Analysis of Microstructure and Performance of Laser Cladding WC-Fe316L Alloy on the Surface of 27SiMn Steel

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Abstract. In order to solve the problem that the hydraulic support column is affected by the sulfur and chlorine water vapor in the mine, the inner wall will inevitably have different forms of defects, such as surface wear and surface corrosion. The pure Fe316L cladding layer and the WC-Fe316L composite cladding layer with the hard phase WC mass fractions of 10%, 20%, and 30% were prepared on the 27SiMn steel substrate for hydraulic support column by homogenizing broadband laser head. The phase composition, microstructure, microhardness and wear resistance of four cladding samples were studied. The results show that the pure Fe316L cladding layer forms a good metallurgical bond with the substrat, the surface of the cladding layer has no crack defects, and the shape is good. The average microhardness of the pure Fe316L cladding layer is increased by 1.4 times compared with the 27SiMn steel base, and it is increased to 331.2HV0.5. At the same time, the wear rate of the pure Fe316L cladding layer is reduced by 30.8% compared with that of the matrix. The mass fraction of WC particles is 10 %, 20%, and 30% of the WC-Fe316L composite cladding layer's microhardness is 1.6, 1.7 and 2.0 times higher than that of the 27SiMn steel matrix to 369.9HV0.5, 408.6HV0.5 and 481.6HV0.5, and each WC The wear rate of Fe316L composite cladding layer was reduced by 45.8%, 66.0% and 82.3% compared with the matri composite cladding layer. The addition of WC particles helps to strengthen the solid solution strengthening and fine-grain strengthening of the composite cladding layer, and the unmelted WC particles also strengthen the dispersion strengthening effect of the composite cladding layer.

1. Introduction
Laser cladding technology was first proposed by AVCO in the United States and applied to repairing surface defects of wear parts. Immediately afterwards, Britain, Germany, and Japan carried out corresponding researches on laser cladding repairing surface defects of workpieces. This research is to melt the target performance alloy powder material on the surface of the workpiece by laser to repair its surface defects and improve its wear resistance, heat resistance and corrosion resistance.

Compared with traditional surface modification technology, laser cladding technology has incomparable advantages. The advantages of laser cladding include low coating dilution rate (5%-10%), small heat-affected zone, small deformation of the workpiece; high cladding processing accuracy, and more automated equipment is used in the process. Precision machining of small micro surface areas can be achieved by laser cladding [1]. Many scholars at home and abroad have done a lot of research on improving the surface defects of workpieces by laser cladding.

The hydraulic support column plays a pivotal role in the service process of coal mining. In order to repair the defects of the inner wall of the column, increase its surface wear resistance and corrosion resistance, and prolong its service life, the surface needs to be remanufactured through surface...
modification technology. Therefore, in this paper, using laser cladding, a pure Fe316L cladding layer and a WC-Fe316L composite cladding layer with a hard phase WC mass fraction of 10%, 20%, and 30% were prepared on the 27SiMn steel substrate of the base material of the hydraulic support column. The microstructure and wear resistance of cladding materials are studied.

2. Experimental Materials and Methods

The 27SiMn steel matrix materials used in this experiment are all line-cut from the hydraulic support column that has been in service. After line-cutting, the sample block of 200mmX50mmX10mm is prepared. The chemical composition of 27SiMn steel is shown in table 1. Among them, the content of hard elements such as C and Cr is relatively small, resulting in poor hardenability and hardenability, and it has a tendency to temper brittleness. The hardness can reach about 230HV after high temperature tempering [2].

| Element | C    | Si   | Mn   | P    | S     | Cu   | Cr   | Ni    | Mo    | Fe    |
|---------|------|------|------|------|-------|------|------|-------|-------|-------|
| Mass fraction | 0.24-0.32 | 1.10-1.40 | 1.10-1.40 | ≤0.035 | ≤0.035 | ≤0.30 | ≤0.30 | ≤0.30 | ≤0.15 | Bal   |

The cladding material Fe316L is provided by Hoganas(China). Fe316L powder particle size is 48-96μm [3]. Its chemical composition is shown in table 2. Fe316L powder morphology and EDS analysis are shown in figure 1.

