Analysis of microstructure and wear resistance of NM400 thick plate

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Abstract. The hardness distribution and microstructure morphology of NM400 low alloy wear resistant steel plate with thickness of 50mm and 60mm were tested and analyzed, and the sliding wear performance of typical measuring points was also analyzed. The results show that the depth of the NM400 (50mm) hardening layer is about 35mm, accounting for about 70% of the plate thickness. The depth of the NM400 (60mm) hardening layer is about 22mm, accounting for about 37% of the plate thickness. With the position of the measuring point gradually away from the surface of the steel plate, the martensite content in the microstructure of NM400 (50mm) and NM400 (60mm) gradually decreased, and the contents of pearlite, bainite and other microstructure gradually increased. The hardness of NM400 (50mm) gradually decreased from 410HV to 335HV, and the hardness of NM400 (60mm) gradually decreased from 410HV to 305HV. The micro-wear morphologies of NM400 (50mm) and NM400 (60mm) at each measuring point are mainly furrow and contact fatigue spalling, and the wear types are mainly abrasive wear and contact fatigue wear. The furrow depth and the number of furrows on the worn surface of the sample at the corresponding measuring point position gradually increased as the measuring point position moved away from the steel plate surface, and the spalling area and the depth of the spalling pit gradually increased. The wear type gradually changed from particle wear to contact fatigue wear.

1. Introduction

The three most common failure forms of metallic materials are wear, corrosion and fatigue. According to incomplete statistics, about 30% of China's energy is consumed in different forms of wear and tear every year, which not only leads to serious consumption of energy and resources, but also causes huge losses to the national economy [1-3]. Low alloy wear resistant steel not only has the characteristic of high hardness, high strength and good toughness, but also has less alloy content and relatively low economic cost. Therefore, it is widely used in the manufacturing of machinery and equipment of mining, coal mining and transportation industries. In recent years, with the development of coal mining and transportation equipment towards large scale and high efficiency, the size of wear-resistant components also increase gradually. However, the wear resistant steels of large specifications used at present are usually characterized by low hardness, poor hardenability and poor comprehensive performance [4, 5]. Therefore, in order to meet the production requirements of large size wear resistant components, it is
necessary to develop thick wear resistant steel with good comprehensive performance. In this paper, the hardness distribution, microstructure and wear resistance of the thick NM400 low alloy wear resistant steel produced by a domestic iron and steel enterprise are studied and analyzed, which provide relevant data support for the development of the thick low alloy wear resistant steel with good comprehensive performance.

2. Test materials and methods
The test material is NM400 low alloy wear-resistant steel produced by a domestic steel plant. The plate thickness is 50mm and 60mm respectively. The chemical composition is shown in Table 1.

|       | C   | Si  | Mn  | P   | S   | Cr  | Mo  | B   | Ti  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.16  | 0.20| 1.40| 0.01| 0.002| 0.20| 0.20| 0.001| 0.02|

Four sets of 10mm×10mm×50mm (plate thickness direction) and 10mm×10mm×60mm (plate thickness direction) were cut out from NM400 (50mm) and NM400 (60mm) test steels by wire-cutting for standby use. After grinding the decarburized layers at both ends of the samples and grinding the sides, the hardness distribution of the samples along plate thickness direction was measured by Wilson 402-MVD Vickers microhardness tester, and the average value of three groups of data was taken as the final hardness at each measuring point. After grinding, polishing, cleaning, drying and etching the sides of a group of samples, the microstructure of the samples at typical measuring points was observed respectively by JSM-7610F scanning electron microscope. The corrosive agent was 4% alcohol nitrate solution. A group of samples were taken and the sides were polished, cleaned and dried and weighed. Rtec MFT-5000 multifunctional friction and wear testing machine was used to conduct reciprocating sliding wear experiment on typical measuring points of the samples. The grinding material was GCr15 steel ball (hardness about 750HV), the load was 50N, the reciprocating stroke was 4.5mm, the reciprocating frequency was 4HZ, and the wear time was 45min. After the wear, the sample is cleaned, dried and weighed to calculate the loss of wear. The macroscopic three-dimensional wear morphology was observed by USP-Sigma white light interferometer, and the microscopic wear morphology was observed by JSM-7610F scanning electron microscope.

