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Authors: Ersan MERTGENÇ

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Examination of Wear and Rockwell-C adhesion Properties of Nitronic 50 Steel Coated with Pack Boriding Method

Ersan MERTGENÇ*[1]

Abstract

The Nitronic 50 steel is a nitrogen containing stainless steel, which has a high corrosion resistance, and high strength but its surface resistance against wear is low, making it extremely limited to use in areas subject to wear. In this study, in order to improve the material surface and to investigate its effect on tribological properties, boronizing process was carried out by used pack boriding method at 850 ° C, 900 ° C and 950 ° C for 4 hours. As a result of coating process, the boride layer has a smooth and flat structure in SEM investigations, the coating thickness varies between 9 µm and 36 µm and the boride layer thickness increases with increasing temperature. While the hardness of the uncoated material was around 250 $HV_{0.05}$, the surface hardness of the material reached up to 1.712 $HV_{0.05}$ with the coating process and increased about 7 times. According to XRD analysis, the surface of the coating layer consisted of phases FeB, CrB, Ni_3B, Fe_2B, Cr_2B and MnB. Wear behavior was performed by ball-on-disk wear test in dry environment. The friction coefficient and wear rate decreases with increasing temperature, while the wear resistance is increased by 20 times compared to unboronized sample. When the wear tracks were examined, the uncoated Nitronic 50 had an adhesive wear mechanism, on the other hand the boronized samples had an adhesive and abrasive wear mechanism together. The Rockwell-C adhesion test was carried out under a load of 1.471 N and the resulting surface damages were evaluated according to the quality map. Boronized steel at 850 °C is defined as HF3 type, at 900 °C and 950 °C at boronized steel it is defined as HF4 type and adhesion is acceptable.

Keywords: Nitronic 50, pack boriding, Rocwell-C adhesion, wear

1. INTRODUCTION

Nitronic steels are seen as an erosion resistant alternative to 13/4 martensitic stainless steel currently used [1]. Nitronic steels are mainly austenitic stainless steels containing nitrogen as an alloying element in the matrix [2]. By adding nitrogen to the content of stainless steels; strength, ductility, toughness, work hardening capacity, erosion and corrosion resistance increases [3-5].

Nitronic 50 is a high nitrogen, weldable stainless steel and superior to SAE 304 and 316 and 316L in strength and corrosion resistance [6] and is also known as 22-13-5 stainless steel [7]. They have almost two times higher yield strength and good corrosion resistance than standard 316 L stainless steel [8], which is due to the high content of

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* Corresponding Author: ersanmertgenc@hotmail.com

[1] Department of Railway Systems, Afyon Vocational High School, Afyon Kocatepe University, Afyonkarahisar, Turkey. ORCID: 0000-0001-8247-2922

chromium and molybdenum in the content, thus rivaling nickel alloys in seawater. Unlike most austenitic stainless steels, they are not magnetic when working in cold or sub-zero temperatures [7]. Nitronic 50 exhibits good mechanical properties at low and high temperatures where corrosion resistance and strength are required to be combined and is used extensively in a variety of applications such as naval construction, pumps, fittings, cables and heat exchangers [9].

Although stainless steels exhibit high corrosion resistance, low surface hardness is a major disadvantage, especially when exposed to wear, and it is important to improve the tribological and mechanical properties of their surfaces. In recent years, researchers have been working extensively on various coating techniques such as Pysical Vapor Deposition (PVD) [10-12], Diamond-like Carbon (DLC) [13-17], Plasma Nitriding [18-20], Boronizing [21-23] to increase surface hardness through surface modification.

Fundamentally boronizing is a thermo-chemical process [24] diffusing the boron atoms from the surface of materials by means of solid, liquid and gas [25]. Boronizing can be carried out in solid, liquid and gas environments. Boron method is widely used because of its low cost and simple. [26]. Pack boronizing is carried out in the temperature range of 700 °C - 1000 °C for 0,5 to 10 hours [27].

When the studies on Nitronic 50 stainless steel are examined; It has been observed that mainly the corrosion properties of the material have been studied. It is noteworthy that different methods have been used for coating, but the effects of pack boring on the material have not been investigated.

In this study, by using pack boriding method, Nitronic 50 steel was treated at 850 °C, 900 °C and 950 °C temperatures for 4 hours, the acceptability of the coating was evaluated by Rockwell-C adhesion test and the effect of coating on the wear behavior was investigated.

2. MATERIALS AND METHODS

Nitronic 50 stainless steel was used in this study. The chemical composition is given in Table 1.

Table 1. Chemical composition of Nitronic 50 steel (wt. %)

C	Si	Mn	P	S	N	Cr	Mo	Ni	V
0.032	0.6	5.04	0.027	0.0005	0.30	21.49	2.17	12.06	0.16

The test samples were cut into Ø16 × 8 mm dimensions and ground up to 1200 grid and polished using diamond solution. Samples were placed in a stainless-steel box with Ekabor-II commercial powder. Then, they were boronized in a temperature controlled chamber type furnace under atmospheric pressure for 4 hours 850 °C, 900 °C and 950 °C. After the completion of boriding process, test specimens removed from the sealed box were eventually allowed to cool down in still air.