| Alloy powder | C    | Si   | Mn   | P    | S     | Cu   | Cr   | Ni    | Mo    | Fe    |
|--------------|------|------|------|------|-------|------|------|-------|-------|-------|
| Fe316L       | ≤0.03 | ≤1.0 | ≤2.0 | ≤0.045 | ≤0.03 | 16.0-18.0 | 10.0-14.0 | 0.4    | Bal   |

(a) Fe316L powder morphology  
(b) Surface Scanning EDS Analysis of Fe316L Powder

**Figure 1.** Powder morphology and EDS analysis.

The WC ceramic powder used in the test is pure WC ceramic spherical powder. The morphology of WC ceramic powder is shown in figure 2. The physical properties of the WC ceramic reinforcement phase are shown in table 3.
Figure 2. WC ceramic powder morphology.

Table 3. Physical properties of WC ceramic phase.

| Material | Density/g/cm³ | Melting point /℃ | Thermal expansion coefficient /10⁻⁶K⁻¹ |
|----------|--------------|------------------|--------------------------------------|
| WC       | 15.7         | 2776             | 5.2 - 7.3                            |

Use an electronic balance with an accuracy of 0.01g to weigh 10%, 20%, and 30% mass fraction of WC ceramic hard phase and Fe316L self-dissolving alloy powder to make composite metal alloy powder. Table 4 shows the mixing ratio of composite metal alloy powder by ball milling.

Table 4. Ball mill mixing ratio of composite metal alloy powder (wt.%).

| Serial number | Matrix powder Type | Add material Type  | Mass fraction |
|---------------|--------------------|--------------------|--------------|
| 1             | Fe316L             | Spherical WC       | 0            |
| 2             | Fe316L             | Spherical WC       | 10           |
| 3             | Fe316L             | Spherical WC       | 20           |
| 4             | Fe316L             | Spherical WC       | 30           |

The process parameters of WC-Fe316L composite alloy powder are: laser power: 4000W, spot size: 15mmX3mm, defocus: 0mm, powder feeding speed: 3.5rpm, manipulator moving speed: 550mm/min, shielding gas pressure: 0.5Mpa, carrier gas flow: 4l/min, laser maximum output power: 6000W, output power adjustment range: 10%-100%.

According to the ball milling mixing ratio of the 4 kinds of composite metal alloy powders listed in table 4, 4 kinds of single-pass composite metal alloy cladding layers were prepared on the 27SiMn steel substrate. As shown in figure 3. In order to facilitate the writing and reading of this article, each cladding layer is now numbered N1: Fe316L, N2:10wt.%WC+Fe316L, N3:20wt.%WC+Fe316L, N4:30wt.%WC+Fe316L.
The analysis sample is processed by wire cutting technology to process the cladding layer composite material into X-ray diffraction analysis (XRD) samples, metallographic samples, hardness test samples and friction and wear samples. The size of the XRD sample and the metallographic sample is 15mmX15mmX2mm. The surface of the XRD sample is polished with 300 to 1500 mesh sandpaper, and then the sample is analyzed by X-ray diffractometer. The metallographic sample is polished with 400 mesh, 800 mesh, 1000 mesh, 1500 mesh and 2000 mesh sandpaper in sequence, and then polished with W3.5, W2.5, W1 water-soluble diamond abrasive paste in sequence, and then with aqua regia etching solution (Concentrated hydrochloric acid: concentrated nitric acid=3:1) is processed, cleaned with ultrasonic, and finally put into a vacuum incubator for drying, and then the microstructure is observed through an optical microscope. The size of the hardness test sample is 15mmX12mmX4mm, and the hardness test is carried out by a microhardness tester. The measurement method is to measure a point every 0.1mm from the surface of the cladding layer to the direction of the substrate. Take and measure 10 points along the same horizontal height perpendicular to the laser scanning direction at 1mm intervals, and take the average of the 10 points as the hardness value on the unified horizontal line. Draw the hardness curve from the surface of the sample cladding layer to the substrate in the Origin software. In this paper, the equipment for measuring the wear resistance of each sample cladding layer is the HT-1000 ball-disk friction and wear tester. The friction and wear test of the cladding layer of the sample is carried out at room temperature. The friction and wear test parameters are: Normal load 9.8N, friction time 45min, friction radius 2mm, friction disc speed 1440r/min, wear distance 814m. The test grinding material is Si3N4 high hardness ceramic ball. Its surface microhardness can reach 1700HV. The wear volume of the sample can be measured by the surface profile displacement sensor equipped with the friction and wear tester, measured 5 times at different positions of the wear scar, and take the average value.
3. Experimental Results and Analysis

