Study on Wear-resistant Surfacing Flux Cored Wire for Shield Machine Hob

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Abstract. The hob is an important tool for the shield machine, which improves its wear resistance and is of great significance for extending its life and improving the reliability of the shield machine. Based on the working condition of the hob, Ni-Cr-B-Fe surfacing flux-cored wire was designed. The effects of Ni and B content on the microstructure and properties of deposited metal were studied by XRD and SEM. Optimize Ni and B content to provide technical data. The powder 40\%Ni-10\%Cr-50\%Fe-B alloy flux-cored wire studied was used for hob surfacing, which significantly improved its wear resistance.

1. Introduction
With the continuous development of China's urban construction, the role of subways in alleviating urban traffic pressure has become increasingly prominent. Shield machines are important construction machinery for subway construction. The hob is the cutting tool used on a shield machine. The hob is composed of a hob body. The middle of the hob body is mounted with an alloy through a knife ring. The knife ring is fixed on the hob body by a fixed ring. The hob is a tool with interchangeable cutting rings, which is usually divided into single-edged, double-edged and multi-edged. They are usually mounted on the shield cutter head in a radial or spiral distribution. The shield machine digs forward under the pressure of the jack, and the shield disc of the shield machine rotates. At the same time, the cutter mounted on the shield disc of the shield machine rotates under the influence of friction and pressure while the knife disc revolves. The cutting edge of the cutter ring is used to produce rolling cutting effect on the rock surface. In the shield construction, the wear of the cutter head is a major obstacle in the construction of the shield method. The shield machines in the weathered granite formation, and the hob wears quickly [1]. Material wear and corrosion not only reduces production efficiency, but also has a crucial impact on production quality and product performance. If it is not taken seriously, it may even threaten personal safety and cause greater economic losses. Therefore, it is particularly important to take necessary measures to improve its wear resistance. Surface deposited technology refers to the melting of powder, wire or rod on the surface of a material by heat sources such as electric arc, plasma arc, laser, etc. to form a coating with different composition and performance from the base material to improve wear resistance, corrosion resistance and other special properties. Overlay welding is a surface modification technology used for metal, especially large engineering equipment. Usually, one or more layers of film are cladding on the surface of the material to improve the performance of the workpiece. At the same time, it can repair parts and optimize the comprehensive performance of the material, increase equipment life, save energy, reduce maintenance and repair costs, and improve production efficiency [2] [3]. At present, brazing cemented carbide is often used as hobs’ abrasion-resistant working layers. Cemented carbides have complex manufacturing
processes and poor toughness. The strength of brazed joints is also low, which affects the service life of hobs. There are relatively few studies on the wear resistance of hob using surfacing technology. In this paper, Ni-Cr-B-Fe based surfacing flux-cored wire is studied, and engineering application tests are performed on the hob.

2. Surfacing Flux-cored Wire Design

Flux-cored wire consists of flux powder and steel tube used for encapsulating powder. The steel tube uses carbon steel SPCC, which chemical composition is (wt.%), 0.06% C, 0.02% Si, 0.43% Mn, 0.012% S, 0.023% P, Fe and impurities that do not affect performance. The flux cord wire powder is commercially available pure Ni powder and Cr powder, the Ni and Cr contents of Ni powder and Cr powder are not less than 99.5% and 99.10%, respectively. In order to improve the transition coefficient of B, an Fe-B alloy powder was prepared, Its composition is (wt.%) 19.32%B, 73.90%Fe, 6.35%Cr, 0.43%C, the main phases are FeB, Fe2B, Fe3B, B and a small amount of CrC. The filling rate of the flux-cored wire is 45% (the filling rate is the ratio of the mass of the powder and the sum of the mass of the powder and the steel pipe), and the diameter of the wire is 1.6mm.

