Effect of Heat Treatment on the Microstructure and Wear Resistance of NiCrMoV Steel

Hongxing Wang\textsuperscript{a, b, *}, Zhangzhong Wang\textsuperscript{a, b}, Yajun Xue\textsuperscript{b}, Cangsheng Wang\textsuperscript{b}, Zhe Lv\textsuperscript{b}, Bao Yue\textsuperscript{b}

\textsuperscript{a}Key Laboratory of Advanced Structural Materials and Application Technology of Jiangsu Province, 1Hongjing Avenue, Nanjing 11167, PR China
\textsuperscript{b}School of Materials Science and Engineering, Nanjing Institute of Technology, 1Hongjing venue, Nanjing 211167, PR China
Email: wanghx@njit.edu.cn

Abstract. The effect of an applied load within a 50-200 N range, speed of 10-45 mm/s, and sliding of 10-120 min on the wear behavior of a NiCrMoV low alloy steel quenched in air at 1123-1323 K, followed by tempering at 873 K, was investigated. The material’s microstructure was further studied. The wear was measured using a ball-on-disc type wear machine at room temperature under dry sliding conditions. The micromorphology, worn surface and debris were investigated using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The results indicate that all the tempered specimens’ microstructure of the NiCrMoV low alloy steel consists of ferrite and carbide and that the grain size increases with an increase in quenching temperature. The friction coefficient and mass loss increased with an increase in the applied load, the sliding speed and time, as well an increase in quenching temperature. The friction coefficient and mass loss significantly increased at a load of 200 N. The worn surface of all the specimens revealed a discontinuous adherent layer. Furthermore, the microstructure revealed that the specimens underwent a combination of delamination, plastic deformation, fatigue, and oxidation. The wear mechanism involves predominantly adhesion with a mixture mode of abrasive, adhesion, and oxidation.

1. Introduction
With the increasing velocity of railway passenger vehicles, rising demands for stable and reliable braking systems are being pushed forward. The braking process is a complex phenomenon and involves many activities like transforming kinetic energy into frictional heat, wear at the contract surface, and friction-induced noise.

Efforts are being undertaken to enhance the riding quality of passengers, especially during emergency braking. A number of research investigations are working to improve the reliability of brake disc material. For example, Samrout and El Abdi [1, 2] have studied the fatigue behavior of the brake disc steel for French T.G.V. under thermal mechanical cyclic loadings. An anisothermal elastoplastic model was proposed to predict the brake disc response. Dufrénoy et al. [3, 4] investigated the damage mechanisms of brake discs. Zhiqiang Li et al. [5] studied the fracture behavior of brake disc steel in low cycle fatigue tests under different temperatures, and simultaneously observed changes in the microstructure and crack initiation in hot spot regions under cyclic tensile tests. S.C. Wu et al. [6] predicted peak temperatures and macroscopic hot spots under consecutive emergency braking using a novel extended finite element method (XFEM) and crack tip region meshing refinements based on virtual-node polygonal finite element method (VPM). Additional work [7, 8] has been published for information on the design and regular maintenance of high-speed railway brake discs.
Railway brakes pad/disc systems must have good wear resistance, a stable coefficient of friction during service, high thermal conductivity, and low thermal expansion properties. To the best of our knowledge, no previous investigations have examined the effect of quenching temperature on the wear and friction of a NiCrMoV low alloy steel. Accordingly, the present work was undertaken to produce cast steel using a low-cost sand casting technique. The influence of an applied load range of 50-200 N, speed of 10-45 mm/s, and sliding time of 10-120 min on the tribological behavior of the NiCrMoV cast steel after heat treatment was investigated. The worn surface and debris were additionally studied to ascertain the wear mechanism.

