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Research Article

Investigation of the effect of boriding on the wear behaviour of AISI 1050 carbon steel

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ABSTRACT

In this study, AISI 1050 carbon steel samples were boronized with the powder pack boriding technique at 875°C for 2, 4 and 6 hours using Ekabor 2 boriding powder. The boride layer thicknesses obtained with the boriding time increased and after 2, 4 and 6 hours of boriding, a 30.6, 40.0 and 71.8 µm boride layer, predominantly composed of Fe_2B phase, was obtained. Boride layers were formed in tooth-like morphology. Thanks to this boride layer, the surface hardness of the substrate was improved 6.2-6.4 times and a maximum surface hardness of 1543.8 HV was reached. With the Daimler-Benz Rockwell-C adhesion tests, it was determined that the adhesion quality of the boride layer was generally at the HF1 level. With the boriding carried out, the specific wear loss of AISI 1050 steel was reduced from 421.25 mm^3/Nm x10^{-6} to 17.67 mm^3/Nm x10^{-6}, and the wear resistance was increased approximately 24 times.

1. Introduction

Boriding is a surface coating process performed with a thermochemical technique. In this process, boron (B) atoms are transferred to the metal substrate by diffusion and it is aimed to increase the surface quality by obtaining high hardness, excellent wear and improved corrosion resistance [1-5]. Among the boriding methods that can be performed in a solid, salt solution, electrolytic, plasma and gas environments. The solid boriding is used more widely than others due to its low cost and ease of application [6-8].

The solid boriding method is carried out by keeping the metal substrate in boron powder at temperatures between 850-1050 °C for 1-10 hours. [9-11]. At the end of this waiting period, the formation of a single- or bi-phase layer (FeB+Fe2B) is observed on the surface by the diffusion of boron atoms onto the metal substrate [12,13]. The FeB phase is more fragile. In addition, the two phases have different expansion coefficients, the formation of the Fe2B phase is more desirable than the formation of the double-layer FeB+Fe2B phase. [7, 14, 15].

Boriding process is also widely used in non-ferrous metals. Liu et al. were borided 99.9% pure tungsten discs at 950-1050 °C for 2-8 hours with the pack boriding process. After boriding, a boride layer consisting of WB+W2B phases with 18-116.2 µm thickness was obtained. As a result, in the applied tests, it was determined that the neutron attenuation capabilities of the samples increased with boriding [16]. Gunen et al. boronized Monel 400 alloy at temperatures of 900-1000 °C Celsius at 2-6 temperatures. A boride layer had 35-290 µm thickness and a hardness of 1002-1476 HV0.025, consisting of the N2B phase, was obtained with the boriding process. The boron activation energy was calculated as 300.7 kjmol-1 [17]. Yıldız boronized Cobalt-Magnesium (CM) and Nickel-Magnesium (NM) alloys at 900 °C for 1.5-4.5 hours with pack boriding technique. NiB in the NM alloy and Co2B in the CM alloy were obtained. While the layer thickness obtained in the CM alloy was 47.9-145.21 µm, 67.21-179.84 µm boride layers were obtained in the NM alloy [18]. Kaner et al. boronized powder metal pure chromium samples for 2, 4, 6 and 8 hours at 1000 °C to obtain a boride layer consisting of CrB, Cr2B, Cr2B3 and Cr3B4 phases [19]. Kanca boronized Invar-36 superalloy with powder-pack boriding technique for 975 °C for 5 and 7 h, and a boride film consisting of FeB, NiB and Fe2NiB phases had 176.9-189.1 µm thickness was obtained. The tribological investigations carried out showed that the boride film decreased the wear loss of Invar-36 superalloy 28.6-105 times [20].

In borided iron-based materials, high hardness, improved tribological properties and chemical stability are

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obtained on the surface due to the boride films formed on the substrate surface [21-25]. Because of these results, boriding is applied in many areas (implants, agricultural machinery, tools, etc.) [2, 3, 26, 27]. Many studies have been conducted in the literature on the effect of boriding on wear. Boriding is also a highly effective thermochemical process in increasing the wear resistance of various steel alloys. In particular, it provides high wear resistance to steel under low loads due to its brittle structure [22]. Arslan et al. borided AISI 8620 steel by electrolysis method. They found the wear loss of the unborided and borided samples to be 0.265 ± 0.01 mm3 and 0.003 ± 0.001 mm3, respectively [14]. Türkmen et al. borided SAE 1020 steel with the powder boriding method. As a result of the tribological studies carried out, they determined that the abrasion resistance increased approximately 47 times [7]. Ulutan et al. applied the powder boriding process to AISI 4140 steel and identified that the wear resistance increased nearly 3-4 times compared to the unborided sample [8]. Taktak reported that when he borided 52100 and 440C steel alloys with powder boriding, their abrasion resistance improved 3 and 2.5 times, respectively [24]. Sezgin and Hayat obtained a boride film of 26.13-109.04 μm, consisting of FeB, Fe2B and MnB phases, with the powder pack boriding technique for 2, 4, and 6 h at 850-950 °C for novel high manhanese steels. With the corrosion tests carried out, it has been reported that the borided samples have a higher corrosion resistance than the unborided samples [28].

