EFFECT OF BORONIZING PARAMETERS AND MATRIX STRUCTURES ON THE WEAR PROPERTY OF DUCTILE IRON

Ass. Prof. Dr. Toktaş A.[1], Ass. Prof. Dr. Toktaş G.[2], MSc. Mech. Eng. Gülsün K.[3]
[1,2]Department of Mechanical Engineering, Balıkesir University - Balıkesir, TURKEY
[3]Balıkesir Electromechanical Industrial Plants Corporation, 10100, Balıkesir, TURKEY

E-mail: atoktas@balikesir.edu.tr, gzeytin@balikesir.edu.tr, kenan.gulsun@besttransformer.com

Abstract: *In this study, the effects of matrix structure (pearlitic, tempered martensitic, lower ausferritic, and upper ausferritic), boronizing temperature (800, 825, and 850°C) and time (3, 4.5 and 6 hours) on the wear behaviour of Cu-Ni-Mo alloyed ductile iron were investigated. Wear tests were performed on ball-on-disc type wear tester under the load of 6.8 N, at sliding speed of 6.5 mm/s, at room temperature and dry sliding conditions. The mass losses were measured after wear tests and the friction coefficients were obtained during wear tests. The hardnesses and thicknesses of boride layers, microstructures and worn surface examinations (SEM) of the matrix structures and borided layers were performed. The surface hardnesses of borided samples were obtained three or four times more than that of the matrix structures. The best wear performance was observed for the sample borided at 850°C for 6 h. The mass loss of this boronizing condition is 0,2 mg and this value is nine times less compared with that of the as-cast pearlitic structure.*
KEYWORDS:DUCTILE IRON, MATRIX STRUCTURE, BORONIZING, MASS LOSS

1. Introduction

Bronizing, which is conventionally carried out by holding the materials at 700-1100°C in a boron-rich environment for diffusion of boron atoms into the material in order to form a boride layer, is very attractive thermochemical surface treating technique for ferrous alloys[1]. Boronizing medium can be in the form of a solid powder, paste, liquid, or gas. Pack boronizing is the most widely used boriding process because of its relative ease of handling, safety, and the possibility of changing the composition of the powder mix, the need for limited equipment, and the resultant economic savings[2,3].

The boronizing treatment mostly forms two boride phases; FeB (more externally) and Fe_2B. The significant features of these borides are their high melting points (1540°C for FeB and 1390°C for Fe_2B), metallic resistivity, high hardness, and excellent wear, friction, and corrosion resistance[4]. The coefficient of expansion of Fe_2B ($2{,}9\times10^{-8}$ K^{-1}) is less than that of iron ($5{,}7\times10^{-8}$ K^{-1}) and hence this phase remains in compression after cooling, while that of FeB ($8{,}7\times10^{-8}$ K^{-1}) is greater than iron or Fe_2B and therefore remains in tension[2]. This disparity in residual stress can result in the formation of cracks in the region of the FeB-Fe_2B interface, especially when a component is subjected to thermal and/or mechanical shock[5].

Generally, the formation of a monophase (Fe_2B) with saw-tooth morphology is more desirable than a double-phase layer with FeB and Fe_2B for industrial applications[6]. The degree of teething depends on the quantity of alloying elements, carbon concentration, temperature and time[7]. Industrial boriding can be carried out on most ferrous materials such as structural steels, cast steels, Armco iron, grey iron and ductile iron[8]. The most significant parameters that determine the characteristics of boride layer are processing temperature and time. Alloying elements mainly retard the boride layer thickness (or growth) caused by restricted diffusion of boron into the substrate because of the formation of a diffusion barrier[9].

Ductile iron is a member of cast iron family which draws great interest due to its unique mechanical properties. Most of this superiority is achieved by heat treating and surface hardening processes. Ductile iron can gain variety of matrix structures via heat treating, an example of which is ausferrite. Almost all surface hardening processes, applicable for steels, can be successively performed on ductile irons. The aim of the present study is to investigate the effect of boronizing parameters (temperature and time) and matrix structure on the wear properties of Cu, Ni, and Mo alloyed ductile iron.