3. Test results and analysis
The microstructure morphology of the typical measuring points of the two samples is shown in Fig. 1. It was found that the microstructure of the two samples was typical lath martensite structure. At 1/4 plate thickness, the microstructure of the NM400 (50mm) sample was mainly mixed with martensite and bainite, while the microstructure of the NM400 (60mm) sample was mainly mixed with martensite, bainite and a small amount of pearlite. At 1/2 plate thickness, the microstructure of NM400 (50mm) sample was mainly pearlite and a small amount of mixed microstructure of bainite and martensite, while the microstructure of NM400 (60mm) sample was mainly pearlite.
The hardness distribution of the two samples along the thickness of the plate is shown in Fig.2. It was found that the hardness of the surface position of the two samples and that of the 1/2 plate thickness position were significantly different, which was mainly caused by the obvious difference in the microstructure formed by the different cooling rates along the thickness direction during the quenching process of the test steel \[6,7\]. As shown in Fig.2 (a), the hardness distribution of sample NM400 (50mm) along the direction of plate thickness can be roughly divided into three parts. Part A (hardening layer) of the hardening layer from 0 to 18 mm steel plate surface, 33-50 mm, the highest hardness is about 410 HV, the hardness is relatively stable, combined with Fig.1 (a) shows that the quenching cooling rate of the measuring point location in the induce martensitic phase transformation were greater than the critical cooling rate, the microstructure formed by almost all of the martensite structure, higher hardness. Part B from 18 to 22 mm steel plate surface, 28-33 mm, the part by about 410 HV hardness rapidly dropped to about 335 HV, change relatively quickly, according to Fig.1 (b), the part of each measuring point location is far away from the steel surface, and quenching cooling rate gradually decreased, when martensite phase transformation occurs at the critical cooling rate, microstructure of the martensite structure content gradually decreases, the bainite and pearlite content increases, the hardness decreases rapidly. Part C is 22-28mm away from the surface of the steel plate, with the lowest hardness and only about 335HV, which is relatively stable. Combined with Fig.1 (c), it can be seen that all measuring points in this part are relatively far from the steel plate surface, and the quenching cooling rate is lower than the critical cooling rate of martensitic phase transition. The martensitic structures in the microscopic structure almost all disappeared, mainly pearlite and a small amount of bainite, with low hardness \[8-10\]. As shown in Fig. 2 (b), the hardness distribution of sample NM400 (60mm) along the thickness of the plate is similar to that of sample NM400 (50mm), which will not be repeated here. It should be noted that the hardness of part A (hardened layer) of sample NM400 (60mm) is similar to that of sample NM400 (50mm), but the depth is far less than that of sample NM400 (50mm). In addition, the depth of parts B and C of NM400 (60mm) is much higher than that of NM400 (50mm), but the hardness is much lower than that of NM400 (50mm). Combined with Fig. 1 and Fig. 2, it can be concluded that the depth of NM400 (50mm) hardening layer is about 35mm, accounting for about 70% of the overall plate thickness. The depth of the NM400 (60mm) hardening layer is about 22mm, accounting for about 37% of the overall plate thickness.
The wear loss at typical measuring points of the two samples is shown in Fig.3. It can be found that with the position of the measuring point gradually away from the surface of the steel plate, the wear loss of the sample at the corresponding position also increases gradually. In addition, it is found that the wear loss of sample NM400 (60mm) is slightly larger than that of sample NM400 (50mm) at each typical measuring point.

The three-dimensional macroscopic wear morphologies of typical measuring points of the two samples are shown in Fig.4. It can be found that the macroscopic wear morphologies of the samples at all measuring points are approximately "U", and with the measurement points gradually moving away from the steel plate surface, the width and depth of the wear marks at the corresponding positions of the samples gradually increase. In addition, it can also be found that the roughness inside the grinding mark corresponding to the position of the sample also increases gradually with the position of the measuring point gradually away from the surface of the steel plate.
Fig 4. Three-dimensional macroscopic wear morphology of test steel. (a, b, c) NM400 (50mm); (d, e, f) NM400 (60mm).

The micro-wear morphologies at typical measuring points of the two samples are shown in Fig.5. It is found that the micro-wear morphologies of each measuring point of the two samples are mainly furrow and spalling, and the wear types are mainly abrasive wear and contact fatigue wear. With the position of the measuring point gradually away from the surface of the steel plate, the furrow depth and the number of furrows on the worn surface of the sample at the corresponding measuring point position gradually increased, and the spalling area and the depth of the spalling pit gradually increased. In addition, it can be found that the wear degree of sample NM400 (60mm) at each typical measuring point is slightly greater than that of sample NM400 (50mm).

