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ARTICLE

Growth Kinetics and Tribological Properties of NbC Coating on Different Steel Substrates Prepared by Pack Cementation Method

Ran Xuelin[1], Zhang Jin[1], Wang Wei[2], Gong Xiufang[2], Tu Yepeng[1], Guo Mengxin[1], Li Songxia[1]

[1] School of New Energy and Materials, Southwest Petroleum University, Chengdu 610500, China; [2] Dongfang Turbine Co., Ltd, Deyang 618000, China

Abstract: The growth kinetics process and tribological properties of niobium carbide (NbC) coatings prepared by the pack cementation method on the 40Cr and 45 steel substrates were investigated with the main raw materials of iron niobium powder, ammonium chloride, and alumina under the conditions of different temperatures (1123~1273 K) and different treatment durations (1~4 h). Results show that the coating is compact and well bonded with the substrate interface, and it is mainly composed of NbC phase. The thickness of the coatings on 40Cr and 45 steel substrates is 1.703±0.285~8.457±0.240 and 1.987±0.355~9.247±0.275 μm, respectively. The growth kinetics study shows that the coating growth is controlled by the diffusion process, and the thickness has a parabolic relationship with the treatment duration. The activation energies of the NbC growth process on the 40Cr and 45 steel substrates are 113.80 and 102.76 kJ/mol, respectively. After treatment at 1273 K for 4 h, the hardness of NbC coating reaches more than 21 560 MPa, which is 5.49~8.06 times higher than that of the steel substrate. With GCr15 steel ball as the grinding material, the average coefficient of friction of NbC coating on the 40Cr and 45 steel substrates is 0.393 and 0.342, respectively; the average coefficient of friction of substrate is 1.3~1.6 times higher than that of the NbC coating. The volume wear rate of NbC coating is about 34.9%~37.5% of that of the steel matrix, indicating that the NbC coating has excellent wear resistance and wear reduction performance. The friction and wear mechanism of NbC coating is abrasive wear, adhesion wear, and oxidation wear.

Key words: pack cementation method; NbC coatings; different substrates; growth kinetics; friction

The protective coating on the steel surface can improve the surface properties of the steel and thus prolong the service life of the steel. The coatings of transition metal (TM)-carbides, TM-nitrides, and niobium carbide (NbC) have all been widely applied to enhance the mechanical properties of components because of their high hardness, high melting point, low coefficient of friction, superb wear resistance, and good corrosion resistance[1-10], showing great potential in industrial application.

Currently, the preparation methods of NbC coating have been investigated to improve the surface mechanical properties of components, such as laser cladding (LC)[11-13], chemical vapor deposition (CVD)[14], physical vapor deposition (PVD)[15], in-situ synthesis (ISS)[1,7,16], and thermo-reactive deposition (TRD)[3,4,7,17-20]. Although the operation is difficult to control, TRD technique still attracts much attention because it does not require vacuum or controlled atmospheres in the complex system[4,7,11,14,15,20]. In addition, TRD process is economical and environmentally friendly. TRD technique can form the metallurgical bonding between the coating and the substrate through the atomic diffusion, and the prepared coating presents excellent adhesion to the substrate and consequently good seizure resistance[7]. Therefore, TRD technique is considered as an attractive preparation method with great potential.

During TRD process, the specific methods for NbC coating

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Corresponding author: Zhang Jin, Master, Professor, School of New Energy and Materials, Southwest Petroleum University, Chengdu 610500, P. R. China, E-mail: jzhang@swpu.edu.cn

preparation are the pack cementation, salt bath, and double glow plasma[4,20]. During the pack cementation, the specimen and reaction medium are placed in a crucible sealed by the high-temperature-resistant glue at high temperatures[4,9]. The coating is generated by the combination of carbide- and nitride-forming elements, such as tantalum, chromium, tungsten, molybdenum, vanadium, and niobium, and the carbon diffuses from the substrate to the surface[3,4]. The growth kinetics of carbide coatings prepared by the pack cementation method on different substrates, such as AISI L2 steel and AISI 1045 steel, has been researched[4,19]. However, the effect of different substrates on the growth kinetics of NbC coating is still obscure. The 45 steel and 40Cr steel are commonly used in the petroleum industry, and their failure is mainly caused by the wear or corrosion. The composition of 45 steel and 40Cr steel is similar, except for the Cr content. Therefore, the influence of the substrate composition on the growth kinetics and wear resistance of NbC coatings can be investigated based on these two steels.

In this research, the NbC coatings were prepared on different substrates by the pack cementation method. The influence of different substrates on the growth kinetics of NbC coatings was discussed. The typical carbon steel (45 steel) and low alloying steel (40Cr steel) were selected as the base material. The effects of substrates on the phase, thickness, morphology, and growth kinetics of NbC coatings were analyzed. The slow reciprocation friction experiments were conducted to analyze the tribological properties and friction mechanism of the steel substrates with NbC coating.

1 Experiment

The base materials were 45 steel and 40Cr steel, and their chemical composition is listed in Table 1. Before preparation, the two steels were prepared into the specimens with the size of 20 mm×10 mm×5 mm. Then, the specimens were polished, cleaned by 600#, 800#, and 1200# sandpaper, and dried. The ferrocolumbium powder (30wt%) was used as the source of mud, the alumina (65wt%) was used as filler, and the ammonium chloride (5wt%) was used as the activator. At the beginning of the preparation, the substrate and uniformly mixed reaction medium were embedded in a crucible. Then, the crucible was sealed and kept in a drying oven at 80 °C for 2 h to remove the moisture. Finally, the crucible was placed in a resistance heating furnace at 1123, 1173, 1223, and 1273 K for 1~4 h under atmospheric conditions for thermal diffusion-reaction deposition. After the preparation, the specimen was taken out of the crucible and cooled in the furnace. Then, the residue on the specimen surface was removed by alcohol and the damp cloth. Finally, the vacuum quenching was applied to all the coated specimens.

Table 1 Chemical composition of 45 steel and 40Cr steel substrates (wt%)

Element	45 steel	40Cr steel
C	0.42~0.50	0.37~0.44
Cr	≤0.25	0.80~1.10
Ni	≤0.25	≤0.25
Mn	0.50~0.80	0.50~0.80
P	≤0.035	≤0.035
S	≤0.035	≤0.035
Si	0.17~0.37	0.17~0.37
Fe	Bal.	Bal.