For microstructure analysis, samples were cut along longitudinal section, sanded with SiC abrasive paper up to 120 - 1200 grit, polished with 1 µm alumina suspension and etched with stainless steel etch (HCl: HNO_3: H_2O to 1: 1: 1). Coating layer, matrix microstructure, wear tracks and boride thickness measurements were examined by using a Leo 1430VP scanning electron microscope (SEM). The presence of boride in the coating layer was confirmed by x-ray diffraction (Shimadzu XRD-6000) using CuKα (λ = 1.5406 Å) radiation at 20˚ - 90˚.

Shimadzu HMV-2 micro-hardness tester was used for hardness measurements. The measurements were made under conditions of 50 g load for 10 seconds from the cross-sectional surfaces of the coated samples to the matrix.

The wear tests of Nitronic 50 stainless steel coated by pack boring method were carried out in the ball disk system ball-on-disc system, dry conditions at room temperature, under 5 N load, 0.3 m / s wear rate and 500 m distance. 8 mm diameter WC-Co balls were used in the wear tests. The surface of each sample was cleaned with alcohol before and after the abrasion wear tests. After the tests, the wear volumes of the samples were quantified by multiplying cross-sectional area by the width of wear track obtained from a Tribotechnic Rugosimeter. The wear rate was calculated with the following formula.

Wear rate = Wear volume / (Applied load × Sliding distance), mm^3 / Nm.

The Rockwell-C adhesion test was developed in Germany and standardized in VDI 3198. The Rockwell-C adhesion test, also known as the quality test for coated compounds, is applied at a load of up to 1471 N. It is mapped between HF1 and HF6 according to the condition of damage to the coating in figure 1 [28]. According to this test, which is easy to apply and evaluated especially during quality control processes during production; HF1-HF4 describes adequate adhesion, ie the acceptability of the coating, whereas HF5 and HF6 represent insufficient adhesion [29,30].

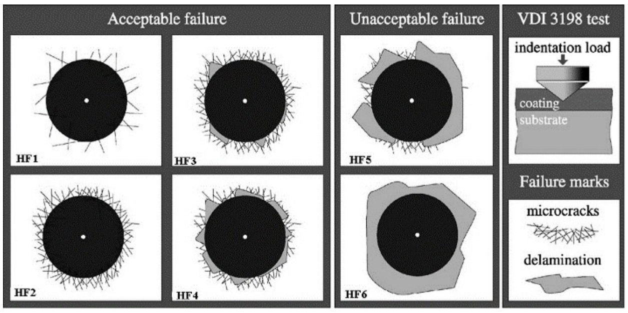

Figure 1. Principle of the VDI 3198 indentation test [28]

3. RESULTS AND DISCUSSIONS

3.1. Characterization of Coating Layer and Thickness

The microstructures of Nitronic 50 steel from the cross section of 850 °C, 900 °C and 950 °C for 4 hours are shown in figure 2.

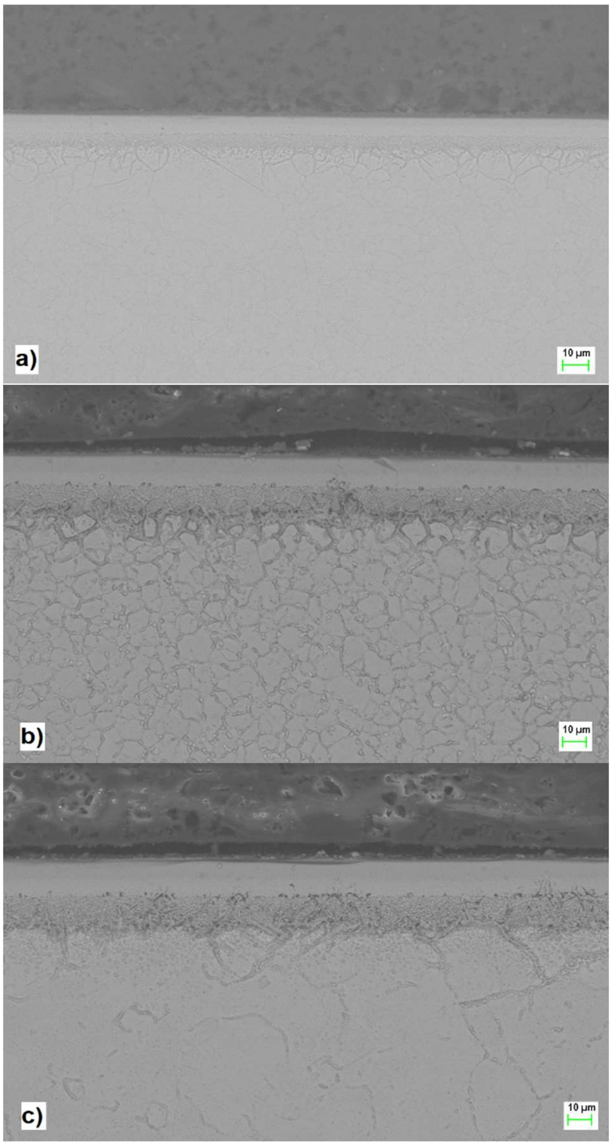

Figure 2. SEM cross-sectional views of boronized Nitronic 50 steel for 4 hours at a) 850 °C, b) 900 °C c) 950 °C