2. Experimental
Specimens were taken from NiCrMoV low alloy steel prepared by sand cast method, with a chemical composition (wt%): C 0.19, Si 0.35, Mn 0.75, Ni 1.15, Cr 1.20, Mo 0.52, V 0.25, Ti 0.02, and the balance Fe. The specimens were heat treated (850-1050°C×1h in air quenched, and 600°C×1 h tempered). Prior to heat treatment, the specimens were cut into a 15 mm×10 mm×6 mm size. The rockwell hardness was measured using a Rockwell hardness instrument (HR-150) at a load of 150 kg and dwell time of 15 s. Wear tests were conducted using an MFT-3000 type ball-on-disc tribometer instrument. The specimens were etched with 4% nital to investigate their microstructure using scanning electron microscopy (SEM. JSM-6380LV), equipped with energy dispersive spectroscopy (EDS). The worn surface and debris were also studied using these methods.

3. Results and Discussion
3.1 Effect of Quenching Temperature on Microstructure of NiCrMoV Steel
The microstructure of the NiCrMoV cast steel and heat-treated steels are shown in Fig.1. The microstructure of the as-cast specimen exhibited polygonal ferrite and granular carbide as a mixture of ferrite and second constituents (Fig. 1(a)). After quenching at different temperatures followed by tempering at 873 K, the ferrite maintained the parallel orientation of the quenched martensite. This alignment formed during the rapid cooling process from the austenitizing temperature. It was discovered that the lath size increased with an increase in the quenching temperature. Conversely, the bulged grain boundaries appeared when the quenching temperature reached 1323 K. It is possible that the precipitates appear less frequently at higher quenching temperatures, where there is less grain boundary restriction movement and therefore the boundaries exhibit bulging (Fig. 1(f)).
Figure 1. SEM micrographs of the (a) as-cast and at different air quenching temperature (b) 1123K; (c) 1173K; (d) 1223K; (e) 1273K; (f) 1323K (Corresponding higher magnification images is shown in inset).

3.2 Effect of Quenching Temperature on Hardness of NiCrMoV Steel
The hardness of the heat-treated specimens under various quenched conditions are provided in Fig. 2. It was observed that the hardness first increased and then decreased with an increase in the quenching temperature. The hardness of the heat-treated specimens reached its maximum value when quenched at 1223 K. The effect of the solid solution strength dominates over the increase in grain size and the lath width with increases in quenching temperature; these competing influencing effects led to an increase in hardness. The hardness of the heat-treated specimens is affected not only by the microstructure, but also by the amount of carbon and alloying elements in the martensite and residual austenite. When quenched at a lower temperature, there is less carbon and fewer alloying elements dissolved in the austenite. In this manner, the amount of saturated carbon and alloying elements in the martensite after quenching was small, resulting in the material’s low hardness following tempering. When the quenching temperature exceeds 1223 K, there are too much carbon and alloying elements dissolved in the austenite, and the austenite becomes stable with a decrease of the Ms point. This results in additional residual austenite in the microstructure after quenching and the material’s decreased hardness.
3.3 Effect of Applied Load on Wear Resistance of NiCrMoV Steel

Fig. 3 shows the friction coefficients of the as cast and heat-treated materials at the same sliding time in the case of 30 mm/s sliding velocity. Additionally, 50 N, 100 N, 150 N, and 200 N applied loads are shown in Fig. 3(a)-(d). As seen in Fig. 3, the average friction coefficient of the specimens quenched at 1123K, 1173K, 1223K exhibited a slight increase at an applied load from 50 N to 150 N. Conversely, specimens quenched at 1273K and 1323K exhibited a light decrease. The average friction coefficient of all heat treated specimens increased when the applied load exceeded 150 N. On the other hand, the average friction coefficient increased with an increase in quenching temperature, as shown in Fig. 3(a). The mass loss of all specimens increased with an increase in the applied load, as shown in Fig. 3(b).