3.1. Phase Analysis of Cladding Layer

X-ray diffraction analysis can quickly realize the qualitative analysis of the coating surface phase \[^{[4]}\]. By analyzing the diffraction peaks of the N1 cladding layer (Fe316L cladding layer), it can be known that its phase composition includes \(\text{CrC}, \text{Cr}_2\text{C}_6, \text{Cr}_7\text{C}_3\), \(\gamma-[\text{Fe,Cr,Ni}]\) etc. \(\text{CrC}, \text{Cr}_2\text{C}_6, \text{Cr}_7\text{C}_3\) are the main hard phases in the coating, and their existence lays the foundation for the hardness and mechanical properties of the coating. The basic phase of the cladding layer is austenite \(\gamma-[\text{Fe,Cr,Ni}]\), which improves the toughness of the cladding layer and supports the \(\text{CrC}, \text{Cr}_2\text{C}_6, \text{Cr}_7\text{C}_3\) and other carbides in the coating\[^{[5]}\]. On the basis of iron-based alloy powder Fe316L, 10\%, 20\% and 30\% WC particles are added to the inside. The sample N2 cladding layer is mainly composed of \(\gamma-[\text{Fe,Cr,Ni}]\), \(\text{CrC}, \text{Cr}_2\text{C}_6, \text{Cr}_7\text{C}_3\), and \(\text{Cr}_2\text{C}\) phases, of which \(\text{CrC}, \text{Cr}_2\text{C}_6, \text{Cr}_7\text{C}_3\) and \(\text{Cr}_2\text{C}\) have high hardness. With the increase of WC content, new high-strength carbide \(\text{Fe}_3\text{W}_3\text{C}\) appears in the N3 cladding layer. With the further increase of WC content, carbide hard phases such as \(\text{Fe}_6\text{W}_6\text{C}, \text{Fe}_2\text{MoC}\) and \(\text{Mn}_7\text{C}_3\) appear in the N4 cladding layer \[^{[6]}\]. \(\text{Fe}_2\text{MoC}\) and \(\text{Mn}_7\text{C}_3\) do not appear in the N2, N3 cladding layer because the content of Mo and Mn in the Fe316L powder is low, and it is not easy for the C element to form carbides. When the added WC content is large, the Mo and Mn elements and the C element form carbonization The probability of the substance will be much greater, so the carbide hard phases such as \(\text{Fe}_2\text{MoC}\) and \(\text{Mn}_7\text{C}_3\) appear in the N4 cladding layer \[^{[7]}\]. In addition, with the increase of WC content, the diffraction peaks of the cladding layer become more and more complicated, and the presence of these carbides can greatly increase the strength and hardness of the cladding layer.

**Figure 4.** Phase diffraction pattern on the surface of the cladding layer.
3.2. Microstructure Analysis of Cladding Layer