Boride layer has a flat and smooth structure and increase in boride layer thickness with increasing temperature [31, 32].

In steels, the thickness of the boride layer is strongly influenced by the alloying elements as a chorium, nickel and carbon in the substrate material [33]. Especially the presence of chromium makes it difficult to diffuse boron atoms due to its lower solubility compared to iron and prevents the growth of iron borides [34, 35]. The presence of as high as about 21 % chromium in Nitronic 50 steel results in a reduced boride layer thickness compared to steels. boride layer thickness was given table 2 and measured at

850 °C 13 μm, 900 °C 29 μm and 950 °C 36 μm. It is observed that an increase in the boride layer thickness is caused by the change in the process temperature for a treatment time of 4 h. This is due to the fact that the substrate material has high alloying elements, especially chromium and nickel.

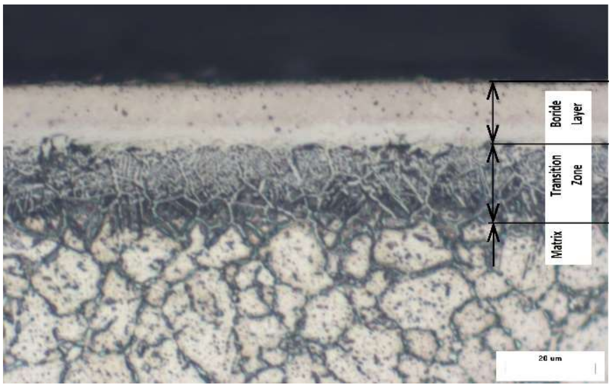

Figure 3. Zones of the coating layer of boronized Nitronic-50 steel for 950 ° C and 4 hours

When the figure 3 is examined, it is seen that there are 3 zones in coated Nitronic 50 steel; zone 1: coating layer FeB/CrB and composed of rich Fe, B, Cr, Ni alloys, zone 2: diffusion zone with higher hardness than matrix but lower hardness than boride layer, zone 3: steel matrix free of boron [36, 37].

3.2. X-Ray Diffraction Analysis

Figure 4 shows the x-ray diffraction analysis of boronized Nitronic 50 steel at 850 °C, 900 °C and 950 °C for 4 hours.

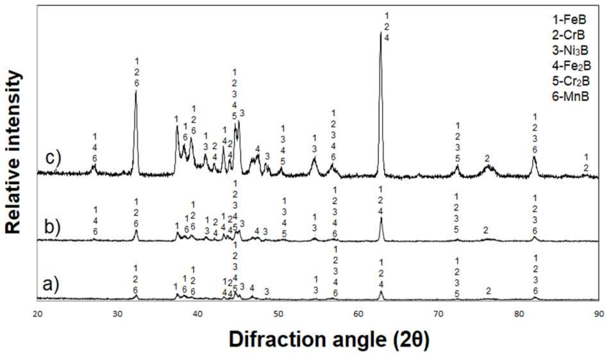

Figure 4. X-ray diffraction patterns of boronized Nitronic 50 steel for 4 hours at a) 850 °C, b) 900 °C c) 950 °C.

According to xrd analysis, FeB, CrB, Ni_3B, Fe_2B, Cr_2B and MnB phases were formed on the surface of the material depending on the process temperature. FeB and CrB phases increase with increasing temperature in boronizing treatment. The reason for this is that the diffusion process is accelerated with increasing temperature and the layer thickness increases. Due to the high amount of alloying elements such as Mn, Mo, Cr and Ni in Nitronic 50 steel, different phases were obtained due to these elements. The microstructure and the mechanical properties of the boronized material depend largely on the chemical composition of the material, the boriding temperature and the boriding time [38]. It is the reason why chromium based phases settle in dominant peaks due to the chemical composition of the material. On the other hand, the presence of FeB phase as the dominant peak in iron-based peaks is close to the surface, while Fe2B phase settles between FeB phase and matrix [35, 39, 40]. The coexistence of the CrB and FeB peaks is due to the fact that these phases are very difficult to distinguish due to their similar structure [41].

3.3. Hardness of Boride Layer

Micro-hardness measurements were performed from cross-sectional area from surface to matrix (figure 5).