Generally, when the applied load increased, the friction coefficient decreased. This is expected behavior for metal-metal sliding contact since the applied load leads to increased oxidation of the metal surface. Uyyuru et al. [9] reported that with increases in the normal load, the friction coefficient decreases i.e. inverse proportionality exists between the applied normal load and the measured friction coefficient. Although increasing the applied load results in a decrease in the friction coefficient, a slight increase in the friction coefficient was seen when the applied load reached 200N for all specimens. This is believed to be caused by an insufficient amount of tribolayer formation between the sliding interfaces. Similar observations were reported by Natarajan et al. [10] They observed a higher friction coefficient at low applied loads when compared with friction coefficient values observed at high applied loads. This is a result of the transfer film’s stability during sliding up to long distances; therefore, this temperature increment is also small at low loads; whereas, at high loads, the transfer film is destroyed at a faster rate and the temperature increase is also high.

Figure 2. Influence of quenching temperature on rockwell hardness

Figure 3. Influence of applied load on friction coefficient (a)50N; (b)100N; (c)150N; (d)200N
Micrographs are presented in Fig. 4(a)-(d) for the worn surface of the specimen quenched at 1323 K followed by tempering at 873 K under applied loads ranging from 50 N to 200 N with a sliding velocity of 30 mm/s. Differences in appearance between the worn surface of the specimen at low and high loads can be observed. The worn surface of the specimen exhibited mild deformation and a flat adherent layer with slight grooves under a load of 50 N, as shown in Fig. 4(a). A great deal of loose wear debris additionally covered the worn surface. Such features can often be linked to adhesive wear, caused by the ploughing and micro-cutting of hard asperities on the steel counter-face, or detached particles that were removed from the specimen which are then retained at the contact surface.

As the applied load reached 100 N, the worn surface became smooth, with small and shallow delamination craters appearing on the worn surface. Simultaneously, it can be seen that the wear debris was pushed along the sliding direction by the steel ball squeezing into the soft matrix, as shown in Fig. 4(b). As the applied load reached 150 N, the worn surface became smoother than that of the applied load at 100 N, and deeper delamination craters appeared on the worn surface. Moreover, plastic deformation increased and some cracks grew (Fig. 4(c)). When the applied load was increased to 200 N, the worn surface became rough and broken under the high normal and shear force through the steel ball, as shown in Fig. 4(d). These clues suggest the transition from mild to severe wear. Consequently, the friction coefficient and mass loss of the specimen abruptly increased, as shown in Fig. 3.

![Figure 4. SEM images of worn surface for specimen quenched at 1323 K followed by tempering at 873 K under different applied loads (a)50N; (b)100N; (C)150N; (d)200N](image)

Fig. 5 shows SEM micrographs of the typical worn debris morphologies and EDS analysis of region “A–C” of the specimens quenched at 1323 K at applied loads of 100 N, 200 N, and quenched at 1123 K at an applied load of 200 N at a 30 mm/s sliding velocity. It can be seen from Fig. 5(a) that the shape of the debris morphologies consists of particles with different sizes and irregular lumps. The size of the lumps debris increased with an increase in the applied load from 100 N to 200 N, as shown in Fig. 5(e). This increase in the applied load resulted in an increase in plastic deformation; further, the adherent layer on the worn surface was prone to fracture and was removed under the higher shear force.

As shown in Fig. 5(e), the size of the debris morphologies of the specimen quenched at 1123 K was smaller than that quenched at 1323 K under the same applied load. The reason for the difference in the debris size is possibly the amount of carbide present and the underlying microstructure.

The EDS analysis of the wear debris formed under applied loads of 100 N and 200 N, denoted areas A and B, are depicted in Fig. 5(b),(d),respectively. It can be seen that the O content in the wear...
debris increases slightly with an increase in the applied loads. Conversely, there is a clear increase in the Cr content of the wear debris. This is because of the serious wear on the surface of the steel ball under an applied load of 200 N.

