SLIDING WEAR BEHAVIOR OF NIOBIUM CARBIDE COATED AISI 52100 BEARING STEEL

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Abstract

Sliding wear behavior of niobium carbide coated AISI 52100 bearing steel balls against AISI 1045 quenched steel discs was investigated. Thermo-reactive diffusion (TRD) treatment was carried out at 1000 °C for 4 hours by pack cementation method. NbC phase with 11 μm in thickness was identified by SEM microscopy and XRD technique. Ball-on-disc wear tests were carried out without lubrication under 2 and 10N load at sliding speeds of 0.1 and 0.3 m/s. A 300% increase in sliding speed resulted in 24% and 27%, increasing in friction coefficient of niobium carbide coated AISI 52100 steel balls for 2N and 10N. Wear resistance of AISI 52100 steel was improved up to 78 times after TRD treatment depending on applied load and sliding velocity. Wear mechanisms are adhesive-oxidative for hardened balls and abrasive-oxidative for coated balls against hardened AISI 1045 steel discs.
Keywords: Sliding wear; Steel; Niobium carbide coating; Friction.

1 INTRODUCTION

Thermo-reactive deposition/diffusion (TRD) treatment is a method for surface coating steels with a hard and wear-resistant layer of carbides, nitrides, carbonitrides [1] or borides [2] by the diffusion of carbon, nitrogen or boron in the steel substrate into a deposited layer of the carbide-, nitride- or boride-forming element.

The TRD treatment can be performed using salt baths [3,4], fluidized beds [5,6] or pack cementation [7-12] at high temperatures (850-1050 °C) with treatment times of 0.5-10 hours, resulting in a layer of depth 5-15 μm.

Pack cementation TRD powder usually consists of a metallic element (carbide-, nitride- or boride-forming); one inert filler that does not take part in the formation reactions of the layers, usually Al_2O_3 or SiC; and an activator, for example NH_4Cl that, when dissociated, chemically binds with the carbide-, nitride- or boride-forming element to form chlorides that will then react with the substrate to generate, for example, carbide layers [12,13].

Niobium carbide can be used in high-temperature environments because it has a high melting point (3873 °C) [14], hardness [15], fracture toughness, Young's modulus [7], wear resistance [16] and corrosion resistance [1].

The wear resistance of NbC layers has previously been investigated in a number of steel substrates: AISI 1040 [17,18], AISI D2 [3], AISI H13 [3,15] and AISI M2 [15]. Niobium carbide layers have proved to be an efficient coating for improvement of the wear resistance of steel substrates. For example, it was found that the niobium carbide layer improved the wear resistance of AISI 1040 steel by up to 1000-fold [18]. The niobium carbide layer on AISI H13 hot work tool steel demonstrated intermediate wear behavior between a VC coating and a boride coating [3] and better wear resistance than ion nitrided AISI H13 [15].

The aims of this work are to produce a wear resistant coating of niobium carbide on AISI 52100 steel balls using the pack cementation method and evaluate its tribological behavior. AISI 52100 steel can be used in tools for cold work dies, cold extrusion tools, bearings, etc. Increasing the quality of the tools is only about 5% of its cost and its preparation time, making it feasible to consider any surface treatment as an investment [19]. Ball-on-disc wear tests were conducted according to ASTM G99-05 standard at sliding speeds of 0.1 and 0.3m/s and under loads of 2 and 10N.

2 EXPERIMENTAL PROCEDURE

AISI 52100 steel balls, 6 mm in diameter, with a chemical composition of: 0.98-1.1 wt.% C, 0.15-0.35 wt.% Si, 0.25-0.45 wt.% Mn and 1.30-1.60 wt.% Cr, were TRD treated in a solid medium consisting of Fe-Nb, Al_2O_3 and NH_4Cl at 1000 °C for 4 hours. Niobium carbide coating

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was carried out in an electrical resistance furnace under an argon atmosphere at atmospheric pressure. The hardened AISI 52100 steel balls were also analyzed.

AISI 1045 steel discs, 6 mm in thickness, were cut from a bar of diameter 25.4 mm. The steel discs were sanded with silicon carbide abrasive paper up to 600 grit and polished with 1 μm alumina suspension. The AISI 1045 plain carbon steel discs usually had a chemical composition of: 0.43-0.48 wt.% C, 0.60-0.90 wt.% Mn, 0.15-0.35 wt. % Si, 0.30-0.40 wt.% Cr, 0.02-0.05 wt.% Al, 0.025 wt. % P and 0.02-0.04 wt.% S. The discs were water quenched and tempering was not performed.

