units of microns. The parameters R_a and R_y are the average absolute deviation of the roughness irregularities from the mean line and the largest value of the maximum peak to valley height parameters along the assessment length, respectively (Gadelmawla *et al.*, 2002). To understand the mechanism of material removal during wear testing, the subsurface hardness and cross-sectional micrograph of the worn surface were examined with microhardness under a load of 25 g and OM examination, respectively.

3. Results and discussions

The principal micro-constituents consisted of a pearlitic matrix with ferritic rings of varying thicknesses surrounding the graphite nodules, which had a good nodularity (Figure 2). Image analysis of optical micrographs of unetched DI gave a volume fraction of graphite of 11 per cent, a graphite nodularity of 93 per cent, a distribution of graphite particles of 285 nodules/mm^2 and a mean graphite nodule size of 19.5 μm.

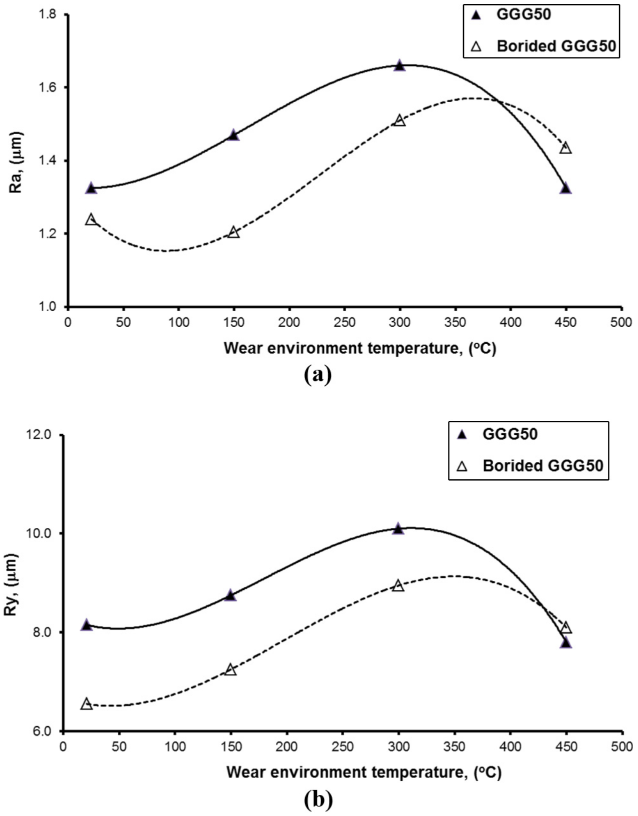
Figure 3 gives an overview of the appearance of the boride layer. As a result of metallographic investigation of borided DI, it has been determined that the boride layer has a finger-like structure, and this structure is homogeneously distributed over the surface. After boriding DI at 900°C for 3 h, a 30-μm layer of boride was produced. On cross-section of the borided DI surface, there was a compact layer of FeB and Fe_2B borides, as seen in Figure 3. FeB and Fe_2B phases in the boride layer of the DI investigated by the OM are distinguished by the contrast difference. Sen *et al.* (2014a, 2014b) reported that FeB is dominant phase for borided GGG 50 ductile cast iron.

Figure 4 shows the microhardness profile measured on the cross-section of the DI borided at 900°C for 3 h. It can be seen that the average hardness value of the boride layer reaches 1,200-1,250 $HV_{0.05}$, which is considerably higher than that of the untreated DI due to the formation of two-phase boride layers. The hardness of the boride layer diminishes gradually from the surface to substrate.

The variation of the relative wear resistance experienced by the untreated and borided DI is provided in Figure 5 as a function of temperature. The wear resistance of the borided DI has a high value of 1.074 at room temperature, which is higher than that of untreated DI. The wear resistance of the borided DI has an approximately linear relationship with its wear environment temperature and diminishes to a low value of 0.69 at a temperature of 450°C. However, the wear resistance is relatively high for the untreated DI at a temperature of 150°C. This temperature corresponds to the beginning temperature of strain aging beneath the worn surface (Figure 6). The strain aging of the subsurface layer was contributed to increase in the wear resistance of the untreated DI (Figure 5). The trend displayed in the wear resistance has been observed in Celik's results (2005). The subsurface hardness of the borided DI decreased to a low value of 222 $HV_{0.025}$ at the temperature of 350°C. But the value is still higher than that of the untreateated DI. As a consequence of its low subsurface hardness at the temperature of 300°C (Figure 6), the untreated DI presented lower wear resistance than the borided DI. It can be concluded from Figures 5 and 6 that when the temperature reaches up to 450°C, the boride layer is completely peeled off and loses its high hardness (Yan *et al.*, 2001).