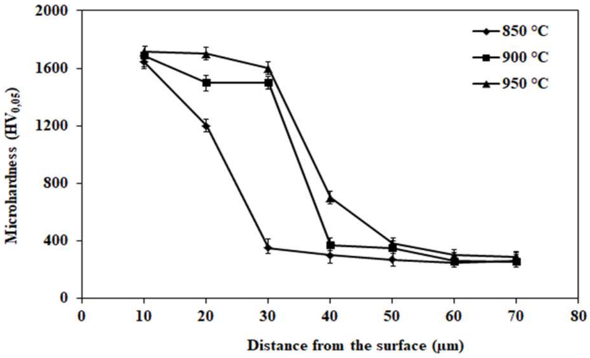

Figure 5. Micro-hardness profiles of boronized samples at 850 °C, 900 °C and 950 °C for 4 h.

The hardness of boronized Nitronic 50 steel was between 1080 $HV_{0.05}$ and 1.712 $HV_{0.05}$, while the hardness of untreated steel was found to be (<) 247 HV0.05. Hardness of boronized Nitronic 50 steel increased by seven times compared to the hardness of non-treated Nitronic 50 steel.

3.4. Wear Properties

In Table 2, coating thickness, friction coefficient and wear rate values of non-boronized and boronized samples are given.

Table 2. Friction coefficient and wear rates of boronized Nitronic 50 steel.

	Conditions			
	Uncoated	850 °C – 4 h	900 °C – 4 h	950 °C – 4 h
Coating layer	-	13	29	36
Friction coefficient	0.71	0.64	0.63	0.61
Wear rate x 10^{-8} (mm^3 / Nm)	81.15	10,85	5.42	3,43

When the wear test results of Nitronic 50 steel were examined, it was found that the friction coefficient was 0.71 in the non-boronized sample, whereas the friction coefficient in the boronized samples at different temperatures for 4 hours ranged from 0.64 to 0.61. Wear rate was 81.15 mm^3 / Nm in non-boronized sample and lower values were obtained in boronized samples. The lowest wear rate was measured as 3.43 mm^3 / Nm in boron-treated sample at 950 °C for 4 hours.

When the wear tests of steels are examined in the literature, the coefficient of friction changes between 0.5 – 0.7 [42, 43, 44] and this shows that this study is consistent with the literature. On the other hand, surface investigators such as Kovaci et al. [16], Cuao-Moreu et al. [45], Teng et al. [46] and He et al. [47] have studied the tribological properties of metal specimens by coating different metal surfaces with different materials, temperature, time and method. The reason for the serious decrease in wear rate is the wear resistance of the hard coating layer on the surface of the material [48-50]. As seen from the XRD analysis, the amount of high hardness phases such as FeB and CrB increased.

The SEM images of the wear marks on the ball on disk system, against WC-Co balls, at 5 N load, 0.3m / s wear rate and 500 m distance are given in figure 6.