As can be understood from the outcomes of previous studies, boriding increases the mechanical properties of the surface and improves corrosion and wear resistance in both non-ferrous metal alloys and various steel alloys. However, some alloying elements such as Cr, Ni and Si have a negative effect on the formation and morphological properties of the boride film. Some of them cause the thickness of the layer to be formed as a result of boriding process to decrease, while others cause a flat layer by disrupting the tooth-like morphology of the boride film. For this reason, boriding process is a thermo-diffusional coating process that is more widely applied in plain carbon steels. In this study, AISI 1050 steels, which are used in a wide range of parts in many different machinery manufacturing, are boronized. The microstructural properties, hardness profile and adhesion strength of the borided boride film were investigated and its effect on the wear behaviour of AISI 1050 steel was presented.

2. Materials and Methods

In this study, AISI 1050 steel alloy samples with a diameter of 20 mm and a height of 10 mm were used as substrate material. The samples were borided using Ekabor 2 boriding powder in 50 mm diameter and 50 mm high AISI 304L stainless steel alloy boriding boxes. The boriding process was carried out at 875 °C for 2, 4 and 6 hours. After boriding, the cross-sections of the surfaces of the samples were obtained. The cross-sectional surfaces of the borided samples were sanded with 100-1200 grit sandpapers. The sanded sample surfaces were polished using 3 and 1 μm diamond suspensions, respectively. The polished surfaces were etched using 3% Nital solution. The thickness of the boride films was measured with the Nicon Eclipse LV150N optical microscope (OM) and Clemex image analysis software. In addition, the microstructures of the boride films were examined with the scanning electron microscope (SEM) (FEI QUANTA 250 FEG) in the backscattered electron (BSE) mode was performed.

Microhardness changes of boride films from surface to substrate were performed using Future-Tech FM-700 (Future-Tech Corp, JAPAN) Vickers microhardness tester for 100 gf and 10 s. Tribological examinations were carried out with a Anton Paar CSM Tribometer model wear tester (Switzerland) in accordance with ASTM G99-17 (2017) standards. The tests were carried out with 6 mm diameter 100Cr6 balls under 10N load with a sliding distance of 1000m and a sliding speed of 0.2 m·s-1. The wear type of the boride film was identified by performing SEM examinations of the worn surfaces.

3. Results and Discussion

In Figure 1, SEM micrographs are given from the cross-sectional surfaces of boride films obtained in AISI 1050 steel borided with box boriding technique for 2, 4 and 6 hours at 875 °C boriding temperature. As it is well known, since boron atoms diffuse faster in the [001] direction of the lattice structure, boride grains grow faster in the [001] direction than in other directions, perpendicular to the surface. For this reason, boride films are formed in a sawtooth-like morphological structure. Thanks to this sawtooth morphological structure, improved adhesion strength between the boride film and the substrate is obtained [27, 29]. As seen in Figure 1, this sawtooth morphological boride film was formed in AISI 1050 steel as well. In addition, it was observed that the formed boride film was generally Fe_2B compound. Another phenomenon observed from SEM micrographs was the porous structure of the boride film surface of AISI 1050 steel. Kirkendall explained that in thermo-diffusional methods, the porous structure occurs when the diffusion rate differs locally. This phenomenon is termed the "Kirkendall effect" [9, 30].