The phase composition of NbC coating was analyzed by X-ray diffractometer (XRD) with the scanning angle of 20°~80° and scanning step of 0.05°/step. The specimens were treated for metallographic observation by XQ-2B equipment. Then, the specimens were ground, polished, and etched by 4vol% nitrate alcohol to determine the coating thickness. The microstructures were observed by the scanning electron microscope (SEM) after the specimens were etched by the aqueous solution (10wt% KOH+10wt% $K_3[Fe(CN)_6]$). The Vickers hardness of coatings was measured. The quadrangular pyramid diamond indenter was used with the load of 20 g and loading time of 15 s. Three points were selected and measured of each substrate and the average hardness was used for analysis. The wear experiments were conducted by the MFT-4000 equipment. The GCr15 steel ball was used as the grinding material under the applied load of 20 N, the wear velocity of 60 mm/min, and the wear scar length of 10 mm. The worn surfaces of the specimens were also observed by SEM. Additionally, the composition of different areas was analyzed by the energy disperse spectroscope (EDS).

2 Results and Discussion

2.1 Characterization of NbC coating

Fig. 1 shows XRD patterns of NbC coating on different substrates after pack cementation at 1273 K for 4 h. As shown in Fig. 1, the coatings on both 40Cr steel and 45 steel mainly consist of NbC phase. The characteristic diffraction peak of NbC mainly occurs at 2θ=34.716°, 40.301°, 58.311°, 69.678°, 73.264°. However, the characteristic diffraction peaks of the NbC coating in this research are obviously different from those of the standard card (PDF#38-1364) [21]. It is worth noting that the preferred orientation of grain growth of TM-carbides and TM-nitrides during the heat treatment is on the

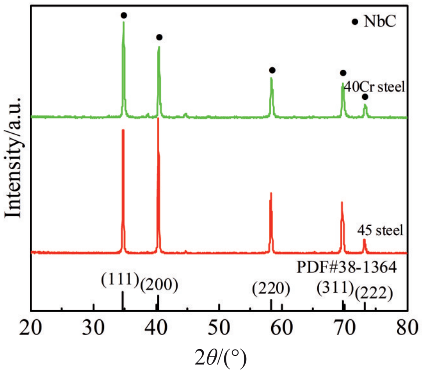

Fig.1 XRD patterns of NbC coatings on different substrates

(111) and (200) planes[2,20,22]. The intensity of the characteristic diffraction peak can be used to calculate the texture coefficient of different planes, and therefore the existence of the preferred orientation during the growth process can be verified[2,14,22]. The standard value of the disordered NbC phase is obtained according to the value set by American Society for Testing Material. Fig. 2 presents the calculated texture coefficients of different planes (*hkl*). Although the texture coefficient of different crystal planes is different, the values are all close to 1, indicating that the coatings do not have obvious preferred orientation during the growth process. The growth orientation of the coating may be closely related to the crystal orientation of the substrate[23,24]. Additionally, the growth orientation is also related to the preparation process, raw material, and other factors[22,23], which should be further researched.

The SEM cross-sectional morphologies of NbC coatings on the 40Cr steel and 45 steel are shown in Fig. 3. It can be seen that the NbC coating is dense, compact, and firmly bonded with the steel substrates. Besides, the NbC coating thickness is uniform of 8 and 9 μm on 40Cr steel and 45 steel substrates, respectively. Fig. 4 shows EDS line scanning results of NbC coatings on different substrates. The matrix composition is the main factor affecting the NbC coating thickness. For 45 steel substrate, the higher the carbon content in the matrix, the thicker the coating thickness. However, for 40Cr steel substrate, the content of solid solution carbon in the matrix at austenitic temperature is the main factor affecting the coating thickness[17]. The preparation temperature in this research is above the austenitization temperature of the two steel substrates. Thus, the carbides in 40Cr steel are entirely dissolved in the matrix during treatment. The carbon content of 40Cr steel is slightly lower than that of 45 steel, resulting in a relatively thin coating thickness on 40Cr steel substrate. The carbides in 40Cr steel can affect the carbon activity in austenite and inhibit the growth of coating[25]. As a strong carbonization-forming element, Cr has a strong affinity with C, which reduces the activity of C element in the matrix, thus affecting the diffusion rate of C element in 40Cr steel substrate. Therefore, the coating on 40Cr steel substrate is thinner than that on 45 steel substrate.

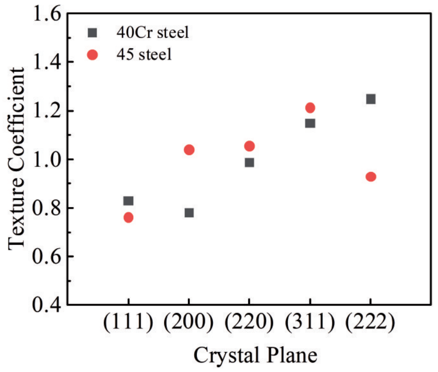

Fig.2 Texture coefficients of crystal planes of NbC coatings on different substrates

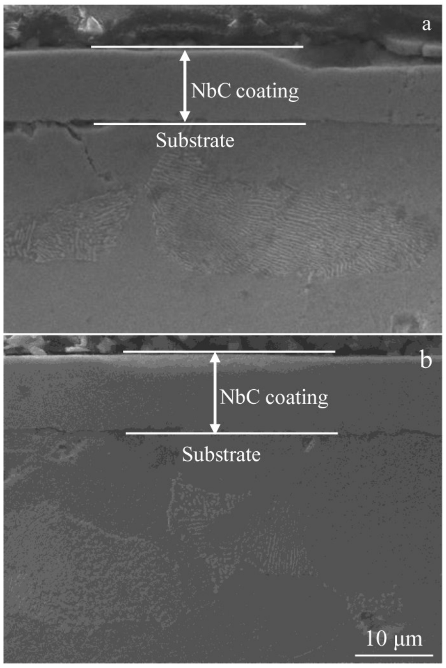

Fig.3 SEM cross-sectional morphologies of NbC coatings on 40Cr steel (a) and 45 steel (b) substrates

