Effect of nano-WC content on microstructures and wear resistance of laser cladding Fe-based alloy coatings

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Abstracts
Three kinds of Fe-based power with different content of nano-WC were successfully prepared on 35CrMoV steel using laser cladding technique. The influence of nano-WC on the macro-morphology, microstructure and wear resistance of Fe-based coatings under different wear conditions was investigated by scanning electron microscopy and three-dimensional non-contact surface mapping. It has been found that a lot of fine grains and equiaxed grains synthesized with the addition of nano-WC. Both the volume fraction of eutectics and wear resistance of Fe-based coatings are greatly increased with a moderate addition of nano-WC, which is attributed to the exist of the partial dissolution of hard and high temperature WC phase in the composite coating. The wear rates increase more than 2–3 times with the addition of nano-WC range from 5 wt% WC to 10 wt% WC. Hence the addition of nano-WC strengthening phase is an effective and feasible way to improve the mechanical properties, especial for the tribological properties.

1. Introduction
Laser cladding method is one of the advanced surface repair technologies [1–3], the metallurgically bonded surface coating is formed on the matrix alloy. It can be used to enhance the strength, hardness, wear resistance of the material surface and other properties [4–6]. Nickel base, copper base, zinc base and iron base alloy powders are widely used in laser cladding material. The nickel-based powder has poor high temperature resistance [7, 8], copper-based powder has low hardness and is not suitable in friction and wear environment [9], and cobalt-based material has high cost [10]. However, nano-WC powder has high hardness, good high-temperature behavior as well as good wettability with Fe solution [11–14], and has been well applied in the preparation of iron-based composite coatings. At the same time, its mechanical properties are excellent, among which the friction and wear properties are outstanding. The nano-WC reinforced iron-based composites are selected for the experiment. At present, the element of Mo is a high temperature metal, which is beneficial for the grain refinement and improving high temperature wear property [15]. The addition of the WC-Ni hard particles is good for the improvement of microhardness and wear resistance for the Ni-based alloy coatings [16].

The previous results show that WC-Ni [17], nano-Nd2O3 [18] and Cerium [19] are good choices for the improvement of wear property, but studies on nano-WC has been inadequate, especially for the combination of nano-WC and Fe-based coating. Meanwhile, it is well known that nano-WC is conducive to formation of fine grains and polygonal equiaxed grains, which is beneficial to the improvement of the wear performance [20]. Therefore, the research work focused on the effect of different contents of nano-WC particles on Fe-based alloy coatings is very valuable. The macro morphology, microstructure, wear appearance and wear behaviors for the laser cladding Fe-based/nano-WC coatings were analyzed.
2. Materials and experimental procedures

Stainless steel (35CrMoV) plate (300 mm in length, 200 mm in width and 15 mm in thickness) with a nominal composition of Fe-2.5C-1.4Si-17Cr-4Ni (wt%) was used as the substrates. Spherical shaped Fe-based powder (80–150 μm (figure 1(a))) and spherical shaped nano-WC powder (20–50 nm (figure 1(b))) were thoroughly mixed. The morphologies of the mixture of Fe-based alloy powders with nano-WC powders particles is shown in figures 1(c) and (d), where spherical-shaped Fe-based alloy particles and evenly distribution nano-WC particles can be clearly discoverable.

The contents of nano-WC powders were 0 wt%, 5 wt% and 10 wt%, respectively. Prior to coating preparation, the mixed powder was heated at 80 °C for 1 h, and the steel substrate was cleaned in acetone solution and then preheated by a furnace at temperature of approximately 200 °C for 1 h to avoid cracking. The Fe-based coatings with different content of nano-WC were melted by DLS-3000 C laser cladding equipment. The optimized parameters are as follow, the laser power of 2 kW, the beam traverse speed of 600 mm min⁻¹, the beam diameter of 3 mm, overlapped tracks of 50% and high purity argon shielding gas with a flow rate of 15 l/min. The cladding thickness in this work is about 1.5 mm.