In Figure 2, the thicknesses of the boride films formed in AISI 1050 steel as a result of different boriding times are presented. The thickness of the boride films obtained as a result of boriding for 2, 4 and 6 hours at 875 °C boriding temperature were measured as approximately 30.6, 40.0 and 71.8 μm, respectively. Atik et al. reported that when they borided AISI 1010 steel at 900 °C for 8 hours, they obtained a 140 μm thick boride film [31]. For the same boriding parameters as temperature and boriding time, the boride film thickness was measured as 130 µm in AISI 1040 steel. Petrova and Suwattananont, on the other hand, obtained a 76 µm thick boride film consisting of FeB and Fe2B boride compounds in AISI 1018 steel in consequence of boriding at 850 °C for 4 hours [32]. Boztepe and Bayramoğlu reported that after boriding at 900 °C for 6 hours, a 79 µm thick boride film consisting of FeB and Fe2B phases was obtained on the surface of AISI 1050 steel [33].

In Figure 3, the microhardness change of the boride film formed in AISI 1050 steel borided for 2, 4 and 6 hours at 875 °C boriding temperature, depending on the depth, is presented graphically. In microhardness measurements, the microhardness of the substrate material was determined as 230-240 $HV_{0.1}$. After 2, 4 and 6 hours of boriding, the maximum microhardness values of the surfaces were measured as 1431.9, 1499.7 and 1543.8 $HV_{0.1}$, respectively. Therefore, the microhardness values of the surface of AISI 1050 steel have been improved by approximately 6.2-6.4 times. As seen in Figure 1, the boride films formed generally consisted of Fe_2B phase. The measured hardness values are in agreement with similar studies in the literature in which the Fe_2B phase is formed. Milinovic et al. reported that when they borided AISI 1015 steel at 970 °C for 8 hours, they obtained a boride film consisting of Fe_2B phase with a hardness of 1541 HV [34]. Türkmen and Yalamaç measured the microhardness of the boride film consisting of Fe_2B phase in AISI steel in the range of 1329.19 ± 54.96 - 1541.85 ± 168.21 $HV_{0.1}$ after 4 hours of boriding at 850 °C [9].

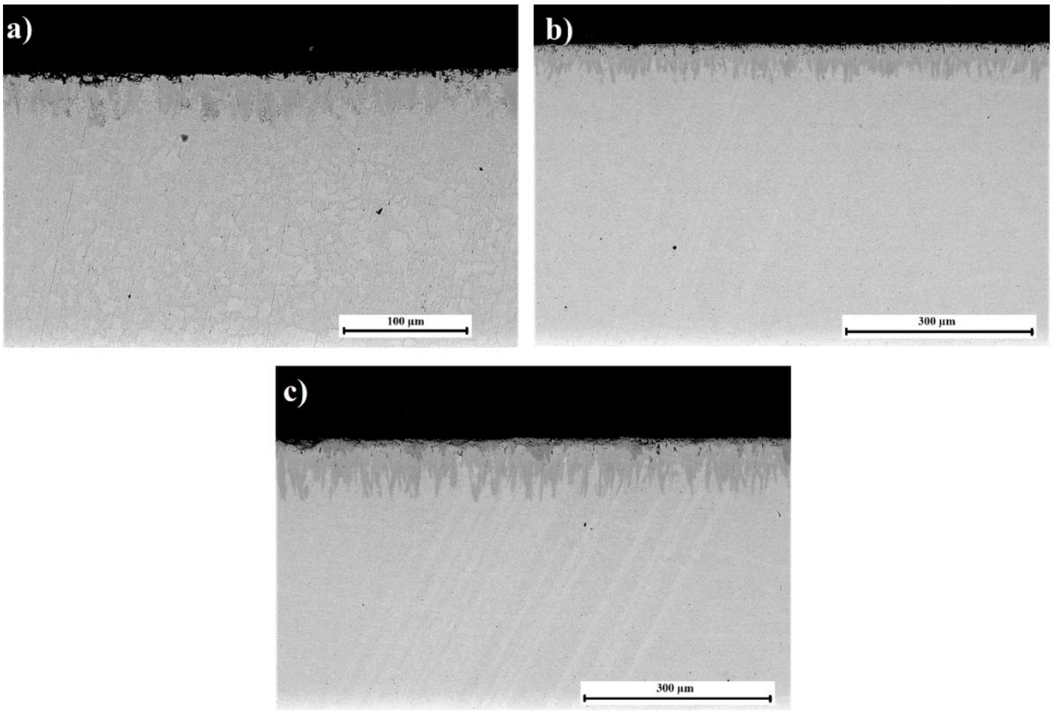

Figure 1. Cross-sectional SEM micrographs of the borided samples: a) 2 h, b) 4 h and c) 6 h