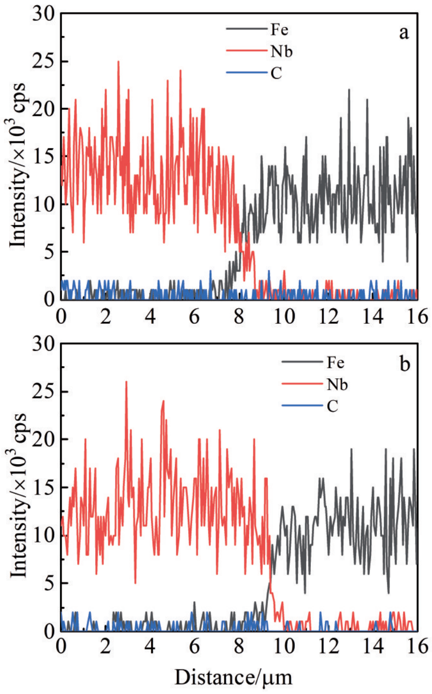

Fig.4 EDS line scanning results of NbC coatings on 40Cr steel (a) and 45 steel (b) substrates

Fig. 5 shows the etched cross-section and surface morphologies of NbC coatings on 40Cr steel and 45 steel substrates. It can be seen that the equiaxed grains form throughout the coatings on substrate surfaces, indicating that NbC coating does not grow preferentially during the growth process. It is reported that the TM-carbide coating on steel prepared by

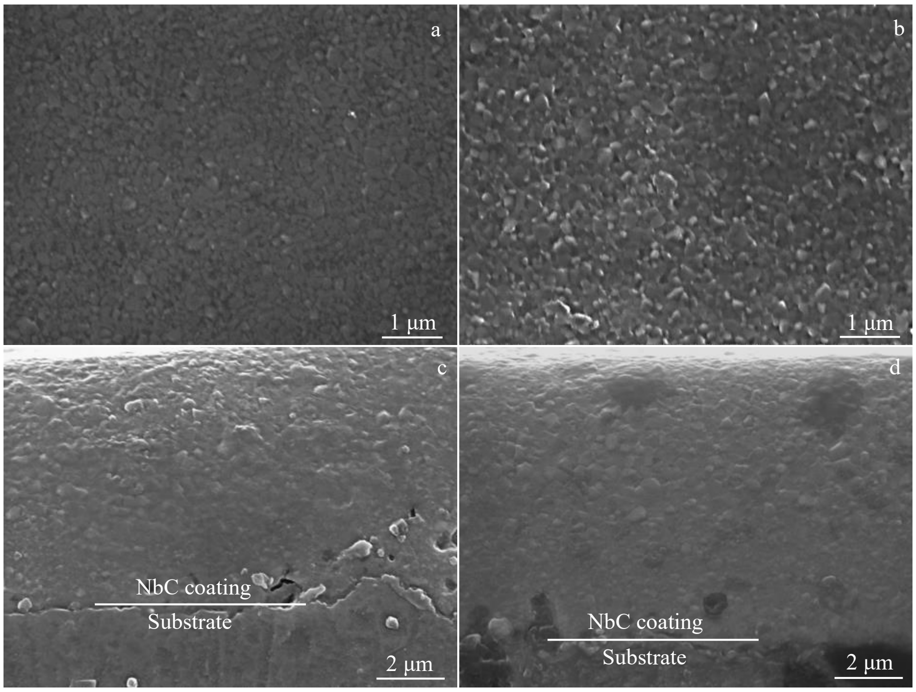

Fig.5 SEM surface (a, b) and cross-section (c, d) morphologies of NbC coatings on 40Cr steel (a, c) and 45 steel (b, d) substrates

TRD treatment is composed of columnar grains near the substrate and equiaxed layers near the coating surface. However, no columnar grains appear in this research. The size of equiaxed grains is increased gradually from the substrate surface. The average grain size of NbC coatings is 0.14±0.006 and 0.17±0.010 μm on 40Cr steel and 45 steel substrates, respectively, suggesting that the grains in the coating on 40Cr steel are finer than those on 45 steel.

The grain morphology of NbC coating may be related to the nucleation and growth behavior of coating. During the pack cementation process, NbC is generated on the substrate, which provides carbon source to react with the Nb atoms supplied by the ferrocolumbium powder. Nb atoms slowly diffuse to the substrate surface by vacancy transition, whereas C atoms diffuse rapidly to the substrate surface by gap transition. When Nb atoms on the subsurface of the substrate reach the equilibrium content, NbC nucleates at the dislocations or grain boundaries on the substrate surface[1,26,27]. Fig. 6 shows the schematic diagrams of NbC coating formation on steel substrates. At the initial stage of coating growth, the growth rate in all directions is almost uniform and the equiaxed grains are generated. Then, NbC coating grows because of the continuous nucleation and grain growth, forming continuous thin layers. Due to the coating growth, the C atoms in the substrate diffuse through the NbC coating to react with the Nb atoms, continuously forming the NbC coating (Fig.5c). When the coating thickness increases, the diffusion distance for C atoms in the substrate becomes longer, decreasing the content of C atoms at the interface and the number of nucleation. This phenomenon results in the grain gowth. Thus, the farther the distance away from the substrate, the larger the grains[2,27].

2.2 Growth kinetics of NbC coating

Fig.7 shows the relationship between the thickness of NbC coating and the treatment duration at different temperatures on different steel substrates. The thickness of NbC coating on different substrates is increased with prolonging the diffusion