The roughness of the AISI 52100 steel balls and AISI 1045 steel discs were measured using a Leica DCM 3D confocal microscope. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis was performed on the cross-section and wear scars of the balls, and the disc wear tracks using Zeiss DSM-940A and JEOL JSM-6701F instruments. X-ray diffraction (XRD) analysis of the niobium carbide coatings was performed using Cu K$_\alpha$ radiation over a 2θ range of 20-90° using a Shimadzu 6000 diffractometer. Micro-hardness tests were performed on a Future-Tech FM-800 tester. A 25 g load was used and the indentation time was 10 s.

Ball-on-disc wear tests were carried out in order to investigate the tribological behavior of coated and uncoated AISI 52100 steel balls sliding against hardened AISI 1045 steel discs for 300, 600 and 900 m under an applied load of 2 N and 10 N at sliding speeds of 0.1 m/s and 0.3 m/s in room temperature (25 °C). The wear scar diameter of the balls was measured by optical microscopy and the specific wear rate of the balls was calculated according to Equation 1 [17]:

$$k_b = \frac{\pi d^4}{64RPS} \tag{1}$$

where d is the wear scar diameter of the worn area of the ball, R is the ball radius, P is the applied load and S is the sliding distance.

3 RESULTS AND DISCUSSION

The SEM cross-sectional examinations demonstrated that the niobium carbide layer formed on AISI 52100 bearing steel had a uniform thickness and was firmly bonded to the steel substrate (Figure 1).

Two distinct regions could be identified on the cross-section of the niobium carbide coated AISI 52100 steel ball: (I) a niobium carbide layer consisting of NbC,
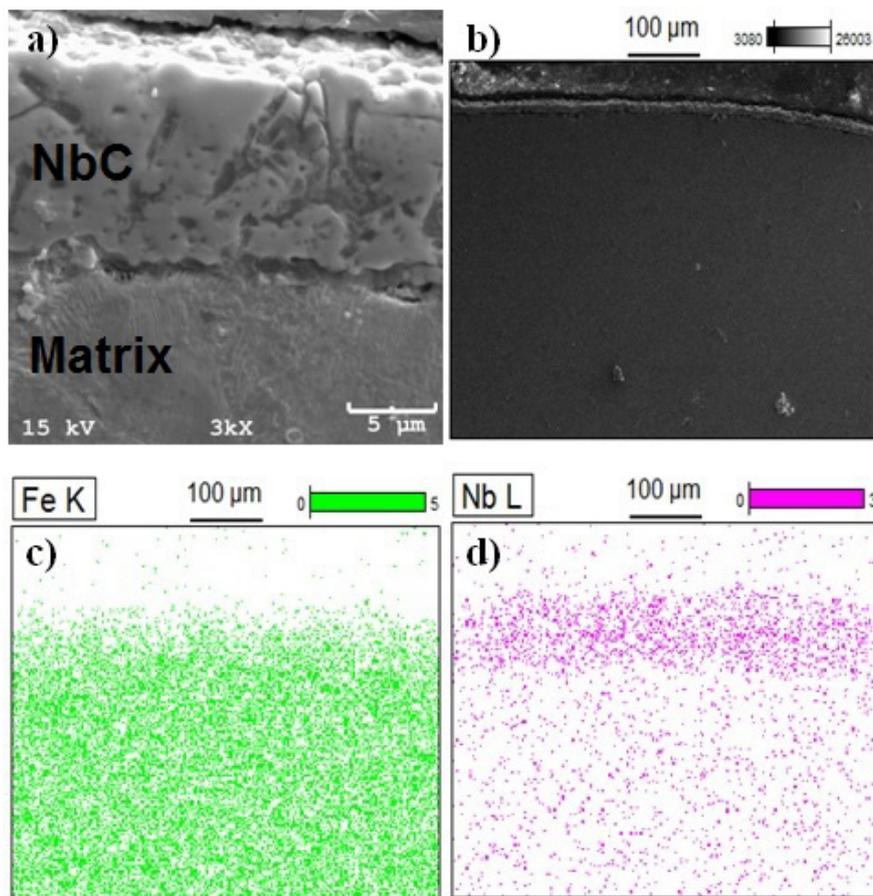
Figure 1. SEM micrographs (a, b) and EDS mapping (c, d) of niobium carbide coated AISI 52100 steel balls.