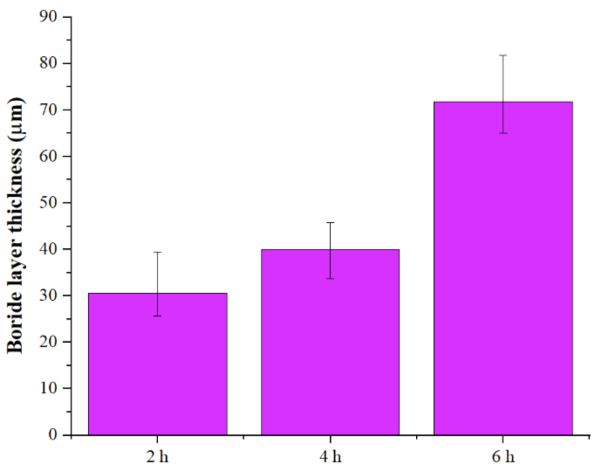

Figure 2. Boride layer thickness for various boriding time

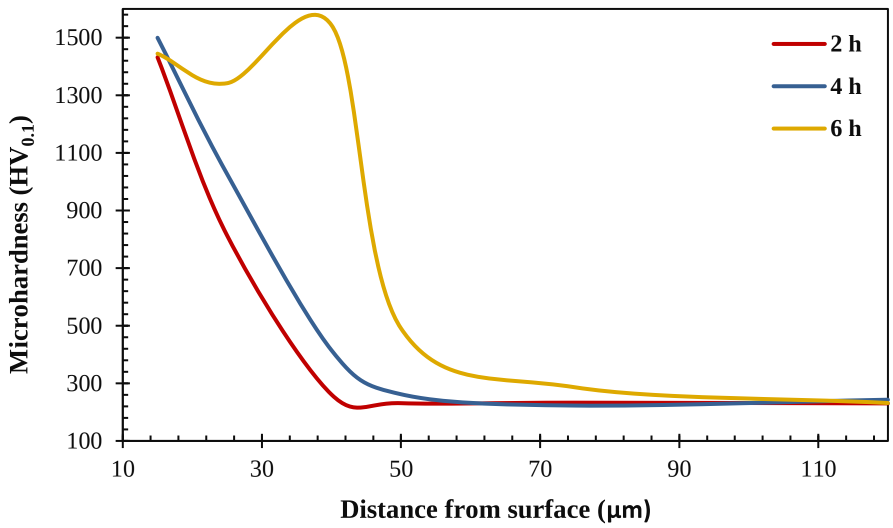

Figure 3. Microhardness variation depending on layer thickness for different boriding times

In Figure 4a-c, SEM images of the craters formed as a outcomes of Daimler-Benz Rockwell-C adhesion tests can be seen on the surfaces of the samples that were borided at 875 °C for 2, 4 and 6 hours, respectively. No delamination failure was observed when the craters were examined. In addition, radial cracks around the craters were clearly seen in the SEM images. While this type of crack was observed in all borided samples, an increase in the number and thickness of cracks was detected with the increase in boriding time. The cohesion quality of the boride films was found acceptable according to the HF1 grade according to the adhesion strength quality maps [35]. Success in adhesion strength is a result of its single-phase structure. It has been reported that the single-phase layer (Fe_2B) has good adhesion properties [9].