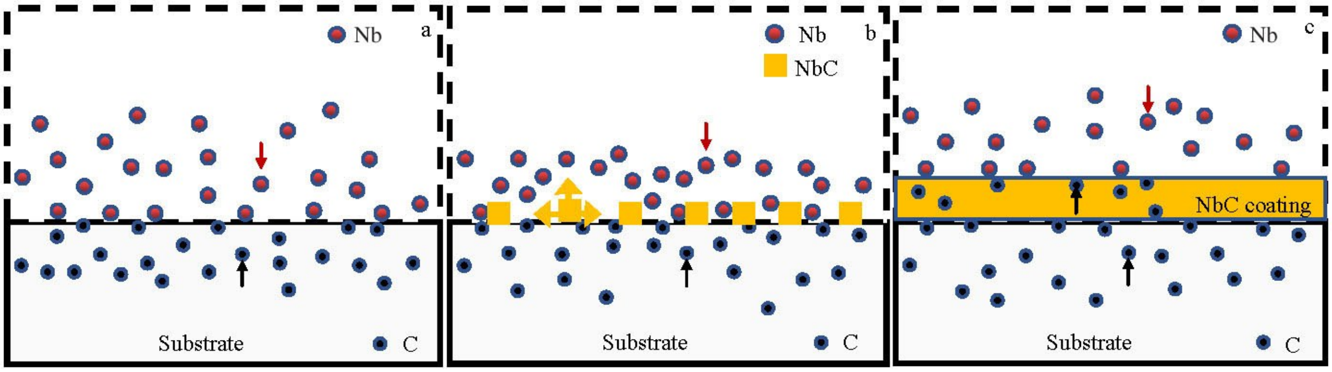

Fig.6 Schematic diagrams of NbC coating formation on steel substrate

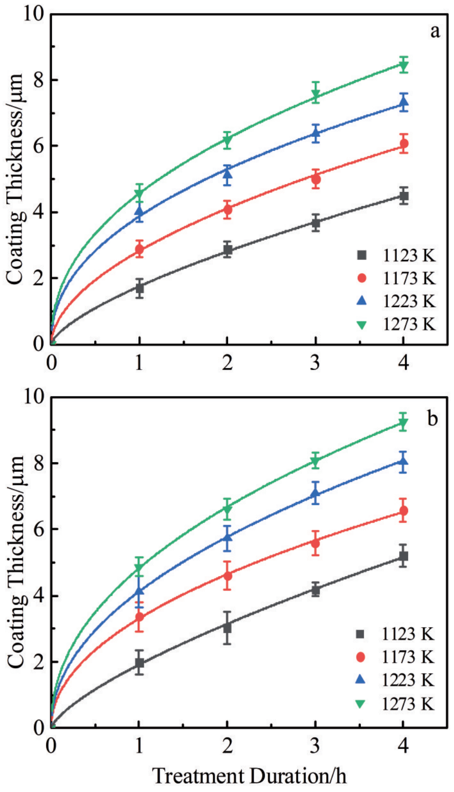

Fig.7 Relationships between NbC coating thickness and treatment duration at different temperatures on 40Cr steel (a) and 45 steel (b) substrates

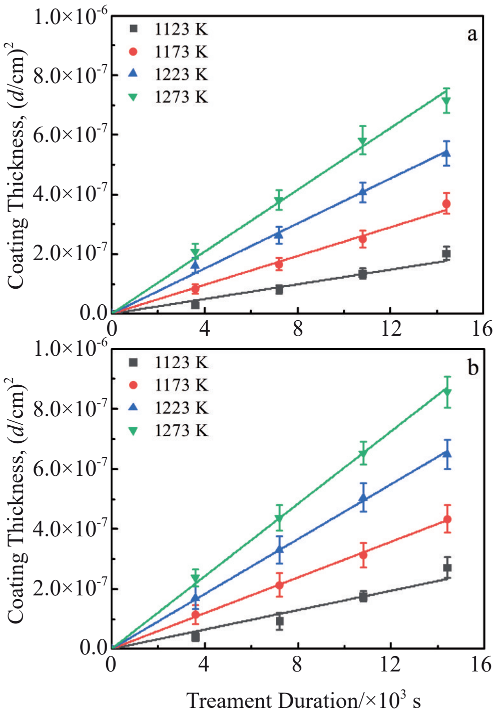

Fig.8 Fitting results of NbC coating thickness with treatment duration on 40Cr steel (a) and 45 steel (b) substrates

Table 2 Diffusion coefficient *D* of NbC coating at different temperatures on 40Cr steel and 45 steel substrates ($\times10^{-11}$ cm^2/s)

Temperature/K	1123	1173	1223	1273
40Cr steel	1.23	2.42	3.78	5.19
45 steel	1.62	2.98	4.58	6.05

duration at different temperatures. It can be seen that the parabolic relationship exists between the coating thickness and the treatment duration, which is consistent with the classical dynamic equation. However, the thickness of NbC coating on different substrates is different even under the same treatment conditions, inferring that the growth kinetics of NbC coating on different substrates is different in TRD process[4].

To establish the classical dynamic equations, two assumptions must be considered in the growth process of TM-nitride or TM-carbide coating. (1) The diffusion of carbon or nitrogen atoms controls the coating growth process due to the relatively large atomic radius of TM[2,16,18-20], i.e., the flux of Nb is small and does not contribute to the boundary motion. Moreover, the coating grows perpendicularly to the substrate. (2) The diffusion of carbon in NbC coating is the main factor influencing the growth of NbC coating[4,16,20]. Based on the classical kinetic theory, the parabolic law of NbC coating thickness can be expressed as follows:

$$d^2=Dt \tag{1}$$

where d is the thickness of NbC coating (μm), t is the treatment duration (s), and D is the diffusion coefficient of atoms (cm^2/s). Fig. 8 shows the fitting results of coating thickness with the treatment duration at different temperatures, which is consistent with Eq.(1). Table 2 presents the values of diffusion coefficient D of different substrates, which are obtained from the fitting lines in Fig. 8. The diffusion coefficient D is temperature-dependent and increased with increasing the treatment temperature. It is worth noting that the diffusion coefficients of NbC coating on different substrates at the same temperature are different. The diffusion coefficient D of NbC coating on 40Cr steel decreases, indicating a deceleration in the carbide formation on the 40Cr steel surface.

In addition, the Arrhenius equation can express the relationship among the diffusion coefficient D, growth rate constant (D_0), activation energy (Q), and the treatment temperature (T), as follows:

$$D=D_0 e^{-\frac{Q}{RT}} \tag{2}$$

where R is the gas constant (8.314 J·mol^{-1}·K^{-1}). Thus, Eq.(3) can be obtained, as follows:

$$\ln D=\ln D_0-\frac{Q}{RT} \tag{3}$$

Fig. 9 shows the linear fitting results of ln$D$-T^{-1}. Then, the activation energy Q of NbC coatings can be calculated from the slope of the fitting lines, as listed in Table 3. The results show that the activation energy required to prepare NbC coating on the 40Cr steel substrate is higher than that on the 45 steel substrate.