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and (II) a steel matrix. The NbC formation was confirmed by XRD analysis (Figure 2).

The layer thickness was about 11 μm (Figure 1a). The Vickers micro-hardness was measured at least five times on each region. The hardness of the hardened AISI 1045 steel discs and hardened AISI 52100 steel balls were 570 $\pm$ 9 $HV_{0.025}$ and 822 $\pm$ 14 $HV_{0.025}$, respectively. The hardness of the niobium carbide layer and the matrix of AISI 52100 balls were 2095 $\pm$ 310 $HV_{0.025}$ and 358 $\pm$ 41 $HV_{0.025}$ respectively. These results are in good agreement with other works [1,7,17,18]. The roughness of the AISI 52100 steel balls were measured using a confocal microscopy technique, and the values were Sa $=$ 1.20 μm and Sa $=$ 2.42 μm for the hardened and niobium carbide coated balls, respectively (Figure 3). Hardened AISI 1045 steel discs showed a Sa $=$ 0.12 μm average roughness.

Figure 4 shows the friction coefficient behavior with variation of sliding speed. It is clear from this figure that the friction coefficient increased with increasing sliding speed in the range 0.1-0.3 m/s. A 300% increase in sliding speed resulted in 24% and 27% increases in the friction coefficients of the niobium carbide coated AISI 52100 steel balls for loads of 2 and 10 N, respectively. These results are in good agreement with Woydt and Mohrbacher [20]. The same increase in sliding speed resulted in 48% and 25% increases in the friction coefficients of the hardened AISI 52100 steel balls for the same loads of 2 and 10 N, respectively. The friction coefficients of the hardened and niobium carbide coated balls sliding against hardened AISI 1045 steel discs, with a 2 N normal load at sliding speeds of 0.1-0.3 m/s were in the ranges 0.42-0.62 and 0.50-0.62, respectively. For a normal load of 10 N the friction coefficients were 0.40-0.50 and 0.45-0.57 for the hardened and niobium carbide coated balls, respectively. This may be due to the increasing temperature of the wear scar, which causes greater oxidation [17]. When niobium carbide coating was formed over AISI 1040 flat end pins sliding against AISI D2

steel discs, the friction coefficient decreased with increasing sliding speed for sliding speed in the range of 0.5-5 m/s [18].

The variation in specific wear rate for niobium carbide coated and hardened AISI 52100 steel balls is illustrated in Figure 5. It is clear from this figure that niobium carbide coated balls presented higher wear resistance than hardened balls. At a sliding speed of 0.1 m/s the specific wear rate of the hardened AISI 52100 steel balls was up to 13 times higher than that of the niobium carbide coated balls. For a sliding speed of 0.3 m/s, the difference in specific wear rate

Figure 3. Confocal images of hardened (a) and niobium carbide coated (b) AISI 52100 steel balls.

Figure 2. X-ray diffraction pattern of niobium carbide layer formed on AISI 52100 steel substrate.
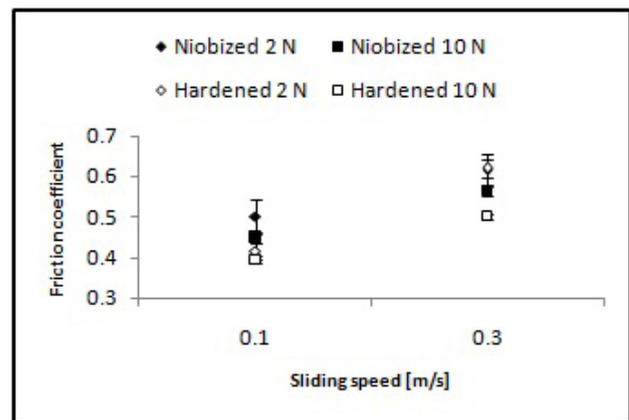
Figure 4. Friction coefficient of hardened and niobium carbide coated balls against hardened AISI 1045 steels disc according to sliding speed.