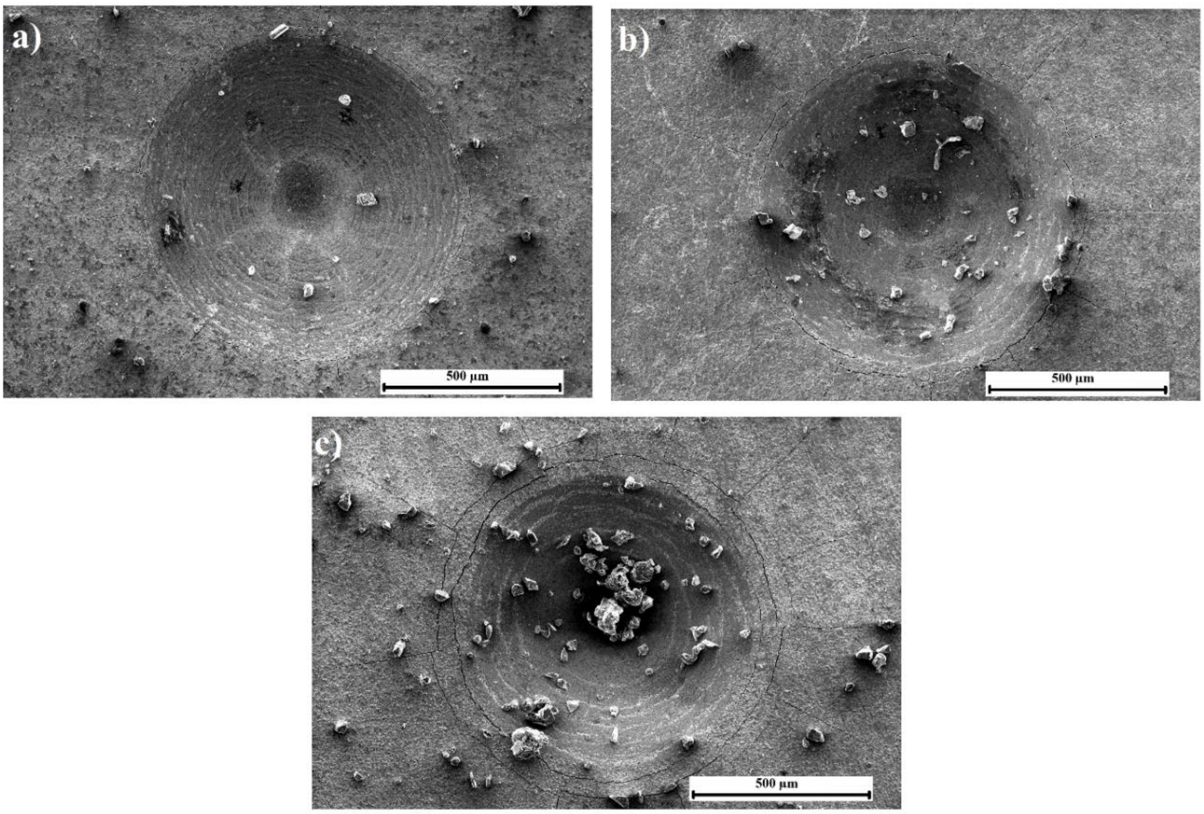

Figure 4. SEM images of craters formed after the Daimler-Benz Rockwell-C adhesion test: a) 2 h, b) 4 h and c) 6 h

The specific wear rates obtained as a result of the wear tests are given in Fig. 5. The specific volumetric wear rate of unborided AISI 1050 carbon steel was determined as 421.25 mm^3/Nm $x10^{-6}$. The specific wear rates of the borided samples at 875 °C for 2, 4 and 6 hours using Ekabor 2 boriding powder with the pack boriding method were determined as 31.47, 17.67, 22.47 mm^3/Nm $x10^{-6}$, respectively. Therefore, the wear resistance of AISI 1050 steel has been increased ~13-24 times by boriding. Küçükkurt borided AISI M35 and AISI M42 high speed-tool steels at 850, 900 and 950 °C for 2, 4 and 6 hours using Ekabor II powder in his master's thesis. After the wear tests, the lowest specific volumetric wear rate in AISI M35 steel was reported as 1.540 mm^3/Nm $x10^{-5}$. In AISI M42 steel, the lowest specific wear rate was measured as 1.820 mm^3/Nm $x10^{-5}$ [36]. Güneş and Yıldız borided AISI 310 stainless steel alloy with Ekabor II powder in their study. 10 N load and 1000 m road parameters were used in the wear tests. In consequence of the wear tests, the lowest specific volumetric wear rate was determined as mm^3/Nm $x10^{-5}$ in the borided sample at 1050 °C for 6 hours [37]. García-Leon et al. determined the specific volumetric wear rate of borided AISI 316L steel as 14.1 mm^3/Nm $x10^{-6}$ [38]. Soydan et al. thespecific wear rates of AISI 4140, AISI 8620 and AISI 1050 steels, which they boron for 6 hours at 950 °C using Ekabor 1 powder, were determined as 16, 18 and 20 mm^3/Nm $x10^{-6}$, respectively, against carburized AISI 1020 steel [39]. As can be seen, the results obtained are in agreement with the literature. In Figure 6, SEM images of the worn layers of the unborided, 2, 4 and 6 hours borided samples are given. In the unborided sample, it is clear from the deep grooves on the worn surface that the wear type is predominantly abrasive wear (Fig. 6a). After 2 hours of boriding, it was observed that the abrasive wear of the sample was greatly reduced (Fig. 6b). Wear failure in the form of pitting was noticed on the worn layer of this sample. It was observed that a flat worn layer was formed in the 4 hours borided sample (Fig. 6c), in which the lowest specific wear rate was determined. In addition, some wear debris was observed in this sample. Similarly, this wear debris was observed in the borided sample for 6 hours (Fig. 6d). However, when the worn layer was examined, delamination areas and some abrasive grooves were detected. With the occurrence of these wear types, the specific volumetric wear rate increased in this sample.