The diffusion coefficient based on the treatment

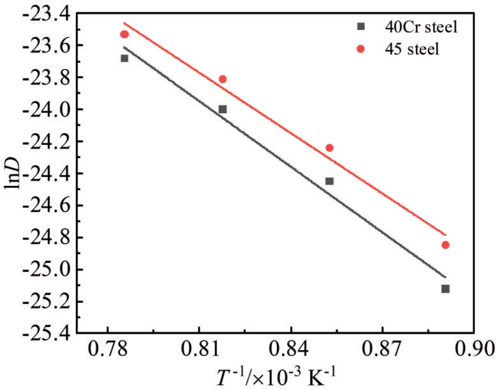

Fig.9 Relationships of ln$D$-1/T of NbC coatings on 40Cr steel and 45 steel substrates

Table 3 Activation energy Q of NbC coating formation on 40Cr steel and 45 steel substrates (kJ/mol)

40Cr steel	45 steel
113.80	102.76

temperature on different substrates can be obtained, as expressed by Eq.(4) and Eq.(5), as follows:

$$D_{40\mathrm{Cr}}=2.298\times10^{-6}\mathrm{e}^{-\frac{13\,687}{T}} \tag{4}$$

$$D_{45}=1.290\times10^{-6}\mathrm{e}^{-\frac{12\,604}{T}} \tag{5}$$

Then, the empirical equation for the thickness calculation of NbC coating on 45 steel and 40Cr steel can be obtained. The coating thickness obtained from experiments is close to that estimated coating thickness d, which is calculated by Eq.(6) and Eq.(7), as follows:

$$d_{40\mathrm{Cr}}=1.61\times10^{-3}\sqrt{\mathrm{e}^{-\frac{13\,687}{T}}} \tag{6}$$

$$d_{45}=1.14\times10^{-3}\sqrt{\mathrm{e}^{-\frac{12\,604}{T}}} \tag{7}$$

The diffusion activation energies of NbC coating on 40Cr steel and 45 steel substrates are 113.80 and 102.76 kJ/mol, respectively. Compared with the experiment results in Ref.[4], these calculated results are reasonable. It can be seen that the diffusion coefficient D and the activation energy Q of NbC coatings on different substrates are obviously different, which indicates that the coating thickness not only is related to the treatment duration and temperature, but also depends on the chemical composition of the substrate. In the coating growth process, the substrate provides C element for the coating growth. In this research, the carbon contents of 45 steel and 40Cr steel are similar, but the content of Cr element in 40Cr steel is relatively higher. Cr element, a strong carbide-forming element, reduces the carbon activity in the substrate, increases the diffusion activation energy, and hinders the diffusion of carbon atoms from the substrate to the surface[17,27]. These phenomena result in different growth kinetics of NbC coating on different substrates.

2.3 Hardness and wear behavior of NbC coating

Friction tests were conducted on the steel substrates with and without the NbC coating prepared at 1273 K for 4 h. After the reciprocation wear test for 60 min, the coefficient of friction is shown in Fig. 10. It can be seen that the change trends of the coefficient of friction of different specimens are similar. The coefficient of friction increases rapidly at the initial stage (running-in period). Generally, the shorter the running-in period, the smaller the change range of the coefficient of friction, and the better the adaptability of material to friction. For the uncoated substrates, their running-in period is about 5 min. Then, the coefficient of friction increases gradually and fluctuates significantly in the subsequent stable stage, indicating that the substrate surface undergoes great changes in the whole wear test.

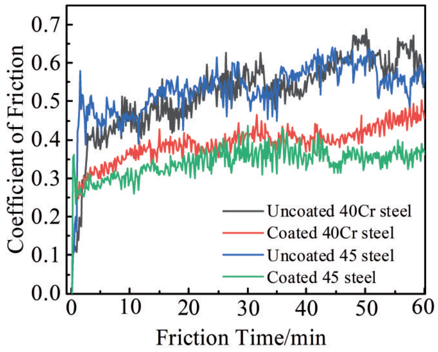

Fig.10 Coefficient of friction of different steel substrates with and without NbC coatings prepared at 1273 K for 4 h

The variation range of the coefficient of friction for the coated specimens is relatively small, indicating that the specimens are relatively stable during the wear process. The average coefficient of friction of the coated specimens is smaller than that of the uncoated substrate, indicating that the NbC coating improves the wear resistance of the steel substrates. The average coefficient of friction of the uncoated 40Cr steel and 45 steel substrates is 0.522 and 0.532, which is about 1.3 and 1.6 times high than that of the coated 40Cr steel (0.393) and 45 steel (0.342) substrates, respectively. The coefficient of friction of the NbC coating is similar to the experiment results (0.33) in Ref.[28]. The lower coefficient of friction can improve the tribological properties of material surfaces[29,30]. Although many other factors can also influence the coefficient of friction, such as contact area, types of grinding ball, and loading force[4,31-33], the NbC coating does enhance the wear resistance of steel substrates.

A white light interferometer was used to obtain the 3D topographies of the wear scars, as shown in Fig.11. It can be seen that the abrasion depth of uncoated 45 steel substrate is deeper than that of uncoated 40Cr steel substrate, indicating that the 40Cr steel has better wear resistance. The abrasion depth of the coated substrates is much smaller, compared with that of the uncoated ones. Additionally, the surface damage of the coated substrates is less severe than that of the uncoated ones.