In this paper, the composition of the surfacing metal is changed by changing the addition amount of Fe-B alloy powder, nickel powder and boron powder. And study on the influence of Ni and B content on the microstructure, hardness and physical properties of the surfacing metal, to provide technical data for optimizing Ni and B additions. Table 1 shows the composition of the power in flux-cored wire.

| Number | Ni powder | Cr powder | Fe-B alloy |
|--------|-----------|-----------|------------|
| A1     | 50        | 10        | 40         |
| A2     | 40        | 10        | 50         |
| A3     | 30        | 10        | 60         |

3. Test Methods

3.1. Test Piece Welding

The test uses Q235 with a thickness of 20mm to prepare a test piece with a size of 200mm × 50mm × 20mm. At the center of the test piece, surfacing test bead along the length of the test piece. Using 80% Ar + 20% CO2 argon-rich gas welding, the welding current 320-350A, arc voltage 32-35V, shielding gas flow rate of 25L/min, wire speed of 520mm/min.

3.2. Sample Preparation

The metallographic specimen was prepared by EDM CNC to cut the test piece after welding along the cross section of the welding bead. Grind the sample in sequence with coarse sandpaper and metallographic sandpaper, and use 5μm diameter diamond polishing liquid as a polishing agent to polish. Hydrofluoric acid, concentrated hydrochloric acid and concentrated nitric acid were configured into a mixed acid solution in a volume ratio of 2:3:5, and etched for about 15 seconds until the metallographic structure was clear, and then the structure was observed and analyzed.

3.3. Test Methods

XJP-6A metallographic microscope (OM) was used to make preliminary observation of the microstructure, and then JSM-6600V scanning electron microscope (SEM) and its own energy spectrometer (EDS) were used to observe the micromorphology. Then, the microstructure was analyzed the point component and line scan component. The phase composition of the deposited metal was analyzed by a Rigaku D/MAX-rC X-ray diffractometer.

A 31 mm × 7 mm × 5 mm abrasion sample was cut from the test piece by EDM, and the abrasive sample to be tested was polished with sandpaper to the same roughness. Adopt M-2000 type friction and wear tester, take the carburized 20CrMnTi with diameter of 40mm as the pair of grinding wheels.
which macro hardness is 59.2 ~ 60.2HRC. The wear test speed is 400r/min, and the applied load is 150N.

During the test, the sample was first cleaned by ultrasonic and then weighed and recorded. The sample was weighed and recorded every 10 minutes. The sample was worn for 40 minutes. After the test, the weight loss was calculated.

4. Microstructure and Properties of Surfacing Metal
The boron content of the boride-reinforced alloy currently studied is mostly less than 1.5%, and its microstructure is a hypoeutectic structure. Because the hardness of the matrix structure is lower than that of the boride, and the amount is large, the wear resistance of the boride-reinforced alloy cannot be fully reflected. In this paper, by adding a large amount of boron in the form of Fe-B alloy powder, the boron content of the Ni-Cr-B-Fe surfacing alloy reaches more than 6.5% to form a hypereutectic high-boron alloy, and study their structure, hardness and phase.

4.1. Effect of Fe-B Powder on Microstructure of Surfacing Alloy
Figure 1 is the microstructures of the surfacing metal in which the added amount (wt.%) of the Fe-B alloy powder is 40%, 50%, and 60%, respectively. It can be seen that with the increase of the amount of Fe-B alloy powder added, the needle-like and network-like eutectic boride in the microstructure increases. The content of Fe-B alloy powder in A1 is 40%, and the pre-eutectic boride is relatively coarse. Borides are mainly precipitated in lumps, fish bones, and needles. At the same time, due to the agglomeration of boron in the local area, fine particulate boride was formed in the agglomerated area. Among the pre-eutectic boride, the residual liquid boron content is small, so a large area of the iron-nickel solid solution bonding phase appears, as shown in Figure 1 (A1).

The microstructures of A2 and A3 are similar, and the boride structures are relatively fine, mainly reticulated boride. Iron-nickel austenite and granular or spotted borides are distributed between the network borides. However, in addition to lumps, slabs, and reticular borides in A2, due to the agglomeration of boron in local areas, fine particulate borides also form in the agglomerated areas. In the area of boron agglomeration, a lot of fine particulate borides were also distributed on the iron-nickel solid solution matrix, showing a honeycomb eutectic structure. A gray iron-nickel solid solution matrix was formed in a local area between the reticulated boride frameworks, as shown in Figure 1(A2).