2. Experimental Procedures

The chemical composition of the ductile iron is given in Table 1. The nodule diameter and nodule count range between 29–37 μm and 100–155 mm^{-2}, respectively. The nodularity is above 90%.

Table 1. *Chemical composition of the ductile iron (wt.%)*

C:	3.730	Mg:	0.044
Si:	2.550	Cu:	1.030
Mn:	0.300	Ni:	1.250
P:	0.045	Mo:	0.180
S:	0.023	Cr:	0.032

The heat treatments, given in Table 2, were carried out in order to obtain various matrix structures, namely tempered martensitic (TM), low ausferritic (LA), and upper ausferritic (UA). Test materials were machined and ground to a cylindrical shape with dimensions of 15 mm diameter and 20 mm length. Pack boronizing technique was performed in a solid commercial Ekabor 2 (B_4C - SiC - KBF_4) powder with grain size range of 75-106 μm. All samples were packed in the powders mix and sealed in a stainless steel container. Boronizing was performed in an electrical resistance furnace under atmospheric pressure at various temperatures (800, 825, and 850°C) for 3, 4.5, and 6 h, respectively. The steel box was followed by cooling in air to room temperature.

Table 2. *Matrix structures and heat treatment parameters*

Matrix	Austenitizing temperature/time, $T\gamma$/ $t\gamma$	Tempering and/or cooling conditions
TM	900 °C /1 h	Oil quenching, tempering at 400 °C for 1 h, air cooling
LA	900 °C /1 h	Austempering at 300 °C for 1 h, air cooling
UA	900 °C /1 h	Austempering at 365 °C for 1 h, air cooling

The hardness of borided surfaces and matrix structures were measured on the cross-sections using Metkon Mh-3 Vickers indenter with a load of 1 kg.

An Eclipse MA100 optical microscope was used to examine the microstructures and depth of boride layers of polished and etched (with 5% nital solution) specimens, and a Zeiss Evo40 scanning electron microscope for the worn surface of specimens.

The ball-on-disc abrasive wear tests were performed on metallographically polished samples at room temperature with the humidity of 45±5%. A constant load of 6,8 N, a sliding velocity of 6,5 mm/s, and a sliding distance of 140 m were used. For the counter body, 5 mm diameter tungsten carbide ball with 68 HRc hardness was selected. The samples were cleaned by ethyl alcohol and dried before and after the wear tests. Then, the mass losses were measured by a balance with sensivity of 10^{-4} g. The friction force was monitored continously by means of a force transducer. The friction coefficients were recorded during the tests. The wear tests were repeated three times for each boriding parameters and matrix structures.

3. Results and Discussion

The microstructures of as-cast (pearlitic), TM, LA, and UA matrix structures of the ductile iron are illustrated in Fig.1. The as-cast microstructure consisted of bull's eye structure; ferrite surrounding graphite nodules in a pearlitic matrix (Fig 1a). While LA structure shows fine acicular ferrite (dark needles) in Fig 1c, UA structure shows coarse feathery ferrite (Fig 1d) in the ausferritic structure.

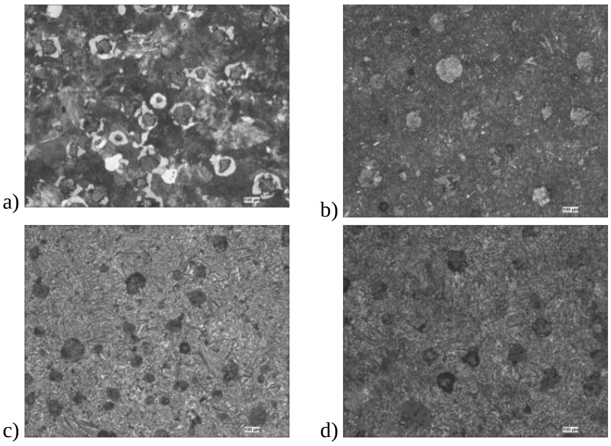

Figure 1. *Microstructures of the matrix structures of a) as-cast, b) TM, c) LA, and d) UA (200X)*