The friction process mainly involves the interactions between the two materials, and the damage degree of the material surface also has a certain relationship with the friction pair[9]. Fig. 12 shows the morphologies observed by optical microscope (OM) of the grinding ball and the steel

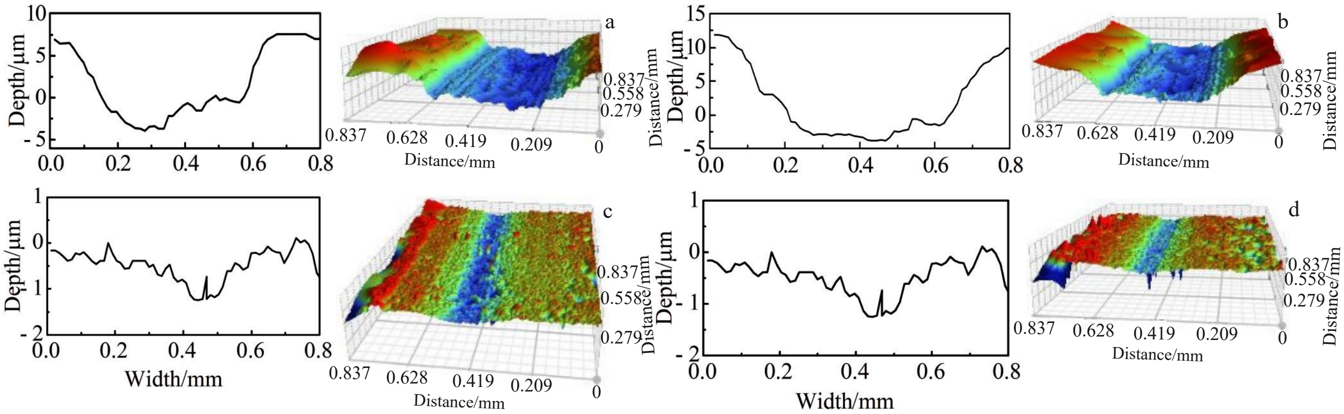

Fig.11 Topographies of 40Cr steel (a, c) and 45 steel (b, d) substrates without (a, b) and with (c, d) NbC coatings after friction tests

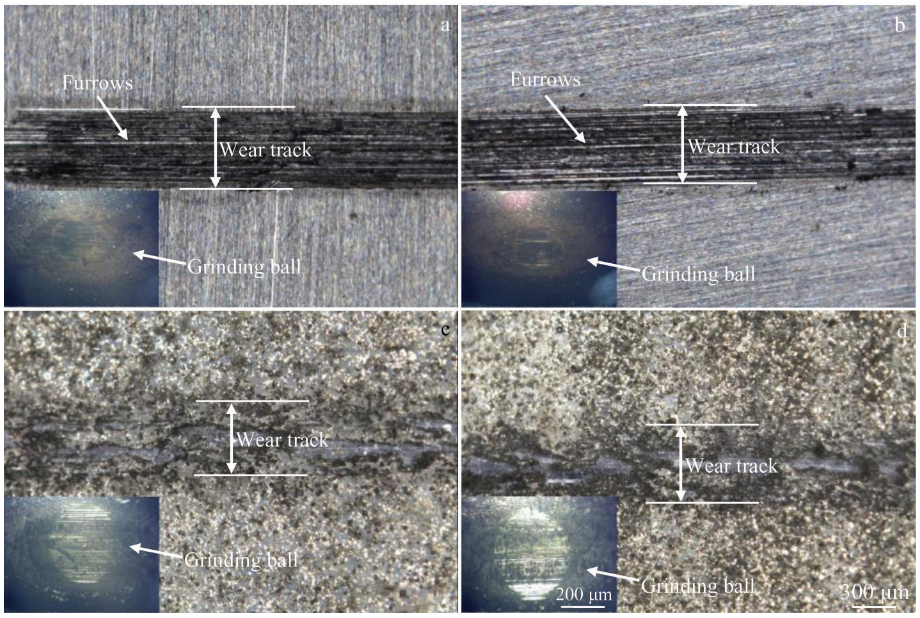

Fig.12 OM morphologies of 40Cr steel (a, c) and 45 steel (b, d) substrates without (a, b) and with (c, d) NbC coatings after friction tests

substrates with and without NbC coatings after the friction experiments to analyze the damage degree. According to the wear track, the damage degree of the uncoated steel substrates is more severe than that of the coated ones. Consequently, the damage degree of the grinding ball used for the coated steel substrates is more serious than that used for uncoated ones. The black particles on the specimen surface and the wear marks of the grinding ball are typical features of abrasive wear. As shown in Fig. 12a and 12b, the steel substrates without coating protection have severe surface damage: many furrows, scratches, and pits on the wear track.

The wear resistance of the material is also affected by the hardness. Fig.13 shows the volume wear rate and hardness of the steel substrates with and without NbC coatings. The hardness of uncoated 40Cr steel and 45 steel substrates is 4057±265 and 2813±304 MPa, respectively; whereas the hardness of the coated 40Cr steel and 45 steel substrates is increased to 22 266±1000 and 22 736±891 MPa, respectively.

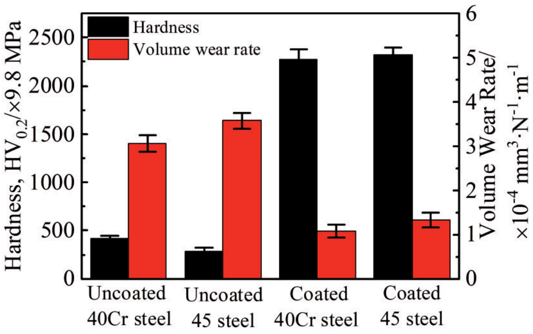

Fig.13 Hardness and volume wear rate of 40Cr steel and 45 steel substrates with and without NbC coatings prepared at 1273 K for 4 h

The hardness of 40Cr steel and 45 steel substrates with NbC coating prepared at 1273 K for 4 h is increased by 5.49 and 8.06 times, respectively. Since the hardness of the coated substrates is much higher than that of the uncoated ones, the damage to the grinding ball is more severe during the friction tests with the coated substrates. The volume wear rate of each specimen surface can better reflect the damage degree of the materials. The volume wear rate of the uncoated 40Cr steel and 45 steel substrates is (3.07±0.19)$\times 10^{-4}$ and (3.57±0.17)$\times 10^{-4}$ $mm^3 \cdot N^{-1} \cdot m^{-1}$, respectively. The volume wear rate of the coated 40Cr steel and 45 steel substrates under the same conditions is (1.07±0.15)$\times 10^{-4}$ and (1.33±0.17)$\times 10^{-4}$ $mm^3 \cdot N^{-1} \cdot m^{-1}$, respectively. Therefore, the specific wear rate of the NbC coating is only 34.9%~37.5% of that of the uncoated substrates.