![Figure 5. SEM images of wear debris morphologies and EDS analysis of the test specimen quenched at 1323K at applied load 100N (a)(b), 200N (c)(d), and quenched at 1123K at applied load 200N (e) (f) at 30mm/s sliding velocity](image)

### 3.4 Effect of Sliding Speed on Wear Resistance of NiCrMoV Steel

Fig. 6 shows the influence of the sliding speed on the friction coefficient for heat treated specimens under a fix applied load of 100 N and a sliding time of 10 min. As can be seen in Fig. 6(a), the average friction coefficient of all heat-treated specimens exhibited a slight increase with increasing sliding speed. When the sliding speed exceeded 30 mm/s, the increasing trend of the average friction coefficient became clearer. The mass loss of all specimens linearly increased with increasing sliding speeds, as shown in Fig. 6(b).
Figure 6. Influence of sliding velocity on friction coefficient (a) 20mm/s; (b) 45mm/s

Micrographs of the worn surface of specimen quenched at 1223 K, tempered at 873 K under a 100 N applied load, underwent sliding for 10 min, and sliding velocities of 10 mm/s and 45 mm/s, are presented in Fig. 7. The worn surface of the specimen reveals an incomplete and smooth adherent layer at a sliding speed of 10 mm/s, as shown in Fig. 7(a). These features are typical adhesive wear characteristics. The wear debris formed under micro-cutting and pushing of the tiny bugle of the steel ball. Part of the wear debris was pushed to the edge of the worn surface by the steel ball, and the other debris was pressed onto the contact surface by the steel ball. The adherent layer formed on the worn surface during dry friction. Due to the inhomogeneous microstructure of the specimen, part of the adherent layer formed on the worn surface detached and fell off under shear stress. At low sliding speeds, the damaged surface cannot be filled by new wear debris. This resulted in the formation of an incomplete surface. At a high sliding speed, the damaged surface was packed with new wear debris, and formed a relatively complete surface.

Figure 7. SEM images of worn surface for specimen quenched at 1123 K followed by tempering at 873 K under different applied speeds(a)10mm/m;(b)45mm/s

Fig. 8 shows the micrographs and EDS analysis of worn debris marked region “A,B” of the specimens quenched at 1323 K. Compared with the wear debris formed at a sliding speed 10 mm/s, the amount of wear debris with a larger size significantly increases when the sliding speed reached 40mm/s. The interface temperature increased with an increasing sliding speed during the dry friction test [11].

The higher interface temperature contributed to the increase in resistance on the sliding interface. Accordingly, the shear stress on the worn surface also increased, and the possibility of larger debris formation greatly increased.

The EDS analysis of area A and B depicted in Fig. 8(a), (c) is given in Fig. 8(b), (d). It can be seen that the O content in the granular wear debris increased with increasing sliding speed, as well as Cr content. This is because of the oxidation wear on the surface of the wear surface due to the accumulation of the frictional heat under an applied load of 200 N at 45mm/s.
3.5 Effect of Sliding Time on Wear Resistance of NiCrMoV Steel

The effect of sliding time on the average coefficient and mass loss of the heat-treated specimens subjected to a constant sliding speed of 30 mm/s and a fixed applied load is presented in Fig. 9. As can be seen, the average friction coefficient of specimens quenched at 1123 K, 1223 K, 1773 K, and 1323 K significantly increased within a sliding time of 30 min. When the sliding time exceeded 30 min, the average friction coefficient did not exhibit an increase. Within 30 min of sliding time, the average friction coefficient of the specimen quenched at 1173 K increased with increasing sliding time. When the sliding time exceeded 60 min, the average friction coefficient of the specimen decreased, as shown in Fig. 9(a). On the other hand, the mass loss increased with an increase in sliding time (Fig. 9(b)).