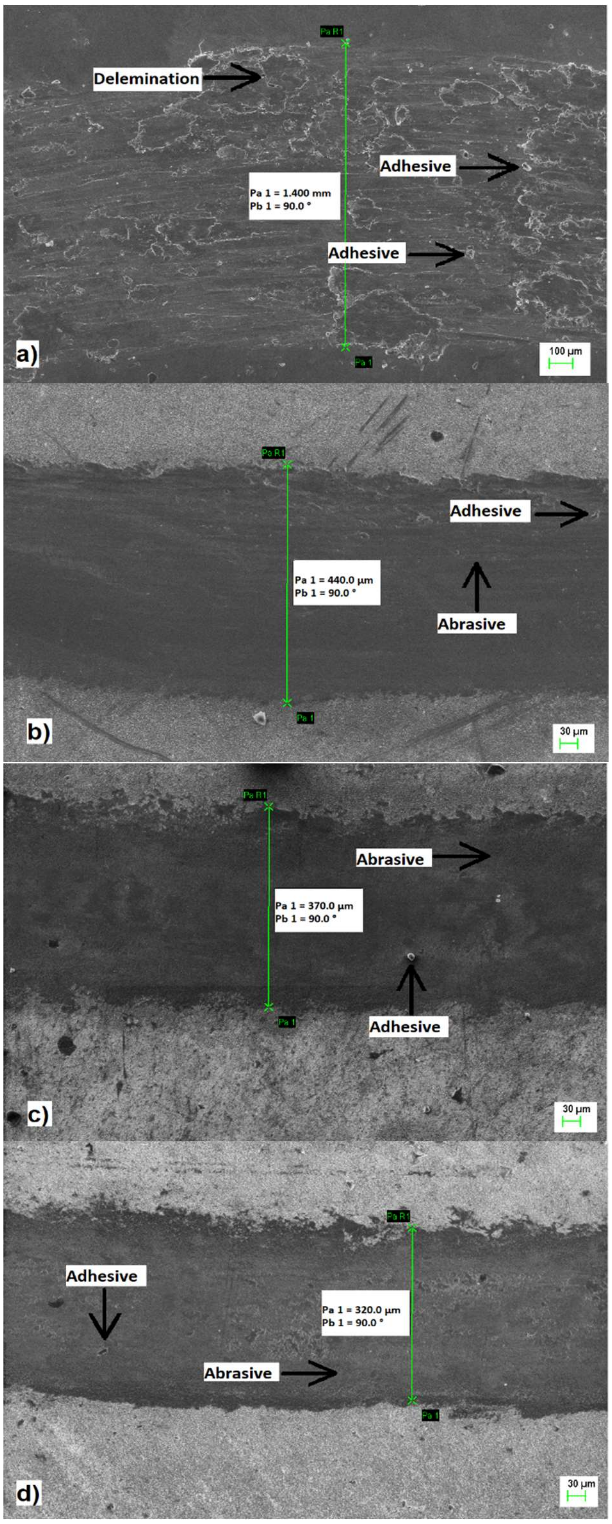

Figure 6. Wear traces of boronized Nitronic 50 steel a) non-boronized, b) 850 °C – 4 h, c) 900 °C – 4 h, d) 950 °C – 4 h

Wear traces vary according to boride layer thickness [33, 51, 52]. When the surface morphology of the wear marks is examined, adhesive wear is seen in the non-boronized sample, while abrasive wear is seen in both the adhesive and abrasive wear by boring samples repeatedly cutting the coating surface by friction pairs. The width of the wear tracks ranges from 1.400 µm to 320 µm and when the tracks are examined, it is seen that the largest wear tracks and damages such as smearing (plastic deformation) in the wear direction are non-boronized specimen (figure 6 (a)) and the narrowest wear tracks are boronized at 950 °C (figure 6 (d)), the highest temperature used for 4 hours in the experiment. With the reduction of boride layer thickness, wear marks become more deeper [53].

3.5. Rockwell-C Adhesion

SEM images obtained from the adhesion test using a standard Rockwell-C hardness tester are shown in figure 7. Damage to the boride layer and adhesion strength are defined according to quality maps. According to the quality map, HF1-HF6 is grouped between HF1-HF4 and HF5 and HF6 are defined as inadequate adhesion [28].

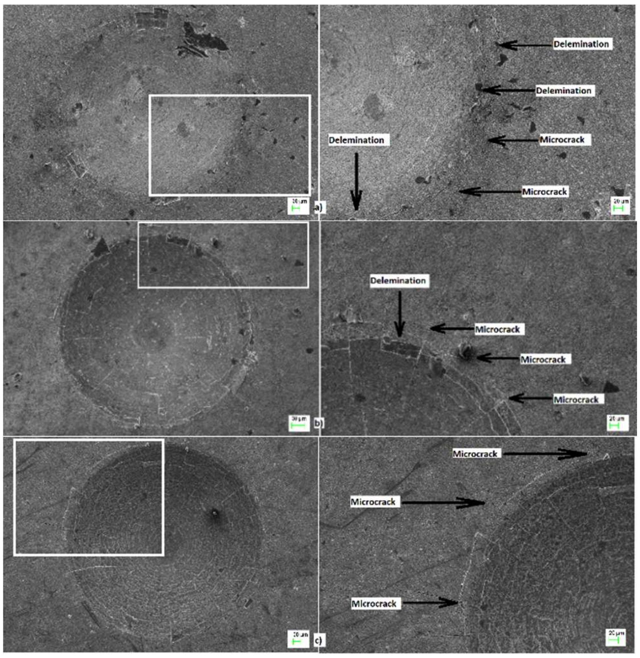

Figure 7. SEM micrographs and radial cracks of VDI adhesion test on boronized Nitronic 50 steel for 4 hours at a) 850 °C, b) 900 °C c) 950 °C.

When the damage images of boronized Nitronic 50 steel are examined for 4 hours, it is observed that radial cracks occur around the craters in the boring at 850 °C (figure 7 (a)) and it is compatible with HF3 according to the quality map. In samples boronized at 900 °C (figure 7 (b)) and 950 °C (figure 7 (c)), delamination occurs along with radial cracks around the indentation craters and the amount of delemination increases with increasing boronizing temperature. This is due to the increase at the process temperature and the depth of the hard and brittle structure FeB phase. However, the images of samples according to the quality test were identified as HF4 and represent sufficient adhesion.

4. CONCLUSIONS

The results obtained from the investigation of tribological properties by coating the Nitronic 50 steel with pack boriding method at 850 °C, 900 °C and 950 °C for 4 hours are given below;

- The coating and the matrix interface exhibit a flat structure, which can be clearly seen the SEM observations. Boride layer thickness increased with temperature increase and reached 13 µm, 29 µm and 35 µm respectively.

- FeB, CrB, Ni_3B, Fe_2B, Cr_2B and MnB phases were formed in all boriding conditions and FeB, CrB phases increased with increasing temperature.