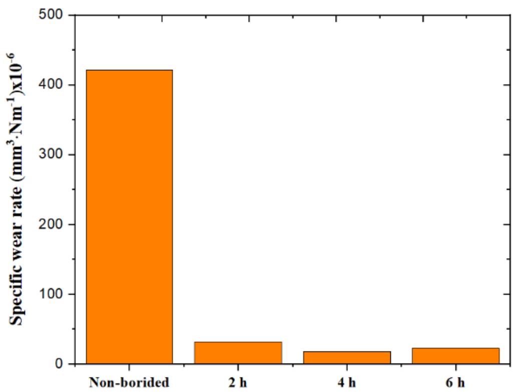

Figure 5. The specific wear rate of the samples

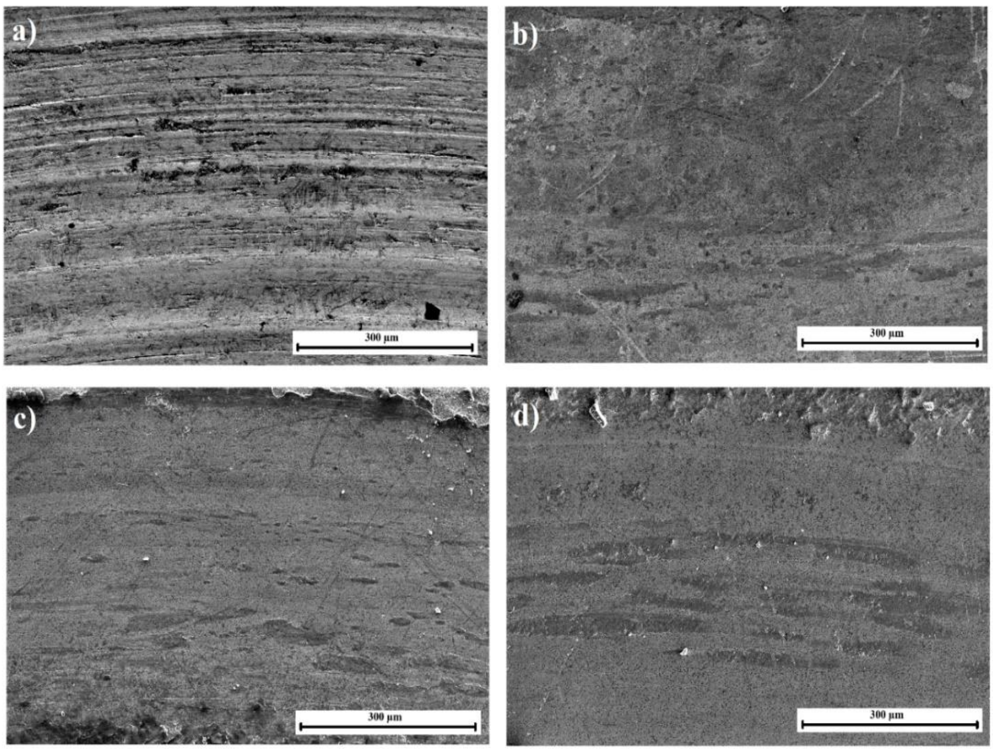

Figure 6. SEM images of the worn surfaces of non-borided (a), 2 h (b), 4 h (c), and 6 h(d) borided AISI1050 steels

4. Conclusion

In this study, the microstructural and tribological properties of the samples borided at 875 °C for 2, 4 and 6 hours using Ekabor 2 boriding powder on AISI 1050 carbon steel and the cohesion quality of the boride films were investigated. The summary of the obtained data is as follows:

- As a result of boriding, a boride film consisting of Fe_2B phase was obtained.
- After 2, 4 and 6 hours of boriding, approximately 30.6, 40.0 and 71.8 µm boride films were obtained, respectively.
- Microhardness values of the surface of AISI 1050 steel were improved by approximately 6.2-6.4 times with boriding.
- The abrasion resistance of AISI 1050 steel increased ~13-24 times with boriding.

Declaration

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

S. İPEK AYVAZ developed the methodology, performed the experiments and wrote the manuscript. T. Author proofread the manuscript.