was up to 78 times, and was higher for the uncoated steel. The specific wear rates of the hardened and niobium carbide coated balls with 2 N of normal load at sliding speeds of 0.1-0.3 m/s were in the ranges 7.21×10^{-7}-7.31×10^{-7} mm³/N.m and 6.74×10^{-8}-8.55×10^{-9} mm³/N.m, respectively. For a normal load of 10 N, the specific wear rates were 3.91×10^{-7}-2.68×10^{-7} mm³/N.m and 2.76×10^{-8}-5.27×10^{-8} mm³/N.m for hardened and niobium carbide coated balls, respectively.
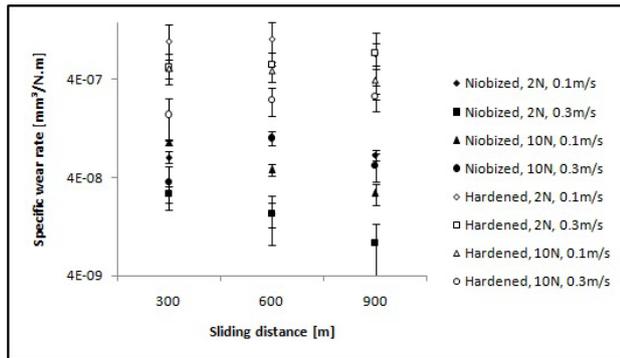
Figure 5. Specific wear rate of hardened and niobium carbide coated balls against hardened AISI 1045 steel disc according to sliding distance.

Table 1 summarize the results of the specific wear rate of the ball for a sliding distance of 900 m.

Wear tracks and EDS spectra of hardened AISI 1045 steel disc against hardened balls are illustrated in Figure 6. As shown in this figure, there was an increase in the transfer layer (darker spots in Figure 6a and Figure 6b) with increasing load. Furthermore, Figure 6d indicates the presence of Cr and Mn on the wear track for hardened AISI 52100 ball sliding against hardened AISI 1045 disc. Chromium and manganese are not alloying elements of the AISI 1045 steel discs so it is reasonable to assume that there was adhesion of the ball material on the wear track of the disc. In addition, the presence of oxygen on Figures 6c and 6d indicate that an oxidative mechanism also occurred on the worn tracks. Thus, the wear mechanisms of the untreated AISI 52100 balls were adhesive and tribo-oxidative wear.

As can be seen in Figure 5 and Table 1 the results seem to indicate that increasing load leads to a decrease in the specific wear rate, specially for hardened AISI 52100 steel balls. In Figure 6 it is noted that for higher applied loads there was the formation of larger spots of transfer layer. The presence of this transfer layer can change significantly the tribological properties of the counterface [21]. Therefore,
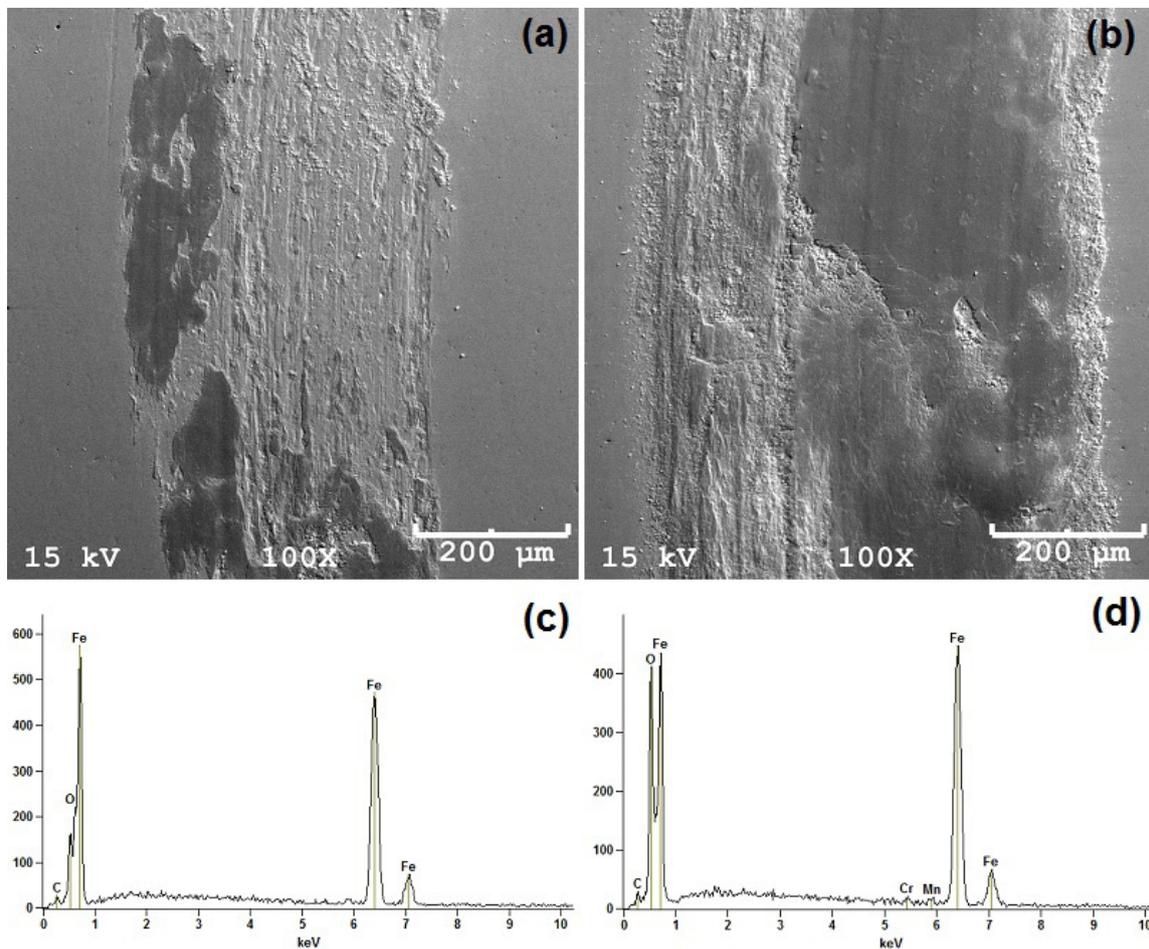
Figure 6. Worn tracks and EDS mapping of AISI 1045 steel discs against hardened AISI 52100 steel balls at 0.1 m/s. (a, c) 2 N load, (b, d) 10 N load. Sliding distance of 900 m.