Figure 8. SEM images of wear debris morphologies and EDS analysis of specimen quenched at 1223K at applied load 100N for 10 min (a), (b) 10 mm/s; (c), (d) 45mm/s

Figure 9. Friction coefficient and mass loss under different sliding time: (a) average friction coefficient; (b) mass loss
The micrographs of the worn surface of the specimen quenched at 1173 K, tempered at 873 K under an applied load of 100 N, sliding velocity of 30 mm/s, and sliding time from 20 to 120 min, are presented in Fig. 10. The surface morphology predominantly consists of a deformed and exfoliated adherent layer, as shown in Fig. 10(a)-(d). It also can be seen that the thickness of the adherent layer retained on the worn surface decreases with increasing sliding time in the process of the dry sliding friction.

Figure 10. Morphologies of the wear tracks of samples quenched at 1123 K followed by tempering at 873K with different sliding time: (a) 20 min; (b) 30 min; (c) 60 min; (d) 120 min

Fig. 11 shows the micrographs and EDS analysis of worn debris marked regions “A, B” of the specimens quenched at 1173 K. Compared with the wear debris formed after sliding for 60 min, the amount of wear debris with a larger size significantly increases when the sliding time reached 120 min. Frictional heat continuously built-up on the surface, which contributed to the increase of the interfacial temperature for the long-term dry friction. The higher temperature on the worn surface resulted in severe plastic deformation and increased frictional resistance. This increased the possibility of forming thinner and bigger wear debris. This is also the main reason for the mass loss and increased friction coefficient with increase in sliding time.

The EDS analysis of area A and C depicted in Fig. 11(a), (c) is given in Fig. 11(b), (d). It can be seen that the O content in the granular wear debris increased with increasing sliding time, as well as the Cr content. This is because of the oxidation wear on the surface of the steel under an applied load of 150 N for 120 min.
4. Conclusions
A NiCrMoV low alloy steel was subjected to varying quenching temperatures in the 1123 K-1323 K range.
(a) The hardness first increased with an increase in the quenching temperature and then decreased due to a decrease in the amount of carbide and an increase in grain size.
(b) The average friction coefficient and mass loss of the heat-treated specimens increased with increasing applied load from 50 N to 200 N, sliding speed from 10 mm/s to 45 mm/s, and sliding time from 10 to 120 min, and quenching temperature. The specimen quenched at 1123 K exhibited the best wear resistance.
(c) The wear mechanism involves mainly adhesion wear with a mixture of abrasive, adhesion, and oxidation modes.

5. Acknowledgements
The work was financially supported by Major projects of key research and development plan of Jiangsu province (industry foresight and common key technology) (Grant No.BE2015031) and Open foundation of Jiangsu Key Laboratory of advanced structural materials and Applied Technology (Grant No.ASMA201506), Outstanding scientific and technological innovation team in Colleges and Universities of Jiangsu Province.

6. References
[1] Samrout H, Abdi R EL, 1998 J int. J. Fatigue, 20 555
[2] Samrout H, Abd R EL, Chaboche J L, 1997 J Int. J. Solids Structure, 34 4547
[3] Dufrénoy P, Weichert D, 2003 J Journal of Thermal Stresses, 26 815
[4] Dufrénoy P, Bodovillé G, Degallaix G, 2002 J European Structural Integrity Society, Elsevier, pp 167
[5] Li Z Q, Han J M, Yang Z Y, Li W J, 2015 J Engineering Failure Analysis, 57 202
[6] Wu S C, Zhang S Q, Xu Z W, 2016 J Int. J. Fatigue, 87 359
[7] Oomen-hurst S, Abad, M. Khanna M D, Veldhuis S C, 2012 J Tribol. Int., 53 115
[8] Salemi A, Abdollah-zadeh A, 2008 J Mater. Charact., 59 (4) 484
[9] Uyyuru R K, Surappa M K, Brusethaug S, 2007 J Tribol. Int., 40 365
[10] Natarajan N, Bilayarangan S, Rajendran I, 2006 J Wear, 161(7/8) 812
[11] Liew K W and Nirmal U, 2018 J Mater. Desi., 48 25