As shown in Figure 1(A3), the mesh-like boride in the microstructure of A3 is more pronounced. Due to the higher boron content, more proeutectic boride is formed, and less liquid phase remains in the boride gap. Therefore, a large area of iron-nickel solid solution matrix does not appear. It is a fine point-like boride, and also presents a finer honeycomb eutectic structure.

![Figure 1. Weld microstructure.](image)

4.2. Effect of Fe-B Alloy Powder on Hardness of Surfacing Alloy
As shown in Figure 2, starting from the base material 250 μm from the fusion line, the micro-hardness was measured by punching a spot every 250 μm to the cladding layer. As the distance from the fusion line increases, the morphology of the microstructure is different, and the microhardness of the A2 cladding layer gradually increases. The microhardness of the base material is low, below about 150HV.
Due to the dilution of the base metal, the cladding layer near the fusion zone has many iron-nickel austenite dendrites and coarse grains, so the microhardness is low. But as the distance increases, the dilution effect of Fe weakens, and the solid solution effect of Cr in austenite becomes more obvious, increasing the microhardness of dendrites. At the same time, there are more grain boundaries between the dendrites, the boride phase between the dendrites increases, and the microhardness of the cladding layer gradually increases. At the top of the deposited layer, the microstructure is a large number of pre-eutectic boride, and the microhardness is increased to about 450HV. In some cases, due to the impact on the softer iron-nickel solid solution, the hardness suddenly decreased. Therefore, the microhardness increases with the distance from the fusion line. When the distance from the fusion line exceeds 1 mm, the microhardness value tends to be stable.

Comparing the microhardness curves of A1, A2, and A3 cladding layers with different additions of Fe-B alloy powder, it can be seen that as the boron content increases, the generated boride increases and the microhardness increases. A3 has the highest microhardness. The average hardness of the top of the cladding layer is 526.6HV, and the highest hardness is 578.8HV.

The microstructure of A1 has a large area of iron-nickel solid solution, large boride, and uneven microstructure. Therefore, the microhardness of A1 fluctuates greatly, and the microhardness of the cladding layer is the smallest, with an average value of 426.6HV. The A2 and A3 borides are distributed in fine needles and networks, and the structure is uniform, so the fluctuation of microhardness is small, indicating that the base metal increases uniformly from the base metal to the deposited metal surface. The microhardness of A2 is similar to that of A3, with an average microhardness of 499.3 HV. Therefore, it can be seen from the microhardness test that the microhardness of the hypereutectic high boron alloy cladding layers A2 and A3 is about three times that of the base material, and the strengthening effect on the surface of the base material is obvious.

![Figure 2. Microhardness of surfacing metal.](image)

4.3. Wear Resistance Analysis of Ni-Cr-B-Fe High Boron Alloy

As shown in Figure 3, with the increase of wear time, the wear loss of A2 and Q235 gradually increased. After 40 minutes of dry friction, the total weight loss of A2 was 7.2 mg, and the weight loss of Q235 was 105.4 mg. It shows that the wear resistance of deposited metal is significantly better than that of Q235 steel, the wear resistance of the surface of the substrate has been significantly improved, and its abrasion loss is only about one-fifth of that of Q235. In the initial stage of wear, the softer eutectic structure in the deposited metal is worn first, and its hardness is about 450 HV, which is significantly higher than the 150 HV of the matrix. At the same time, as the wear continues, due to the presence of more Fe2B hard phase particles in the deposited metal, many hard phase particles with
high hardness are in direct contact with the grinding wheel, which prevents the soft eutectic to a certain extent the tissue continues to wear, reducing lost weight. On the other hand, during the wear process, the elements such as Cr and B in the deposited metal are frictionally oxidized to form oxides such as Cr$_2$O$_3$ and B$_2$O$_3$. They exist between the deposited metal and the grinding wheel, which is equivalent to a solid lubricant and is reduced to a certain extent. At the same time, Cr$_2$O$_3$ can also be squeezed into the deposited metal by the grinding wheel, making it more difficult to remove, and the wear resistance is improved.