Worn surfaces of the untreated and borided DI abraded on a 240-mesh Al_2O_3 abrasive band are given in Figure 7 as a function of temperature. The SEM examination of the abrasive worn surfaces showed that wear progressed by grooving action of the Al_2O_3 abrasive grains. Additionally, on the worn surfaces of the untreated and borided DI tested at elevated temperatures, embedded Al_2O_3 abrasive grains were present, as seen in Figure 7. The results of the roughness measurements conducted on abrasive worn surfaces are given in Figure 8 in terms of R_a and R_y values with wear environment temperature. In the case of abrasive wear test conducted on the borided DI, smoother and flatter worn surfaces were obtained than observed during testing with DI substrate (Figure 7). Thus, on the untreated DI, relatively

Figure 8 Variation of (a) R_a and (b) R_y values with wear environment temperature



wide and deep grooves were accompanied by high R_a and R_y values (Figure 8). Profilometry traces indicated that the resultant surfaces were roughened until 300°C. Above 300°C, the roughness decreased with an increase of temperature due to the softening of the DI substrate (Figure 6).

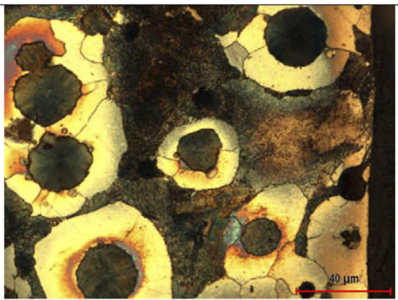
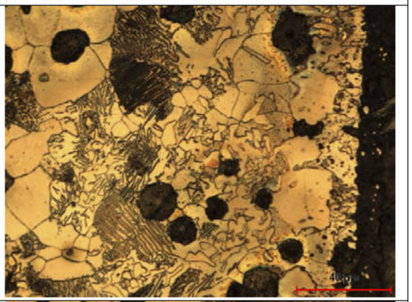
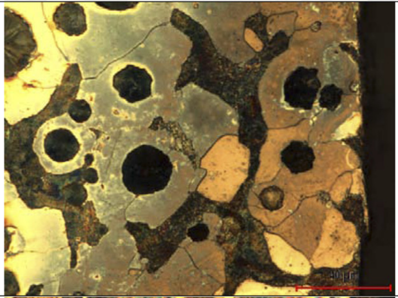
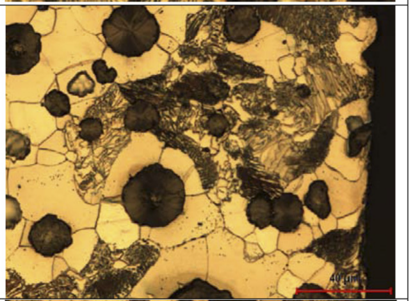
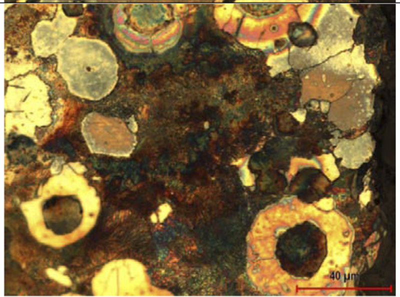
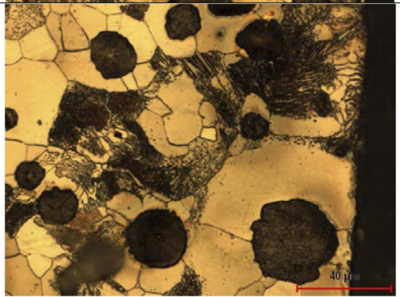
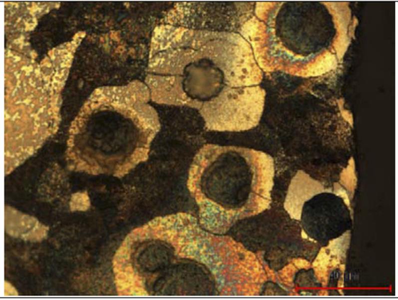
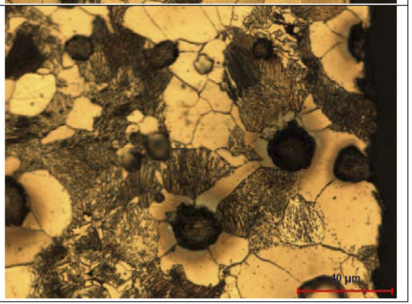
Figure 9 shows cross-sectional OM micrographs of the untreated and borided DI abraded on 240-mesh Al_2O_3 abrasive grains after the wear test of 8.4 m travel distance. The OM micrograph of the borided DI confirms the presence of a double phase layer with FeB and Fe_2B at room temperature. In addition, it must be noted that one type of boride (FeB and Fe_2B) did not exist on the surface of the borided DI at elevated temperatures. Thus, the acceleration of the process of wear under an abrasive loading at elevated temperatures can be related to the presence of cracks induced by internal stresses in the interphase of a double phase layer due to significant differences between expansion coefficients at both phases (Motallebzadeh *et al.*, 2015).