The hardness values of matrix structures are given in Table 3. The TM structure has the highest hardness due to the brittleness effect of martensite. The UA structure has higher hardness than the LA one. This result may be due to the second stage reaction. This reaction occurs at high austempering temperatures, and/or long durations. High carbon austenite decomposes into carbides and ferrite by the second reaction. These carbides rise the hardness and lower the strength and toughness of ductile iron. [10]

Table 3. *Hardnesses and mass losses of the matrix structures*

Matrix	Hardness [HV_1]	Mass loss [mg]
As-cast(pearlitic)	413	1,8
TM	614	1,2
LA	464	1,4
UA	494	1,3

The surface hardnesses of borided samples are given in Figure 2. The values varied between 1280-1685 HV_1. The hardness of the boride layer was found to be three or four times higher than that of the as-cast structure. This result is well agree with the previous study[11]. The hardnesses increased with both the boronizing temperature and time. This increase is more clear at 850°C. The durations at 800 and 825°C made no significant variations in surface hardness values.

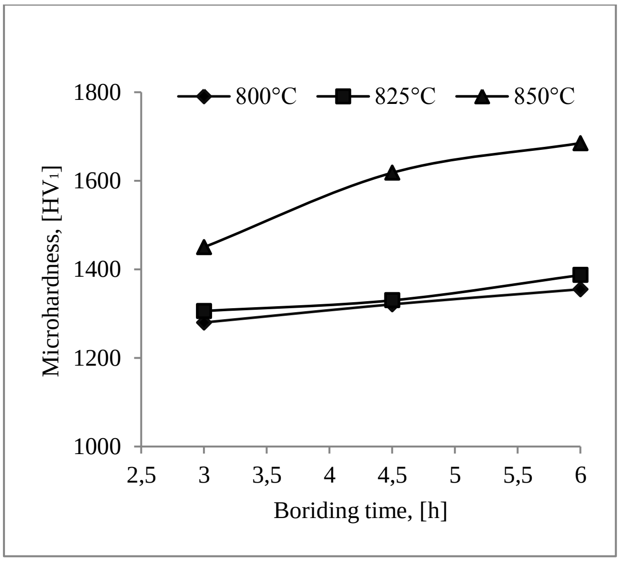

Figure 2. *Microhardnesses of the borided surfaces*

The microstructures of the borided layers are given in Figure 3 for 6h boriding time at 800, 825, and 850°C temperatures, respectively. The layer thickness is increased with the boronizing temperature. The boride layer has a tooth-shaped structure. It is observed that nonuniformed light lines present at interface between the matrix and the borided layer. These lines are tought to be silicon-rich zones. Silicon has no solubility in iron boride. Therefore, during the boronizing process, silicon atoms diffuse inwards and produce silicon-rich zone[11].

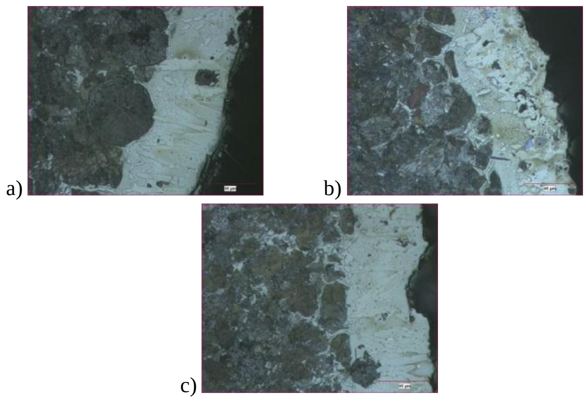

Figure 3. *Microstructures of the boride layers boronized for 6 h at a) 800°C, b) 825°C, and c) 850°C (500X)*

The effect of boronizing parameters on the boride layer thickness is given in Figure 4. As the boronizing temperature and time increased, the boride layer also increased as consistent with the previous studies[12,13]. The thickness and hardness of the boride layer depends on the substrate material being processed, boron potential of the boronizing compound, boronizing temperature-time, boronizing mediums and their compositions[3]. The increase rates of boride layer by the boriding time have close values of approximately 64, 59, and 60% at 800, 825, and 850°C, respectively.