Fig 5. Microscopic wear morphology of test steel (SEM). (a, b, c) NM400 (50mm); (d, e, f) NM400 (60mm).
As shown in Fig. 5 (a), the micro-wear morphologies of the NM400 (50mm) sample surface are mainly manifested as a large number of long furrows and a small amount of shallow contact fatigue spalling, and the wear patterns are mainly abrasive wear. Combined with Fig. 1 (a) and Fig. 2 (a), it can be seen that the microstructure of NM400 (50mm) sample at this position is mainly the lath martensite structure with high hardness and good wear resistance. As shown in Fig. 5 (b), the micro-wear morphology of NM400 (50mm) specimen at the 1/4 thickness of the plate is mainly manifested as furrow and contact fatigue spalling. Compared with the surface position, the furrow is relatively wider and deeper, and the contact fatigue spalling area is also significantly increased. The wear forms include abrasive wear and contact fatigue wear. Combined with Fig. 1 (b) and Fig. 2 (a), it can be seen that the content of martensite microstructure in the NM400 (50mm) sample at this position gradually decreases, while the content of bainite and pearlite microstructure increases gradually, and the hardness decreases greatly, which reduces the abrasion resistance to a certain extent. As shown in Fig. 5 (c), the micro-wear morphology of NM400 (50mm) specimen at the thickness of 1/2 of the plate is mainly manifested as large-area contact fatigue spalling and a small number of deep and wide furrows, and the wear form is mainly contact fatigue wear. Combined with Fig. 1 (a) and Fig. 2 (a), it can be seen that the martensite microstructure of the NM400 (50mm) specimen at this position almost disappears, which is mainly composed of pearlite and a small amount of bainite, with low hardness and relatively poor wear resistance [11-13]. The micro-wear morphology of each typical measuring point of NM400 (60mm) sample is similar to that of NM400 (60mm) sample, so it will not be repeated here. It is worth noting that the furrows on the worn surface of sample NM400 (60mm) at each typical measuring point are deeper and wider than that of sample NM400 (50mm), and the contact fatigue spalling degree is more serious.

The friction coefficient variation curves of the two samples at typical measuring points are shown in Fig. 6. It is found that the friction coefficient of the two samples at each measuring point can be roughly divided into two parts: I and II. Part I can be understood as the wear run and in the early stage, the friction coefficient of sample fluctuations is relatively severe, as worn continues, the friction coefficient of sample first rises rapidly, then decreases rapidly, and the duration is relatively short. This is mainly due to the presence of a large number of micro-protrusions on both the sample and the surface of the grinding piece at the initial stage of wear, and the roughness between the contact surfaces, so the friction coefficient of the sample at the stage is relatively high and fluctuates violently. Part II can be understood as a stable wear stage in the process of wear and tear, at this stage, the friction coefficient of sample less volatile, as worn continues, the friction coefficient of sample stable within a certain range fluctuations for a long duration. This is mainly due to the fact that with the continuous wear, the sample and the micro-protrusions on the surface of the grinding piece become gradually smoothed and the contact surfaces are relatively smooth, so the friction coefficient of the sample at the stage is relatively small and fluctuates relatively stable [14-15].

![Friction coefficient of test steel](image-url)
The average friction coefficient at typical measuring points of the two samples is shown in Fig. 7. It can be found that the average friction coefficient of the sample at the corresponding position also increases as the measuring point is gradually away from the surface of the steel plate. In addition, the average friction coefficient of the sample NM400 (60mm) at each typical measuring point is slightly higher than that of the sample NM400 (50mm). Combined with Fig.5, it can be seen that as the measuring point is gradually away from the surface of the steel plate, the wear degree of the sample is gradually intensified, the furrows on the worn surface are wider and deeper, the contact fatigue spall area is gradually increased, and the roughness is gradually increased, which leads to the increase of the average friction coefficient of the sample.

**Fig 7. Average friction coefficient of test steel.**

4. Conclusions
The depth of the NM400 (50mm) hardening layer is about 35mm, accounting for about 70% of the overall plate thickness. The depth of the NM400 (60mm) hardening layer is about 22mm, accounting for about 37% of the plate thickness. The hardness of both hardening layers reached about 410HV. On the surface of steel plate, the microstructure of NM400 (50mm) and NM400 (60mm) is mainly typical lath martensite structure. At 1/4 plate thickness, the microstructure of NM400 (50mm) was mainly mixed with martensite and bainite, while the microstructure of NM400 (60mm) was mainly mixed with martensite, bainite and a small amount of pearlite. At 1/2 plate thickness, the microstructure of NM400 (50mm) was mainly pearlite and a small amount of mixed tissue of bainite and martensite, while the microstructure of NM400 (60mm) was mainly pearlite.

The micro-wear morphologies of NM400 (50mm) and NM400 (60mm) at each measuring point were mainly furrow and contact fatigue spalling, and the wear types were mainly abrasive wear and contact fatigue wear. The furrow depth and the number of furrows on the worn surface of the sample at the corresponding measuring point position gradually increased as the measuring point position moved away from the steel plate surface, and the spalling area and the spalling pit depth gradually increased. The wear type gradually changed from particle wear to contact fatigue wear.

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