References

1. Hernandez-Ramirez, E.J., A. Guevara-Morales, U. Figueroa-Lopez and I. Campos-Silva, *Wear resistance of diffusion annealed borided AISI 1018 steel*, Materials Letters, 2020. **277**: 128297.
2. Genel, K., *Boriding kinetics of H13 steel*, Vacuum, 2006. **80**: p. 451-457.
3. Er, U. and B. Par, *Wear of plowshare components in SAE 950C steel surface hardened by powder boriding,* Wear, 2006. **261**: p. 251-255.
4. Çavdar, U. and E. Atik, Properties *of boronized, carbonitrided and steamed ıron-based compact,* Materials Testing, 2014. **56**(2): p. 126-130.
5. Altintaş, A., Y. Sarigün and U. Çavdar *Effect of Ekabor 2 powder on the mechanical properties of pure iron powder metal compacts*. Revista de Metalurgia, 2016. **52**(3): e073.
6. Akshay, A.J. and S.S. Hosmani, *Pack-boriding of AISI 4140 steel: boriding mechanism and the role of container design,* Materials and Manufacturing Processes, 2014. **29**: p. 1062-1072.
7. Turkmen, I., E. Yalamac and M. Keddam, *Investigation of tribological behaviour and diffusion model of Fe_2B layer formed by pack-boriding on SAE 1020 steel,* Surface and Coatings Technology, 2019. **377**: 124888.
8. Ulutan, M., M.M. Yildirim, O.N. Celik and S. Buytoz, *Tribological properties of borided AISI 4140 steel with the powder pack-boriding method,* Tribology Letters, 2010. **38**: p. 231-239.
9. Turkmen, I. and E. Yalamac, *Effect of alternative boriding mixtures on boride layer and tribological behaviour of borided SAE 1020 steel,* Metals and Materials International, 2022. **28**: p. 1114-1128.
10. Arslan, D. and S. Akgün, *Mechanical characterization of pack-boronized AISI 4140 and AISI H13 steels,* International Advanced Researches and Engineering Journal, 2021. **5**(1): p. 61-71
11. Kartal, G., O.L. Eryilmaz, G. Krumdick, A. Erdemir and S. Timur, *Kinetics of electrochemical boriding of low carbon steel,* Applied Surface Science, 2011. **257**: p. 6928-6934.
12. Genel, K., I. Ozbek and C. Bindal, *Kinetics of boriding of AISI W1 steel,* Materials and Science Engineering, 2003. **A347**: p. 311-314.
13. Sen, S., I. Ozbek, U. Sen and C. Bindal, *Mechanical behaviour of borides formed on borided cold work tool steel,* Surface and Coatings Technology, 2001. **135**: p. 173-177.
14. Arslan, M., A.C. Ok, G.K. Sireli and S. Timur, *Investigation on stuructural and tribological properties of borided gear steel after phase homogenization,* Surface and Coatings Technology, 2022. **429**: 127967.
15. Martini, C., G. Palombarini, G. Poli and D. Prandstraller, *Sliding and abrasive wear behaviour of boride coatings,*Wear, 2004. **256**: p. 608-613.
16. Liu, Y., X. Liu, C. Lai, J. Ma, X. Meng, L. Zhang, G. Xu, Y. Lu, H. Li, J. Wang and S. Chen, *Boriding of tungsten by the powder-pack process: Phase formation, growthkinetics and enhanced neutron shielding,* International Journal of Refratory Metals and Hard Materials, 2023, **110**: 10649.
17. Günen, A., M. Keddam, A. Erdoğan and M.S. Karakaş, *Pack-Boriding of Monel 400: Microstructural Characterization and Boriding Kinetics*, Metals and Materials International, 2022, **28**: 1851-1863.
18. Yildiz, I., *Surface Characterization and Boriding of Nickel and Cobalt Alloys,* Protection of Metals and Physical Chemistry of Surfaces, 2022, **58**: 772–778.
19. Kaner, S., Y. Kaplan, Ö., Pamuk and S. Aksöz, *Production and Tribological Investigation of Cr Borides by Boriding of Powder Metallurgy Pure Chromium Surface*, Journal of Materials Engineering and Performance, (2022). https://doi.org/10.1007/s11665-022-07195-4
20. Kanca, Y., *Microstructural characterization and dry sliding wear behavior of boride layers grown on Invar-36 superalloy,* Surface and Coating Technology, 2022, **449**: 128973.
21. Garcia-Leon, R.A., J. Martinez-Trinidad, I. Campos-Silva, U. Figueroa-Lopez and A. Guevara-Morales, *Development of tribological maps on borided AISI 316L stainless steel under ball-on-flat wet sliding conditions,* Tribology International, 2021. **163**: 107161.
22. Selcuk, B., R. Ipek and M.B. Karamis, *A study on friction and wear behaviour of carburized, carbonitrided and borided AISI 1020 and 5115 steels,* Journal of Materials Processing Technology, 2003. **141**: p. 189-196.
23. Ueda, N., T. Mizukoshi, K. Demizu, T. Sone, A. Ikenaga and M. Kawamoto, *Borıding of nickel by the powder-pack method,* Surface and Coatings Technology, 2000. **126**: p. 25-30.
24. Taktak, S., *Tribological behaviour of borided bearing steels at elevated temperatures,* Surface and Coatings Technology, 2006. **201**: p. 2230-2239.