- The matrix hardness is around 250 $HV_{0.05}$, while the hardness of the boride layer ranges from 1080 $HV_{0.05}$ to 1712 $HV_{0.05}$, and the surface hardness of the Nitronic 50 steel has increased about 7 times.

- The friction coefficient and wear rate of Nitronic 50 steel boronized by pack boring method decreased with increasing boriding temperature. While wear rate was 81.15 mm^3 / Nm for unborided sample, with boriding treatment decreased to 3.43 mm^3 / Nm and the wear resistance of the material surface increased about 20 times.

- As a result of the wear tests, non-boron steel has been exposed to intensive adhesive wear along with deleminations. In boronized samples, adhesive and abrasive wear types are seen together.

- In the Rockwell-C adhesion test, the boronized sample at 850 °C represents HF3 according to the quality map, while the 900 °C and 950 °C samples were damaged in the HF4 type. Adhesion for coating is acceptable.

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REFERENCES

[1] A. K. Chauhan, D. B. Goel and S. Prakash, “Solid particle erosion behaviour of 13Cr–4Ni and 21Cr–4Ni–N steels,” Journal of Alloys and Compounds, vol. 467, no. 1-2, pp. 459–464, 2009.

[2] A. Kumar, A. Sharma and S. K. Goel, “Effect of heat treatment on microstructure, mechanical properties and erosion resistance of cast 23-8-N Nitronic steel,” Materials Science and Engineering: A, vol. 637, pp. 56-62, 2015.

[3] Y. Qiao, J. Chen, H. Zhou, Y. Wang, Q. Song, H. Li and Z. Zheng, “Effect of solution treatment on cavitation erosion behavior of high-nitrogen austenitic stainless steel,” Wear, vol. 424-425, pp. 70-77, 2019.

[4] C. M. Hong, J. Shi, L. Y. Sheng, W. C. Cao, W. J. Hui and H. Dong, “Effects of hot-working parameters on microstructural evolution of high nitrogen austenitic stainless steel,” Materials and Design, vol. 32, pp. 3711-3717, 2011.

[5] D. H. M. Grajales, C. M. G. Ospina and A. P. Tschiptschina, “Mesoscale plasticity anisotropy at the earliest stages of cavitation-erosion damage of a high nitrogen austenitic stainless steel,” Wear, vol. 267, pp. 99-103, 2009.

[6] A. M. Ritter and M. F. Henry, “Phase transformations during aging of a nitrogen-strengthened austenitic stainless steel,” Metallurgical Transactions A, vol. 16, pp.1759–1771, 1985.

[7] W-G. Guo and S. Nemat-Nasser, “Flow stress of Nitronic-50 stainless steel over a wide range of strain rates and temperatures,” Mechanics of Materials, vol. 38, pp. 1090–1103, 2006.

[8] A. S. Pokrovsky and S. A. Fabritsiev, “Effect of neutron irradiation on tensile properties of austenitic steel XM-19 for the ITER application,” Journal of Nuclear Materials, vol 417, pp874-877, 2011.

[9] F. H. Abed, S. I. Ranganathan, “Constitutive modeling of nitrogen-alloyed austenitic stainless steel at low and high strain rates and temperatures,” Mechanics of Materials, vol. 77, pp. 142-157, 2014.

[10] A. I. Fernández-Abia, J. Barreiro, J. Fernández-Larrinoa, L. N. López de Lacalle, A. Fernández-Valdivielso and O. M. C. Pereira, “Behaviour of PVD coatings in the turning of austenitic stainless steels,” Procedia Engineering, vol. 63, pp. 133 – 141, 2013.

[11] E. D. L. Heras, D. A. Egidi, P. Corengia, D. González-Santamaría, A. García-Luis, M. Brizuela, G. A. López and M. F. Martinez, “Duplex surface treatment of an AISI 316L stainless steel; microstructure and tribological behavior,” Surface & Coatings Technology, vol. 202, pp. 2945–2954, 2008.

[12] H. P. Feng, C. H. Hsu, J. K. Lu and Y. H. K. Shy, “Effects of PVD sputtered coatings on the corrosion resistance of AISI 304 stainless steel,” Materials Science and Engineering A, vol. 347, pp. 123-129, 2003.

[13] R. Lan, Z. Ma, C. Wang, G. Lu, Y. Yuan and C. Shi, “Microstructural and tribological

characterization of DLC coating by in-situ duplex plasma nitriding and arc ion plating," Diamond & Related Materials, vol. 98, pp. 107473, 2019.

[14] E. Marin, A. Lanzutti, M. Nakamura, M. Zanocco, W. Zhu, G. Pezzotti and F. Andreatta, "Corrosion and scratch resistance of DLC coatings applied on chromium molybdenum steel," Surface and Coatings Technology, vol. 378, pp. 124944, 2019.

[15] H. Cicek, "Wear behaviors of TiN/TiCN/DLC composite coatings in different environments," Ceramics International, vol. 44, pp. 4853–4858, 2018.