Figure 5 shows the whole cladding layer of sample N1 and the metallographic microstructure from the cladding layer bonding area to the surface. From figure 5(a) of the overall metallographic microstructure of the cladding layer, it can be seen that there is a white bright band between the cladding layer and the substrate, indicating that the Fe316L coating is metallurgically bonded to the substrate through broadband laser cladding. Figure 5(b) is the metallographic microstructure of the cladding layer bonding zone. After laser cladding, the interface between the molten cladding material and the substrate begins to solidify first. Since the temperature gradient G between the two is extremely large at this time, the solidification rate R of the substrate surface is extremely small. It can be seen from the compositional supercooling theory that metal materials follow during rapid melting and solidification. At this time, the G/R ratio is extremely large, and the crystal growth rate is much higher than the nucleation rate, so the crystal at the junction extends into the coating in the form of planar crystal growth [8]. As the solidification progresses, the temperature of the substrate increases, the temperature gradient G at the junction of the solid and liquid phases gradually decreases, the solidification rate R gradually increases, and the G/R value gradually decreases. Typical columnar crystals pointing from the matrix to the direction of the cladding layer appear in the organization, as shown in figure 5(c) [9]. The temperature gradient G at the top of the cladding layer continues to decrease, the solidification rate R continues to increase, and the G/R value continues to decrease. At this time, the nucleation rate of the crystal is much greater than the growth rate. Therefore, cell crystals and equiaxed crystals with similar growth sizes, different directions, and fine organization are more common, as shown in figure 5(d). The above is the growth morphology of the metallographic structure in the bonding zone, middle and top of the cladding layer, which establishes the good mechanical properties of the cladding layer.

![Figure 5. Metallographic structure of sample N1 cladding layer.](image-url)
In order to further observe the microstructure of each area in the cladding layer of each sample and explore the influence of WC particles on the composition of the surrounding structure. Under the scanning electron microscope, the SEM microstructure of the cladding layer of each sample was observed, and the structure around the WC particles in the sample N4 was analyzed by EDS.

![Figure 6. SEM images of cladding layers of different samples.](image)

Figure 6 shows the SEM image of the cross-section of the N2, N3 and N4 cladding layer. It can be seen from the figure that the three cross-sectional structures from the bonding zone to the surface of the cladding layer are similar in appearance, including planar crystal structure, needle-like dendritic structure and cellular crystal structure. Different from the structure of pure Fe316L cladding layer, the structure of the middle region of WC-Fe316L cladding layer is further refined, from columnar crystal structure to finer needle-like dendritic structure. It can be seen that WC particles can play a role in hindering the growth of dendrites and refining crystal grains.
As shown in figure 7, the structure around the WC particles in the sample N4 cladding layer is composed of a dendritic matrix and a networked eutectic structure between dendrites. From figure 7(a), it can be seen that the WC particle is like a particle in the structure of the cladding layer, and there is a circle of columnar crystals growing along the radial direction of the WC particle on the outer circle [10]. This is because the temperature of WC particles in the molten metal is relatively low, the radial temperature gradient is large, and the surrounding structure crystallizes along the radial direction of the WC particles. As shown in figure 7(c), compared to the structure of other areas of the cladding layer, the structure between the two WC particles is dense and fine, existing in the form of equiaxed crystals. It can be seen that in the area where the WC particles are gathered, the structure of the cladding layer shows the phenomenon of regional grain refinement with the synergistic effect of multiple WC particles [11]. With the increase of WC content, this kind of regional grain refinement phenomenon will become more common, which has a fine grain strengthening effect on the structure of the cladding layer as a whole.

3.3. Analysis of Microhardness of Composite Cladding Layer

Figure 8 shows the microhardness curves at different depths of the cross-section of the sample N1-N4 cladding layer, in which the microhardness curve of the sample N1 cladding layer is used for comparison. The microhardness curve of the cladding layer of each sample is divided into three parts, namely the cladding layer area, the heat-affected area and the matrix material. The average microhardness of N1, N2, N3 and N4 cladding layers are 331.2HV0.5, 369.9HV0.5, 408.6HV0.5 and 481.6HV0.5 respectively. The average microhardness of the matrix is 238.0HV0.5. The average microhardness of the N1, N2, N3, and N4 cladding layers is further increased by 1.4, 1.6, 1.7, and 2.0
times compared with the average hardness of the matrix. The hardness of the cladding layer has been improved compared to the hardness of the matrix. The main reason is that alloy elements such as Cr and C precipitate various high-hardness and high-strength eutectic products between the dendrites, such as CrC, Cr23C6, Cr7C3 etc. The dendrite matrix contains a large amount of Cr element for solid solution strengthening [12].

In addition, as shown in Figure 8, the microhardness curves of the cladding layer regions of samples N1, N2, N3 and N4 all have certain fluctuations. The fluctuation of the microhardness curve of the cladding layer from N1 to N4 decreases with the increase of WC content. This is because the increase of WC content causes the hard phase content distribution in each area of the cladding layer to become more and more uniform.