25. Ipek Ayvaz, S. and I. Aydin, *Tribological and adhesion properties of microwave-assisted borided AISI 316L steel,* Materials Testing, 2022. **64**: p. 249-259.
26. Ipek Ayvaz, S. and I. Aydin, *Effect of the microwave heating on diffusion kinetics and mechanical properties of borides in AISI 316l,* Transactions of the Indian Instute of Metals, 2020. **73**: p. 2635-2644.
27. Carrera-Espinoza, R., , U. Figueroa-Lopez, J. Martinez-Trinidad, I. Campos-Silva, E. Hernandez-Sanchez and A. Motallebzadeh, *Tribological behavior of borided AISI 1018 steel under linear reciprocating sliding conditions,* Wear, 2016. **362-363**: p. 1-7.
28. Sezgin, C.T. and F. Hayat, *The effects of boriding process on tribological properties and corrosive behavior of a novel high manganese steel*, Journal of Materials Processing Tech., 2022, **300**: 117421
29. Medvedovski, E., *Formation of corrosion-resistant thermal diffusion boride coatings,* Advanced Engineering Materials, 2016. **18**: p. 11-33.
30. Krelling, A.P., F. Teixeira, C.E. da Costa, E.A.S. Almeida, B. Zappelino and J.C.G. Milan, *Microabrasive wear behavior of borided steel abraded by SiO_2 particles,* Journal of Materials Research and Technology, 2019. **8**: p. 766-776.
31. Atik, E., U. Yunker and C. Meric, *The effects of conventional heat treatment and boriding on abrasive wear and corrosion of SAE 1010, SAE 1040, D2 and 304 steels*, Tribology International, 2003. **36**: p. 155-161.
32. Petrova, R. and N. Suwattananont, *Surface modification of ferrous alloys with boron,* Journal of Electronic Materials, 2005. **34**: p. 575-582.
33. Boztepe, M.H. and M. Bayramoglu, *Optimization of process parameter of boronized AISI 1050 steel using the taguchi analysis,* The 17th International Conference on Machine Design and Production, 2016. Bursa: p. 1-11.
34. Milinovic, A., S. Brod, D. Krumes, I. Kladaric, S. Klaric and S. Aracic, *An investigation of boride layers growth kinetics on C15 steel*, 16th International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology, 2012. Dubai: p. 135-138.
35. Vidakis, N., A. Antoniadis and N. Bilalis, *The VDI 3198 indentation test evaluation of a reliable qualitative control for layered compounds,* Journal of Materials Processing Technology, 2003. **481**: p. 143–144.
36. Küçükkurt, M., *Borlanmış AISI M35 ve AISI M42 Çeliklerinin Karakterizasyobu ve Aşınma Davranışlarının İncelenmesi*, 2015. Afyon Kocatepe Üniversitesi: Turkey. p. 112.
37. Gunes, İ. and I. Yıldız, *Investigation of Adhesion and Tribological Behavior of Borided AISI 310 Stainless Steel*, Revistamateria, 2016. **21**: p. 61-71.
38. Garcia-Leon, R.A., J. Martinez-Trinidad, R. Zepeda-Bautista, I. Campos-Silva, A. Guevara-Morales, J. Martinez-Londono and J. Barbosa-Saldana, *Dry sliding wear test on borided AISI 316L stainless steel under ball-on-falt configuration: a statistical analysis,* Tribology International, 2021. **157**: 106885.
39. Soydan, Y., S. Köksal, A. Demirer and V. Çelik, *Sliding Friction and Wear Behavior of Pack-Boronized AISI 1050, 4140, and 8620 Steels,* Tribology Transactions, 2008. **51**: p. 74-81.