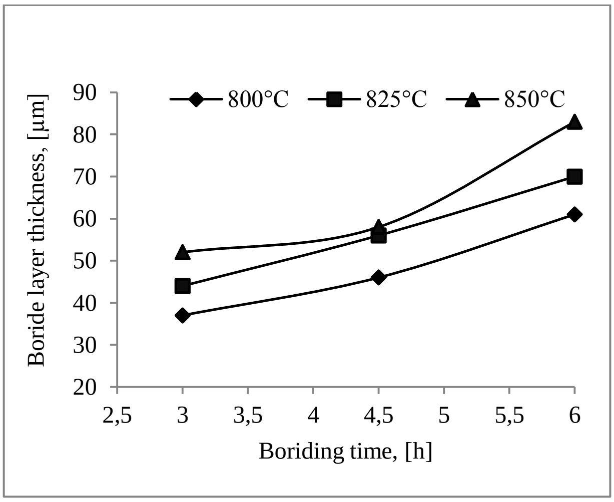

Figure 4. *Thicknesses of the boride layers*

The mass losses of matrix structures are given in Table 3. The values are varied inversely proportion with their hardness values. Namely, the highest hardness structure showed the least mass loss such as in TM structure. This result confirms that hard surfaces are more resistant to wear.

The mass losses by the boronizing temperature and time are given in Fig 5. At 825 and 850ºC boronizing treatments, mass losses are decreased by the process duration. An oppose and unexpected result is observed at 800°C. For all durations at 800ºC, due to having low microhardness values (Fig 2.), the mass losses are unexpectedly lower than that of 825°C. It can be concluded that 800°C boronizing temperature is not enough for the studied alloyed ductile iron. As the alloying elements retard the diffusion rate of boron into the substrate, the higher boronizing temperatures are required for the expected performance. The durations at 850°C is more effective in mass loss as in boride layer. Boronizing at 850°C for 6h showed the least mass loss among all parameters as 0,2 mg. C. Li et al. [14] reported that higher temperature and longer process duration result in more excellent wear resistance. The pearlitic as-cast structure showed nine times more mass loss comparing to that of specimen boronized at 850°C for 6h (Table 4 and Fig. 5).

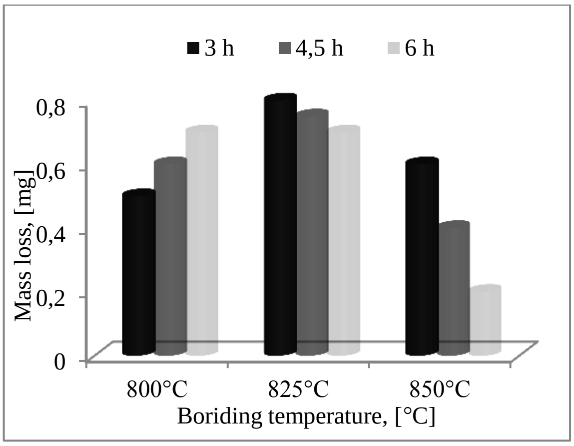

Figure 5. *Mass loses by the boronizing temperature and time*

The friction coefficients of the pearlitic, TM, LA, and UA structures are given in Fig 6. At the beginning of wear tests, the friction of coefficients increased to high values and then lowered and catched the steady state for all structures. The as-cast pearlitic structure has the lowest friction coefficient with more steady distribution.

Having many boriding variables, it was not possible to illustrate the friction coefficient distributions of borided surfaces in a graph. Wider distributions in friction coefficients of borided surfaces were observed compared with that of the matrix structures. The values are ranged between 0.15-0.65 at 800 and 825°C boriding temperatures for all durations. However, a narrow range of values between 0.15-0.3 was observed at 850°C. Moreover, the distributions of friction coefficients were more steady at 850°C.