To sum up, the increase in WC content can not only increase the hardness of the cladding layer, but also reduce the difference in hardness value of each area of the cladding layer. Among the 4 samples, the N4 sample (30wt.%WC-Fe316L) has the highest coating microhardness (481.6HV0.5), and the microhardness distribution in each area is the most uniform.

3.4. Analysis of Friction Coefficient and Wear Rate of Composite Cladding Layer

![Figure 9](image)

**Figure 9.** Coefficient of friction and wear rate of cladding layers of different samples.

Figure 9 shows the comparison of the friction coefficient and wear rate of the 27SiMn steel substrate and the cladding layer of the N1, N2, N3 and N4 samples under the same test conditions. As shown in figure 9(a), the friction coefficient curves of the five have experienced the running-in phase and the stable friction and wear phase at the beginning [13]. The 27SiMn steel matrix friction coefficient curve is at the top of the entire graph; the hardness of the N1 sample block is improved to a certain extent than that of the matrix sample block, but the internal structure is uneven. The dendritic structure is mostly austenite phase, and its hardness is low; there are a small amount of carbides in the intergranular structure, and its hardness is high. Therefore, the friction state of the friction ball will fluctuate, resulting in unstable friction coefficient [14]. The friction coefficient curves of the cladding layers of samples N1, N2 and N3 are intertwined, and their average friction coefficients are very close; the friction coefficient curve of the cladding layers of sample N4 is always at the bottom of the entire graph. The average friction coefficients of 27SiMn steel substrate and sample N1, N2, N3, N4 cladding layer are 0.429, 0.260, 0.252, 0.238 and 0.157 respectively. It can be seen that there is a positive correlation between the average friction coefficient of the sample and its average microhardness, that is, the larger the average microhardness of the sample, the lower the average friction coefficient. According to figure 9(b), the wear rates of the 27SiMn steel substrate and the sample N1, N2, N3, and N4 cladding layers are 63.97, 44.26, 34.65, 21.74 and 10.71×10⁻⁶mm³/N·m respectively. Compared with the matrix, the wear rates of samples N1, N2, N3 and N4 are reduced by 30.8%, 45.8%, 66.0% and 82.3% respectively. It can be seen that the addition of hard material has a
significant effect on improving the wear resistance of the cladding layer. The main reason is that the WC particles increase the average microhardness of the cladding layer, and the ability of the cladding layer to resist wear is enhanced. The 30 wt.%WC-Fe316L composite cladding layer has the best wear resistance.

4. Conclusion
In this paper, a wide band cladding head was used to prepare a pure Fe316L cladding layer on the surface of 27SiMn steel for hydraulic support pillars, and a WC-Fe316L cladding layer with a hard phase WC particle mass fraction of 10%, 20% and 30%. The element distribution, phase composition, cross-section microhardness, microstructure, and wear resistance of the cladding layer are also studied. The main conclusions drawn are as follows:

1. The main phases of the pure Fe316L cladding layer are γ-[Fe,Cr,Ni], CrC, Cr23C6, Cr7C3 etc. Among them, CrC, Cr23C6, Cr7C3 and other carbide hard phases have established good performance of the cladding layer. Compared with the 27SiMn steel matrix, the average microhardness of the cladding layer is increased by 1.4 times to 331.2HV0.5, and its wear rate is 30.8% lower than that of the 27SiMn steel matrix.

2. With the increase of hard phase WC content, the content of CrC, Cr23C6, Cr7C3 hard phase in the WC-Fe316L cladding layer has been increased, and new carbide hard phases such as Fe3W3C and Fe6W6C have appeared.

3. The microhardness of the WC-Fe316L cladding layer with the mass fraction of WC particles of 10%, 20% and 30% is 1.6, 1.7 and 2.0 times higher than that of the 27SiMn steel matrix to 369.9HV0.5, 408.6HV0.5 and 481.6HV0.5. And the wear rate of each WC-Fe316L composite cladding layer was reduced by 45.8%, 66.0% and 82.3% compared with the matrix.

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