[16] H. Kovacı, O. Baran, A. F. Yetim, Y. B. Bozkurt, L. Kara and A. Çelik, "The friction and wear performance of DLC coatings deposited on plasma nitrided AISI 4140 steel by magnetron sputtering under air and vacuum conditions," Surface & Coatings Technology, vol. 349, pp. 969–979, 2018.

[17] C. Jaoul, C. Dublanche-Tixier, O, Jarry, P. Tristant, J. P. Lavoute, L. Kilman, M. Colas, E. Laborde and H. Ageorges, "Tribological properties of hard a-C:H:F coatings," Surface & Coatings Technology, vol. 237, pp. 328–332, 2013.

[18] G. S. Savonov, M. G. G. Camarinha, L. O. Rocha, M. J. R. Barboza, G. V. Martins and D. A. B. Reis, "Study of the influence of the RRA thermal treatment and plasma nitriding on corrosion behavior of 7075-T6 aluminum alloy," Surface & Coatings Technology, vol. 374, pp. 736–744, 2019.

[19] S. Li, S. Hu, A. C. Hee and Y. Zhao, "Surface modification of a Ti2AlC soft ceramic by plasma nitriding treatment," Surface and Coatings Technology, vol. 281, pp. 164–168, 2015.

[20] M. Tsujikawa, N. Yamauchi, N. Ueda, T. Sone and Y. Hirose, "Behavior of carbon in low temperature plasma nitriding layer of austenitic stainless steel," Surface & Coatings Technology, vol. 193, pp. 309– 313, 2015.

[21] E. Mertgenc, O. F. Kesici and Y. Kayali, "Investigation of wear properties of borided austenitic stainless-steel different temperatures and times," Materials Research Express, vol. 6, pp. 076420, 2019.

[22] İ. Türkmen, E. Yalamaç and M. Keddam, "Investigation of tribological behaviour and diffusion model of Fe2B layer formed by pack-boriding on SAE 1020 steel," Surface and Coatings Technology, vol. 377, pp. 124888, 2019.

[23] J. Ballinger, S. A. Catledge, "Metal-boride interlayers for chemical vapor deposited nanostructured NSD films on 316 and 440C stainless steel," Surface & Coatings Technology, vol. 261, pp. 244–252, 2015.

[24] A. Bartkowska, A. Pertek, M. Kulka and L. Klimek, "Laser surface modification of boronickelized medium carbon steel," Optics & Laser Technology, vol. 74, pp. 145–157, 2015.

[25] O. Torun, "Boriding of nickel aluminide," Surface & Coatings Technology, vol. 202, pp. 3549–3554, 2008.

[26] O. A. Gómez-Vargas, J. Solis-Romero, U. Figueroa-López, M. Ortiz-Domínguez, J. Oseguera-Peña and A. Neville, "Boro-nitriding coating on pure iron by powder-pack boriding and nitriding processes," Materials Letters, vol. 176, pp. 261–264, 2016.

[27] O. Ozdemir, M. A. Omar, M. Usta, S. Zeytin, C. Bindal and A. H. Ucisik, "An investigation on boriding kinetics of AISI 316 stainless steel," Vacuum, vol. 83, pp. 175–179, 2009.

[28] N. Vidakis, A. Antoniadis and N. Bilalis, "The VDI 3198 indentation test evaluation of a reliable qualitative control for layered compounds," Journal of Materials Processing Technology, vol. 143–144, pp. 481–485, 2003.

[29] E. Heinke, A. Leyland, A. Matthews, G. Berg, C. Friedrich and E Broszeit, “Evaluation of PVD nitride coatings, using impact, scratch and Rockwell-C adhesion tests” Thin Solid Films, vol. 270, pp. 431-438, 1995.

[30] Y. Kayali and S. Taktak, “Characterization and Rockwell-C adhesion properties of chromium-based borided steels,” Journal of Adhesion Science and Technology, vol. 19, pp. 2065-2075, 2015.

[31] O. Ozdemir, M. Usta, C. Bindal and A. H. Ucisik, “Hard iron boride (Fe_2B) on 99.97wt% pure iron,” Vacuum, vol. 80, pp. 1391–1395, 2006.

[32] I. Ozbek and C. Bindal, “Mechanical properties of boronized AISI W4 steel,” Surface and Coatings Technology, vol. 154, pp. 14–20, 2002.

[33] T. Balusamy, T. S. N. S. Narayanan, K. Ravichandran, II. P. Song and M. H. Lee, “Effect of surface mechanical attrition treatment (SMAT) on pack boronizing of AISI 304 stainless steel,” Surface & Coatings Technology, vol. 232, pp. 60–67, 2013.

[34] Y. Kayali, I. Günes and S. Ulu, “Diffusion kinetics of borided AISI 52100 and AISI 440C steels,” Vacuum, vol. 86, pp. 1428-1434, 2012.