4. Conclusions

Following conclusions can be drawn from the present investigation.

- The hardness value (1,200-1,250 $HV_{0.05}$) of boride layer is much higher than that of substrate (190-200 $HV_{0.05}$). Thus, surface hardness value increased six times by the

Figure 9 Subsurface OM micrographs of the untreated and borided DI abraded on 240-mesh Al_2O_3 abrasive grains at room (25°C) and at elevated temperatures (up to 450°C)

Test Temperature (°C)	Materials	
	Untreated DI	Borided DI
25		
150		
300		
450		

boriding process. The hardness of the boride layer diminishes gradually from the surface to substrate.

- Room temperature abrasive wear resistance of the borided DI increased with increasing its surface hardness. Formation of strain aging of the subsurface layer during wear process at 150°C was contributed to increase in the wear resistance of the untreated DI. Above 150°C, the untreated DI exhibited wear resistance that was similar to that of the borided DI. This indicates that boriding process is not an effective method in enhancing the abrasive wear resistance at elevated temperatures.

References

Abedi, H.R., Fareghi, A., Saghafian, H. and Kheirandish, S.H. (2010), "Sliding wear behavior of a ferritic-pearlitic ductile cast iron with different nodule count", *Wear*, Vol. 268, pp. 622-628.

Béjar, M.A. and Henríquez, R. (2009), "Surface hardening of steel by plasma-electrolysis boronizing", *Materials and Design*, Vol. 30, pp. 1726-1728.

Celik, O., Ahlatci, H., Kayali, E.S. and Cimenoglu, H. (2005), "High temperature abrasive wear behavior of an as-cast ductile iron", *Wear*, Vol. 258, pp. 189-193.

Fichtl, W. (1981), "Boronizing and its practical applications", *Materials & Design*, Vol. 2, pp. 276-286.

Gadelmawla, E.S., Koura, M.M., Maksoud, T.M.A., Elewa, I.M. and Soliman, H.H. (2002), "Roughness parameters", *Journal of Materials Processing Technology*, Vol. 123, pp. 133-145.

Garcia-Bustos, E., Figueroa-Guadarrama, M.A., Rodríguez-Castro, G.A., Gómez-Vargas, O.A., Gallardo-Hernández, E.A. and Campos-Silva, I. (2013), "The wear resistance of boride layers measured by the four-ball test", *Surface and Coatings Technology*, Vol. 215, pp. 241-246.

Li, C., Shen, B., Li, G. and Yang, C. (2008), "Effect of boronizing temperature and time on microstructure and abrasion wear resistance of Cr12Mn2V2 high chromium cast iron", *Surface and Coatings Technology*, Vol. 202, pp. 5882-5886.

Motallebzadeh, A., Dilektasli, E., Baydogan, M., Atar, E. and Cimenoglu, H. (2015), "Evaluation of the effect of boride layer structure on the high temperature wear behavior of borided steels", *Wear*, Vols 328/329, pp. 110-114.

Sahin, Y., Kilicli, V., Ozer, M. and Erdogan, M. (2010), "Comparison of abrasive wear behavior of ductile iron with different dual matrix structures", *Wear*, Vol. 268, pp. 153-165.

Sen, U., Sen, S. and Yilmaz, F. (2004a), "Structural characterization of boride layer on boronized ductile irons", *Surface and Coatings Technology*, Vol. 176, pp. 222-228.

Sen, U., Sen, S. and Yilmaz, F. (2004b), "Effect of copper on boride layer of boronized ductile cast irons", *Vacuum*, Vol. 72, pp. 199-204.

Yan, P.X., Zhang, X.M., Xu, J.W., Wu, Z.G. and Song, Q.M. (2001), "High-temperature behavior of the boride layer of 45# carbon steel", *Materials Chemistry and Physics*, Vol. 71, pp. 107-110.

Yoon, J.H., Jee, Y.K. and Lee, S.Y. (1999), "Plasma paste boronizing treatment of the stainless steel AISI 304", *Surface and Coatings Technology*, Vol. 112, pp. 71-75.

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