The hardness of the coated 40Cr steel substrate is slightly lower than that of the coated 45 steel substrate, which may be due to the larger coating thickness of the 45 steel substrate. As shown in Fig. 13, the volume wear rate of the coated 45 steel substrate is higher than that of the coated 40Cr steel substrate. Therefore, the higher the hardness, the better the wear resistance. However, the wear resistance not only is affected by the hardness of coatings, but also depends on the hardness of the substrate. Since the mechanical properties of 40Cr steel substrate are better than those of the 45 steel substrate, the wear resistance of coatings on 40Cr steel substrate is better. Thus, the coated 40Cr steel substrate has the optimal wear resistance, followed by the coated 45 steel substrate, and the 45 steel substrate has the worst wear resistance. This result is consistent with the results in Fig 11.

The wear mechanism of materials is of great significance to the surface protection. As shown in Fig. 12, the particles, grooves, and scratches appear on the grinding ball and specimen surfaces after wear tests. These typical wear characteristics belong to the abrasive wear. The uncoated substrate directly contacts the grinding ball and causes damage during the friction process. It can be concluded that the original substrate has weak adaptability to the friction process, which causes the great fluctuation of the coefficient of friction of the steel substrate during the friction process. Therefore, at the beginning of the friction test, the grinding ball can easily cause damage on the substrate surface, resulting in the shedding of surface material. In the process of subsequent reciprocation friction, some flakes may rub against the ball and are transformed into the fine hard particles, namely abrasive dust or debris. The debris can adhere to the material surface during the friction, causing adhesive wear[22,26], which can be observed on the wear scar of material surface. The surface of the coated specimens is slightly worn, and the shedding of coating occurs in several places with delamination. Thus, the coating improves the wear resistance of material, and in addition to the abrasive wear and adhesive wear, many other wear mechanisms act together during the friction.

Fig. 14 shows SEM wear morphologies of wear tracks of 40Cr steel substrates without and with NbC coating to analyze the wear mechanism of NbC coating. There are many abrasive particles on the abrasion marks. The significant grooves appear in the severely damaged areas during the wear and tear process, and some small furrows appear in the slightly worn areas, which are the main causes for coating delamination. These features all indicate the abrasive wear. Table 4 presents the element composition of different regions in the coated 40Cr steel substrate, which suggests that the obvious oxidation occurs during the friction process. It is also proved

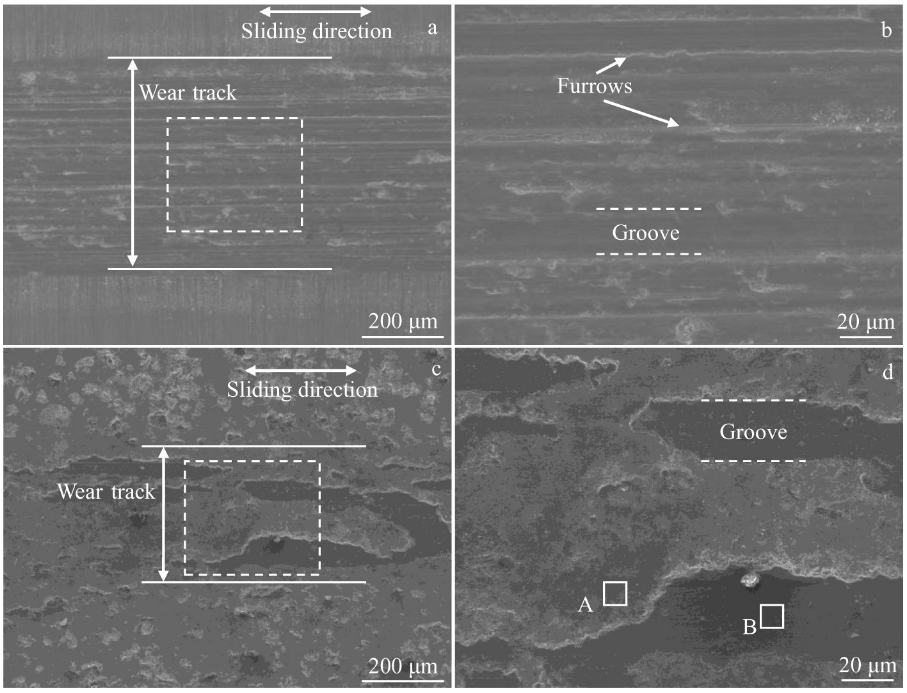

Fig.14 SEM wear morphologies of wear tracks of 40Cr steel substrates without (a) and with (c) NbC coating; magnified images of dotted rectangular areas in Fig.14a (b) and Fig.14c (d)

Table 4 EDS results of region A and region B in Fig.14d (wt%)

Region	C	O	Fe	Nb
A	16.42	15.77	3.89	63.91
B	7.47	24.53	64.23	3.77

that the prominent surface is rich in C and Nb and the dark surface layer is rich in oxygen and iron. The difference in oxygen content in different areas indicates that the substrate is more vulnerable to oxidative wear damage in the friction process after the coating failure. Therefore, the wear mechanism of NbC coating in the friction process is mainly the abrasive wear and oxidation wear. It is reported that the failure mechanism of 45 steel with NbC coating during friction is the abrasive wear[28,34]. In the slow reciprocation friction experiment, the surface can be easily oxidized due to the cyclic reciprocation friction. Therefore, the wear mechanism of 45 steel with NbC coating is abrasive wear and oxidation wear.

3 Conclusions

1) The compact NbC coatings can be obtained on the surface of different steel substrates after pack cementation at 1273 K for 4 h. The average grain size of NbC coatings is 0.14±0.006 and 0.17±0.010 μm on 40Cr steel and 45 steel substrates, respectively. Under the same process parameters, the thickness of NbC coatings on 45 steel substrate is greater than that on 40Cr steel substrate.

2) The thickness of NbC coating is increased with prolonging the treatment duration and increasing the treatment temperature. The thickness of NbC coating has a parabolic relationship with duration in the pack cementation process, and the activation energies of NbC coating on 40Cr steel and 45 steel substrates are 113.80 and 102.76 kJ/mol, respectively.