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wear is reduced when the compact wear debris particles layers are formed [22,23]. For shorter distances it was noted that the formation of a protective transfer layer is very limited, being larger when the sliding distance increase, which is in good agreement with other work [24].

For niobium carbide coated AISI 52100 steel balls sliding against hardened AISI 1045 steel discs, an increment in load resulted in deeper grooves on the wear tracks (Figure 7a and Figure 7b). Despite this fact, increasing the load did not result in increasing oxidation on the disc's wear tracks (Figure 7c and Figure 7d). However, for niobium carbide coated balls, it was found that the increment in sliding speed resulted in greater oxidation. Even when performed at room temperature the increasing in sliding speeds led to increasing surface temperature due to frictional heating [25] and then oxidative wear took place [17,26]. EDS analysis of coated balls after the wear tests confirm that there is an increase of niobium content and a decrease of iron when sliding speed was increased. This suggests a greater formation of niobium oxides than iron oxides. However, when the applied load is increased, there is an increasing in iron content and decreasing of niobium. It is believed that this increment in applied load resulted in delamination of NbC layer, increasing the content of iron oxide on the wear scar. Thus, the wear mechanisms of the niobium carbide coated AISI 52100 balls were abrasive and tribo-oxidative wear.

In Figure 8, it is clear that the niobium carbide layer of the balls was completely smeared off under the 10 N load condition and with a 900 m sliding distance. The carbide layer cracked, and delamination occurred (Figure 9). Hard wear debris acts as abrasive particles, increasing the depth and number of grooves on the wear tracks.

Table 1. Specific wear rate of the ball for a sliding distance of 900 m.