[35] S. Taktak, “Some mechanical properties of borided AISI H13 and 304 steels,” Materials and Design, vol. 28, pp. 1836–1843, 2007.

[36] M. Usta, I. Ozbek, M. Ipek, C. Bindal and A. H. Ucisik, “A comparison of mechanical properties of borides formed on pure Nb and W,” Materials Forum, Vol. 29, pp. 65-70, 2005.

[37] A. Tabur, M. Izciler, F. Gul and I. Karacan, “Abrasive wear behavior of boronized AISI 8620 steel,” Wear, vol. 266, pp. 1106–1112, 2009.

[38] Y. Kayali, A. Büyüksağiş and Y. Yalçin, “Corrosion and wear behaviors of boronized AISI 316L stainless steel,” Metals and Materials International, vol. 19 1053-1061, 2013.

[39] G. Ç. Efe, M. İpek, İ. Özbek and C. Bindal, “Kinetics of borided 31CrMoV9 and 34CrAlNi7 steels,” Materials Characterization, vol. 59, pp. 23–31, 2008.

[40] L. G. Yu, X. J. Chen, K. A. Khor and G. Sundararajan, “FeB/Fe_2B phase transformation during SPS pack-boriding: Boride layer growth kinetics,” Acta Materialia, vol. 53, pp. 2361–2368, 2005.

[41] V. I. Dybkov, W. Lengauer and P. Gas, “Formation of boride layers at the Fe–25% Cr alloy–boron interface,” Journal of Materials Science, vol 4, pp. 4948-4960, 2006.

[42] H. B. Abdelali, C. Claudin, J. Rech, W. B. Salem, PH. Kapsa and A. Dogui, “Experimental characterization of friction coefficient at the tool–chip–workpiece interface during dry cutting of AISI 1045,” Wear, vol. 286-287, pp. 108-115, 2012.

[43] C. Jessop and J. Ahlström, “Friction between pearlitic steel surfaces,” Wear, vol. 432-433, pp. 102910, 2019.

[44] L. R. R. Silva, R. S. Ruzzi, V. C. Teles, W. F. Sales, W. L. Guesser and A. R. Machado, “Analysis of the coefficient of friction at the workpiece-tool interface in milling of high strength compacted graphite cast irons,” Wear, vol. 426-427(b), pp. 1646-1657, 2019.

[45] C. A. Cuao-Moreu, E. Hernández-Sanchéz, M. Alvarez-Vera, E. O. Garcia-Sanchez, A. Perez-Unzueta and M. A. L. Hernandez-Rodrigueza, “Tribological behavior of borided surface on CoCrMo cast alloy,” Wear, vol. 426–427, pp. 204–211, 2019.

[46] Y. Teng, Y. Y. Guo, M. Zhang, Y. J. Yang, Z. Huang, Y. W. Zhou, F. Y. Wu and Y. S. Liang, “Effect of Cr/CrN_x transition layer on mechanical properties of CrN coatings

deposited on plasma nitrided austenitic stainless steel," Surface & Coatings Technology, vol. 367, pp. 100–107, 2019.

[47] X. M. He, X. B. Liu, M. D. Wang, M. S. Yang, S. H. Shi, G. Y. Fu and S. F. Chen, "Elevated temperature dry sliding wear behavior of nickel-based composite coating on austenitic stainless steel deposited by a novel central hollow laser cladding," Applied Surface Science, vol. 258, pp. 535–541, 2011.

[48] A. A. Joshi and S. S. Hosmani, "Pack-boronizing of AISI 4140 steel: boronizing mechanism and the role of container design," Materials and Manufacturing Processes, vol. 29, pp. 1062–1072, 2014.

[49] S. Y. Lee, G. S. Kim and B. S. Kim, "Mechanical properties of duplex layer formed on AISI 403 stainless steel by chromizing and boronizing treatment," Surface and Coatings Technology, vol. 177 – 178, pp. 178–184, 2004.

[50] D. Mu, B. L. Shen and X. Zhao, "Effects of boronizing on mechanical and dry-sliding wear properties of CoCrMo alloy" Materials and Design, vol. 31, pp. 3933–3936, 2010.

[51] I. Campos-Silva, A. D. Contla-Pacheco, A. Ruiz-Rios, J. Martínez-Trinidad, G. Rodríguez-Castro, A. Meneses-Amador and W. D. Wong-Angel, "Effects of scratch tests on the adhesive and cohesive properties of borided Inconel 718 superalloy," Surface & Coatings Technology, vol. 349, pp. 917-927, 2018.

[52] A. M. M. El-Bahloul, "Surface capacity of gears of circular-arc tooth-profile," Wear, vol. 93, pp. 146–154, 1996.

[53] I. Gunes, Y. Kayali and S. Ulu, "Investigation of surface properties and wear resistance of borided steels with different B_4C mixtures," Indian Journal of Engineering & Materials Sciences, vol.19, pp. 397-402, 2012.