3) The NbC coating significantly improves the wear resistance of the steel substrates. The hardness of NbC coating prepared at 1273 K for 4 h is basically higher than 21 560 MPa. The specific wear rate of NbC-coated substrates is only 34.9%~37.5% of that of the uncoated ones. The wear mechanism of NbC coating in the friction process is mainly abrasive wear, adhesive wear, and oxidation wear.

References

1 Cai X L, Xu Y H, Zhong L S *et al. Vacuum*[J], 2015, 119: 239

2 Fan X S, Yang Z G, Zhang C *et al. Surface and Coatings Technology*[J], 2010, 205(2): 641

3 Orjuela G A, Rincon R, Olaya J J. *Surface and Coatings Technology*[J], 2014, 259(C): 667

4 Soltani R, Sohi M H, Ansari M *et al. Vacuum*[J], 2017, 146: 44

5 Zhang X, Tian X B, Zhao Z W *et al. Surface and Coatings Technology*[J], 2019, 364: 135

6 Shan Z J, Pang Z G, Luo F Q *et al. Surface and Coatings Technology*[J], 2012, 206(19-20): 4322

7 Cai X L, Xu Y H, Zhao N N *et al. Surface and Coatings Technology*[J], 2016, 299: 135

8 Fernandes F A P, Gallego J, Picon C A *et al. Surface and Coatings Technology*[J], 2015, 279: 112

9 Sen S, Sen U. *Wear*[J], 2008, 264(3-4): 219

10 Sen U. *Thin Solid Films*[J], 2005, 483(1-2): 152

11 Cao Y B, Ren H T, Hu C S *et al. Materials Letters*[J], 2015, 147: 61

12 Li Q T, Lei Y P, Fu H G. *Surface and Coatings Technology*[J], 2014, 239: 102

13 Li Q T, Lei Y P, Fu H G. *Journal of Materials Science & Technology*[J], 2015, 31(7): 766

14 Kim K W, Kim B J, Lee S H *et al. Coatings*[J], 2018, 8(11): 379

15 Mesquita R A, Schuh C A. *Surface and Coatings Technology*[J], 2012, 207: 472

16 Shen L L, Xu Y H, Zhao N N *et al. Journal of Materials Engineering and Performance*[J], 2016, 26(1): 34

17 Liu X J, Wang H C, Li D W *et al. Surface and Coatings Technology*[J], 2006, 201(6): 2414

18 Oliveira C K N, Benassi C L, Casteletti L C. *Surface and Coatings Technology*[J], 2006, 201(3-4): 1880

19 Sen U. *Materials Chemistry and Physics*[J], 2004, 86(1): 189

20 Yan S J, Wang H F, Sun Q K *et al. Journal of Wuhan University of Technology* (*Materials Science Edition*)[J], 2014, 29(4): 808

21 Xu Y X, Lu J T, Li W Y *et al. Corrosion Science*[J], 2018, 140: 252

22 Zhang J, Li S, Lu C F *et al. Surface and Coatings Technology*[J], 2019, 364: 265

23 Kumar M, Kumar A, Abhyankar A C. *ACS Applied Materials & Interfaces*[J], 2015, 7(6): 3571

24 Pandey A, Dalal S, Dutta S *et al. Journal of Materials Science: Materials in Electronics*[J], 2021, 32(2): 1341

25 Matijevic B. *JOM*[J], 2013, 65(11): 1395

26 Sun C Y, Xue Q, Zhang J *et al. Vacuum*[J], 2018, 148: 158

27 Fan X S, Yang Z G, Xia Z X *et al. Journal of Alloys and Compounds*[J], 2010, 505(1): L15

28 Li S, Wang R K, You Z Y *et al. Materials Research Express*[J], 2019, 6(11): 116 455

29 Katiyar P K. *International Journal of Refractory Metals & Hard Materials*[J], 2020, 92: 105 315

30 Sabzi M, Dezfuli S M, Far S M. *Ceramics International*[J], 2018, 44(18): 22 816

31 Azizpour M J, Tolouei-Rad M. *Ceramics International*[J], 2019, 45(11): 13 934

32 Lu J Z, Cao J, Lu H F *et al. Surface and Coatings Technology*[J], 2019, 369: 228

33 Wang W, Zeng X, Li Y L *et al. Materials Characterization*[J], 2017, 134: 182

34 Zhang J, Li S, Sun Q L *et al. Materials Research Express*[J], 2019, 6(9): 96 432

粉末包埋法制备NbC涂层在不同钢基体上的生长动力学和摩擦性能

冉雪林[1]，张　进[1]，王　伟[2]，巩秀芳[2]，涂叶鹏[1]，郭孟鑫[1]，李松霞[1]

(1. 西南石油大学 新能源与材料学院，四川 成都 610500)

(2. 东方汽轮机有限公司，四川 德阳 618000)

摘　要：采用粉末包埋法，以铁铌粉、氯化铵和氧化铝为主要原料，在不同温度（1123~1273 K）、不同处理时长（1~4 h）下分别研究了NbC涂层在40Cr和45钢上的生长动力学过程及摩擦磨损性能。结果表明：涂层结构致密且与基体界面结合良好，主要由NbC相组成。在40Cr和45钢基体上，涂层厚度分别为1.703±0.285~8.457±0.240和1.987±0.355~9.247±0.275 μm。生长动力学研究表明，涂层生长受扩散过程控制，厚度与时间呈抛物线变化关系；在40Cr和45钢基体上，NbC相生长过程的活化能分别为113.80和102.76 kJ/mol。在1273 K下保温4 h，NbC涂层的硬度可达21 560 MPa以上，为钢基体硬度的5.49~8.06倍。以GCr15钢球作为对磨材料，测得40Cr/NbC和45钢/NbC材料的平均摩擦系数分别为0.393和0.342，而基体的平均摩擦系数为NbC涂层的1.3~1.6倍。NbC涂层的体积磨损率约为钢基体的34.9%~37.5%，表明NbC涂层具有优异的耐磨减磨性能，其摩擦磨损机理主要是磨粒磨损、粘着磨损和氧化磨损。

关键词：粉末包埋法；NbC涂层；不同基体；生长动力学；摩擦

作者简介：冉雪林，男，1996年生，硕士，西南石油大学新能源与材料学院，四川 成都 610500，E-mail：201922000006@stu.swpu.edu.cn