Treatment	Load [N]	Sliding velocity [m/s]	$k_b \times 10^{-8}$ [mm³/Nm]
Niobized	2	0.1	6.74 ± 0.87
		0.3	0.85 ± 0.53
	10	0.1	2.76 ± 0.66
		0.3	5.27 ± 4.00
Hardened	2	0.1	72.11 ± 47.34
		0.3	73.06 ± 2.10
	10	0.1	39.08 ± 3.38
		0.3	26.79 ± 13.18
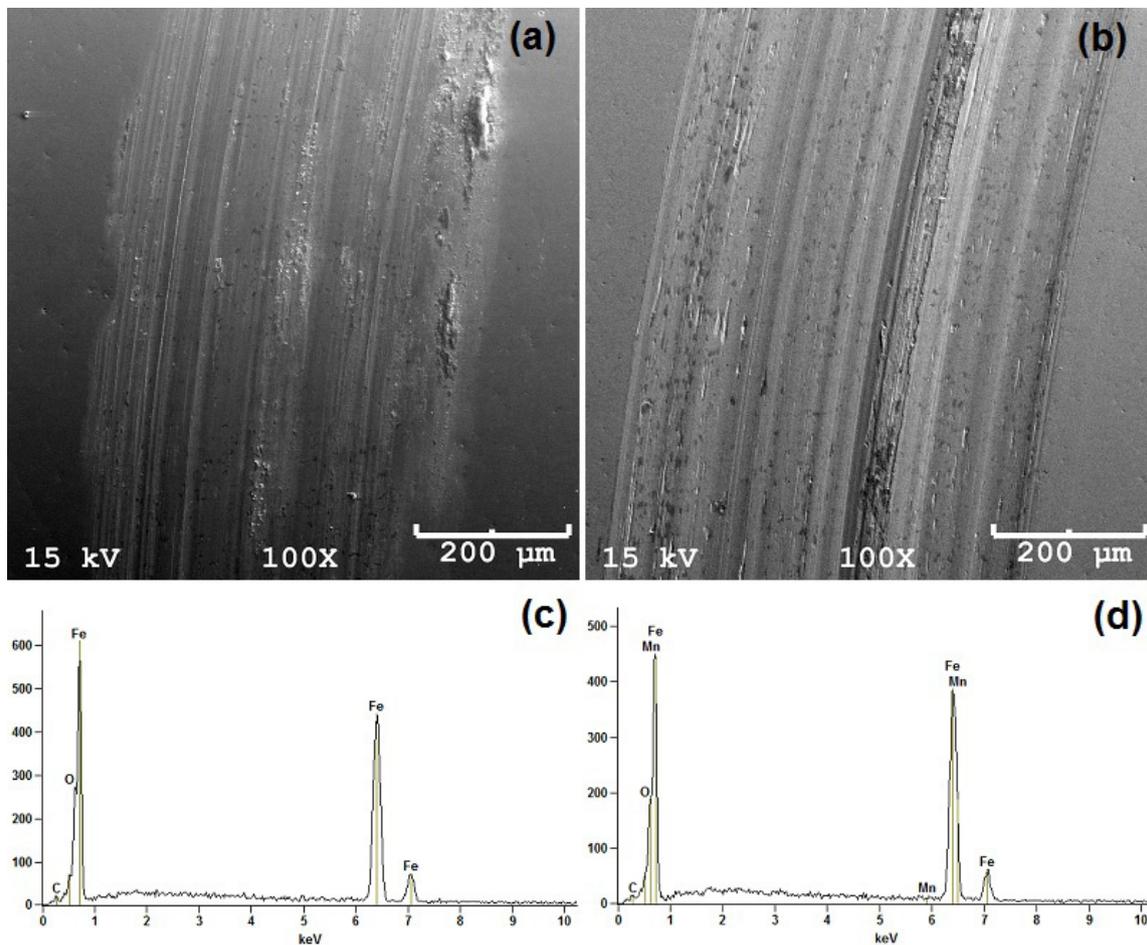
Figure 7. Worn tracks and EDS mapping of niobium carbide coated AISI 52100 steel balls against hardened AISI 1045 steel discs at 0.3 m/s. (a, c) 2 N load, (b, d) 10 N load. Sliding distance of 900 m.
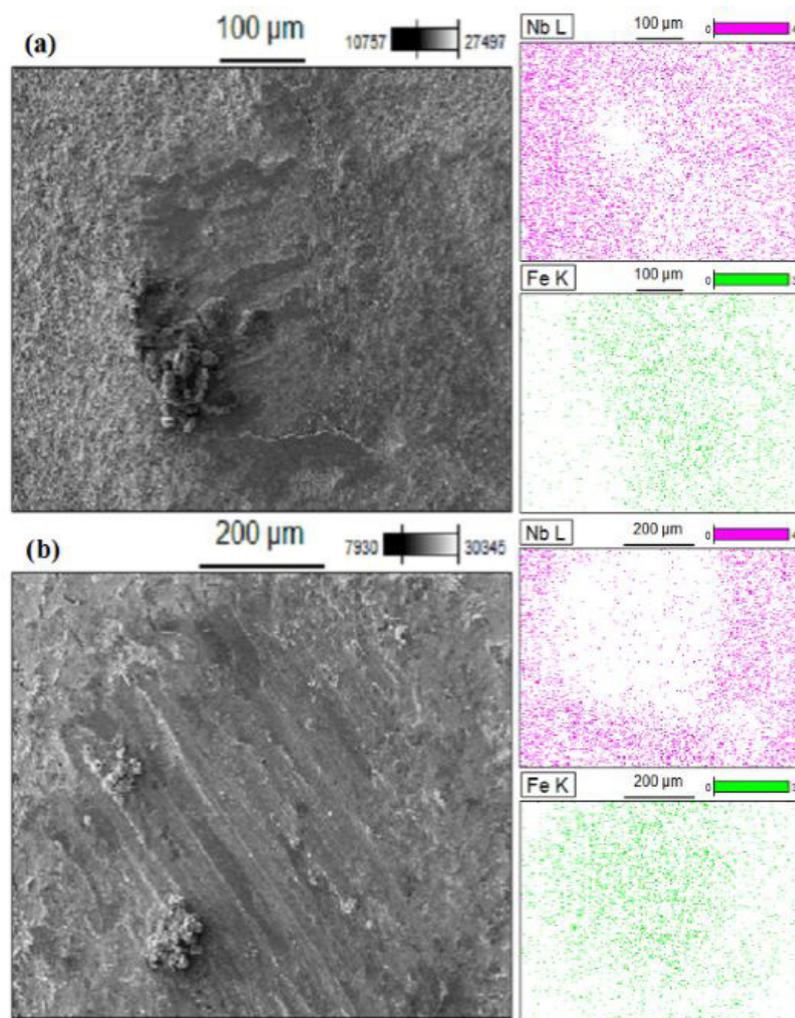
Figure 8. Worn scars and EDS mapping of niobium carbide coated balls (a) 2 N load and (b) 10 N load, at sliding speed of 0.1 m/s and sliding distance of 900 m.
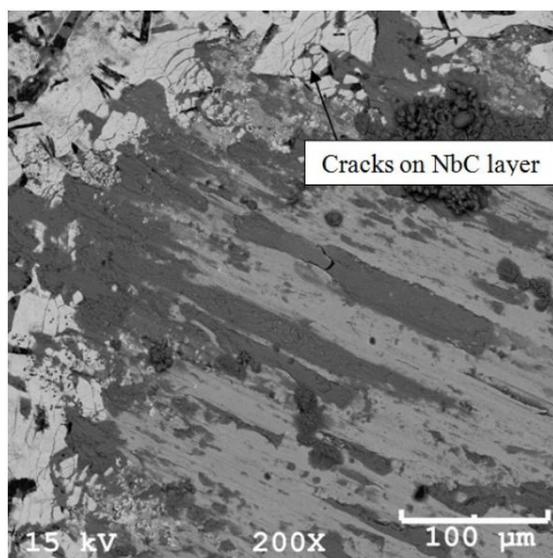
Figure 9. Cracks formed on the worn scar of niobium carbide coated AISI 52100 steel ball 0.1 m/s with normal load of 10 N and sliding distance of 900 m.

4 CONCLUSIONS

When the above results are taken into consideration, the following conclusions can be drawn:

(1) A layer of NbC can be achieved on the surface of AISI 52100 bearing steel balls using the pack cementation method.

(2) The thickness of NbC layer was about 11 μm and its hardness was 2095 $\pm$ 310 $HV_{0.025}$.

(3) The friction coefficients increased with increasing sliding speed.

(4) The friction coefficients of hardened and niobium carbide coated balls sliding against hardened AISI 1045 steel discs, with 2 N of normal load at sliding speeds in the range 0.1-0.3 m/s were 0.42-0.62 and 0.50-0.62, respectively. For a normal load of 10 N the friction coefficients were 0.40-0.50 and 0.45-0.57, respectively.

(5) The specific wear rate of hardened balls was up to 13 times higher than niobium carbide coated balls at a sliding speed of 0.1 m/s and applied load of 10 N and up to 78 times higher for a sliding speed of 0.3 m/s and applied load of 2 N.

(6) The wear mechanism of the hardened balls sliding against the hardened discs was adhesive-oxidative, while the wear mechanism of the NbC coated balls sliding against the hardened discs was abrasive-oxidative, with cracking of the niobium carbide layer.

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