It is precisely because of the superposition of the lubrication and anti-friction effects of Cr$_2$O$_3$, B$_2$O$_3$ and other oxides and the work hardening effect of the deposited metal during wear that the wear loss in every 10 minutes from the 10th minute to the 40th minute is smaller than the first 10 minutes abrasion loss, as shown in Figure 6. Among them, the increase of the grinding loss between the 30th minute and the 40th minute may be caused by the wear-resistant phase falling off after a lot of wear in the surrounding eutectic structure. The Q235 has a larger weight loss per 10 minutes, and the weight loss during the first 30 minutes gradually increases. Between 30 minutes and 40 minutes, a reduction in the weight loss due to work hardening also occurred.

![Figure 3. Variation of wear loss weight of Ni-Cr-B-Fe high Boron alloy and Q235 with time](image)

5. Application of Flux-cored Wire on Hob

The base of the hob ring is made of 30CrMnSi steel, and the blank is prepared by hot forging. The machining method is used to process the blank, and the thickness of the cladding metal is 12mm after processing, that is, the size is 12mm smaller than the required size of the cutter ring to obtain the cutter ring base.

In order to ensure the bonding strength of the flux-cored welding wire and the substrate, and the wear resistance, impact resistance, crack resistance and fatigue resistance of the surfacing metal, the thickness of the surfacing metal must be more than 12mm. The surfacing metal is divided into a transition layer and working layer, transition layer metal is 3-4mm thick, the rest is working layer.

The transition layer is welded with an alkaline electrode E5015 with a diameter of 3.2mm and is welded with a small heat input, which can reduce the dilution rate and the effect of the substrate 30CrMnSi on the composition of the transition layer. After the part of the substrate to be welded is preheated by flame at 120-150°C, the welding current of the electrode surfacing is 90-100A, and the thickness of the transition layer is 3-4mm thick.

The wear-resistant working layer uses A2 flux-cored welding wire with a diameter of 1.6mm. In order to improve the efficiency of additive cladding, the welding heat input can be appropriately increased. Using 80% Ar and 20% CO$_2$ argon-rich gas shielded welding, welding current 320-350A, arc voltage 32-35V, shielding gas flow 2.5L/min, wire speed is 520mm/min.

Figure 4 is a schematic diagram of radial cross-section of a hob ring surfacing and a real picture, and the preliminary trial effect is good.
6. Summary
In this paper, the effects of the composition of Ni-Cr-B-Fe surfacing flux-cored wire powder on the structure, hardness, and abrasion resistance of surfacing metal were studied. The flux-cored wire was subjected to engineering application tests on a hob of a shield machine, and the initial trial results are good. The results show that the amount of Fe-B alloy powder in the powder is 40%, 50%, and 60%. As the content of the Fe-B alloy powder increases, the reticulated boride in the surfacing alloy increases, and the iron-nickel solid solution matrix decreases. The microhardness of the cladding layer gradually increased from the fusion zone to the cladding layer. With the increase of boron content, the volume fraction of boride in the cladding layer increased, and the microhardness increased, but the increase was not obvious. Compared with Q235, the wear resistance of the flux-cored wire surfacing metal is significantly improved.

7. Acknowledgements
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8. References
[1] ZHAO Qing, DUAN Jingchuan, YANG Tao, DUAN Zhihong and YAN Qixiang 2016 Research on service life prediction after abrasion of shield Hob in weathered granite formation Subgrade Engineering. 2 94-8
[2] Jin Jun, Sun Junsheng, Sun Honggen, Lu Qingliang, Xu Jingwei and Yang Yun 2019 Microstructure and performance of nitrogen alloying deposited metal on hot working dies surface Materials reports. 33 3184-8
[3] Meng Ling 2018 Effect of Rare Earth ferrosilicon on structure and properties of hypereutectic high chromium surfacing alloy Materials protection. 51 98-100