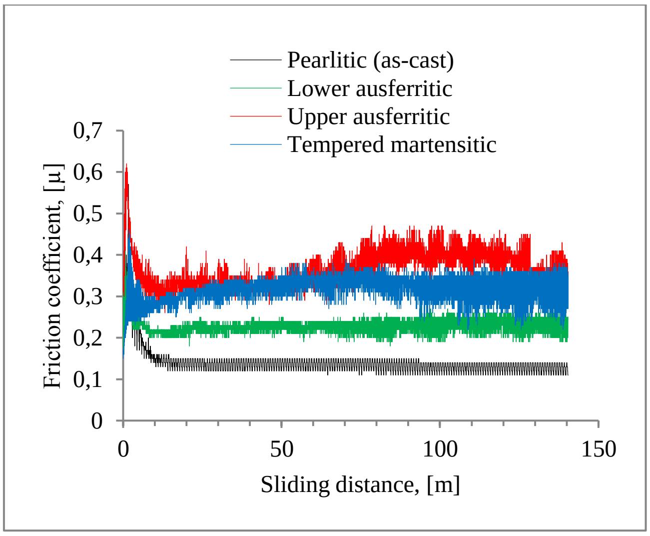

Figure 6. *The friction coefficients of the matrix structures*

Figure 7 illustrates the SEM graphs of worn surfaces of the matrix structures (TM and LA) and surfaces borided for 6 h at 800°C and 850°C temperatures. The micro scratches in the matrix and the micro cracks, formed at graphite-matrix interface, are dominant in the TM structure (Fig 7a). An adhesive wear mechanism is more effective with significant plastic deformation in the LA structure (Fig 7b). The worn surface of sample borided at 800°C for 6 h showed remarkable amount of cracks (Fig 7c)

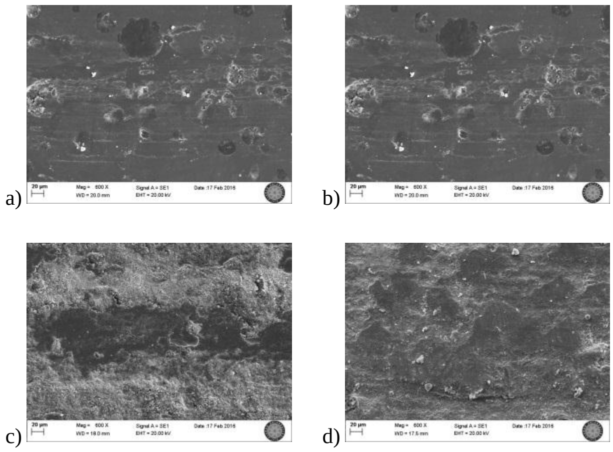

Figure 7. *SEM graphs of the worn surfaces of structures a) TM and b) LA and surfaces borided for 6 h at c) 800°C and 850°C (600X)*

4.Conclusion

The following conclusions can be drawn from the present study:

- The hardness values of the borided surfaces increased three and/or four times higher than that of the as-cast structure.
- The surface hardnesses increased with both the boronizing temperature and time. This increase is more clear 850°C temperature.
- The boride layer thickness increased with both the boronizing temperature and time. This increase rates by the boriding time have approximately close values as 64, 59, and 60% at 800, 825, and 850°C, respectively.
- 800°C boronizing temperature is found to be low to generate expected boride layer on the studied alloyed ductile iron. Many micro cracks were detached on the worn surface of 800°C/6 h borided sample.
- Boronizing at 850°C for 6 h showed the least mass loss among all parameters as 0,2 mg. The pearlitic structure showed nine times more mass loss according to that of this boriding parameter.
- The friction coefficients were more steady for the matrix structures than the borided ones. The as-cast pearlitic structure has the most steady and lowest friction coefficient value.

4.Literature

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