The microstructure of the cladding coatings was analyzed by scanning electron microscope (SEM) at selected locations. The samples were examined in an EM-125 electron microscope at an accelerating voltage of 100 kV. Preparation of SEM samples includes the steps of cutting, polishing, corrosion and metallographic analysis. The tests were performed under three different normal loads (20 N, 40 N and 60 N) for a period of 1 h at 100 r/min. The MicroXAM-800 non-contact optical profiler is used to measure its wear and surface topography 3D characteristics, and the MicroXAM 3D non-contact surface mapping profiler (ADE Corporation, Massachusetts, USA) is used to record the wear volume. The final result is obtained from three averaged testing value.

3. Results and discussion

3.1. Effect of nano-WC contents on the macro-morphology and microstructure

In order to analyze the cladding quality of the coatings, macro-morphology of the cladding coatings was shown in figure 2. It can be noted that there are some of cracks and pores in the cladding layer, which is detrimental to the quality of laser cladding products. Moreover, it is easy to found that the macroscopic feature of the Fe-based coating are relatively flat and the adjacent cladding layer overlaps well (figure 2(a)). For Fe-based with 5.0 wt%
and 10 wt% nano-WC coatings, the surface morphology of the coatings become coarser, but still no macroscopic cracks were found in the surface (figures 2(b) and 2(c)). The higher carbide content has negative effects on the cladding layer quality, due to the higher melting point of WC.

Figure 3 presents SEM morphology Fe-based cladding coatings with different contents of nano-WC, it can be obtained from figure 3 that both dendrites and columnar crystals are distributed in the substrate. The volume fraction of eutectic microstructure mainly composed of nano carbide increases with the increase of nano-WC. The direction of dendrite is obvious in the Fe-based coatings (figure 3(a)), and the dendrite direction was significantly affected by the thermal flow. The direction of heat flow and dendrite are perpendicular to each other. The dendrite has less directional with the addition of nano-WC in the Fe-based coating (figure 3(c)). For Fe-based with 5.0 wt% nano-WC coatings, the grains of the coatings are composed of fine grains the obvious polygon dendrites (figure 3(d)). The microstructure of Fe-based with 10 wt.% WC coatings are the thick dendrites and some of the eutectics grain, and the volume fraction of eutectic microstructure composed of nano carbide is close to 50% (figure 3(f)). Meanwhile, the direction of dendrite growth is not obvious, and a lot of rod-like grain are obtained in cladding coating (figure 3(e)). The main reasons for the above result. On the one hand, the hard nano-WC precipitate was proved to inhibit grain growth more effectively which is beneficial for grain refinement [21]. On the other hand, the laser cladding is a rapid melt and solidification process, during the solidification nucleation and growth process, dispersive precipitation of nano-WC is easy to form the heterogeneous nucleation and increase the number of crystal nucleus, which is beneficial to improve the performance of friction.

3.1.1. Effect of nano-WC contents on the wear morphology

Figure 4 indicates the SEM worn surfaces morphology for the cladding coatings with the adjust testing that the load size is from 20 N to 60 N. It could be found that the size of wear loss became bigger with the increase of applied loads from 20 N to 60 N, as shown in figures 4(c), 4(f) and 4(i). Besides, it can be obtained that the increment content of the addition nano-WC (up to 10 wt%) caused a decrease of the wear loss. The surface material removal was obviously affected by the abrasive wear.

For Fe-based coatings, the wear morphology of the matrix under low load (20 N) presents small furrows and large area of abrasive, indicating that the wear type is spalling (figure 4(a)). The wear morphology of the matrix under medium load (40 N) presents a large area of furrow and some ploughings, and the main wear type is micro-furrow (figure 4(b)). The wear morphology of matrix under high load (60 N) presents the adhesion phenomenon of furrow and small area basically, and the main wear type is plough wear (figure 4(c)). The adhesion and spalling phenomena of the matrix gradually decrease, and the matrix changes to plough wear with the increase of load. For Fe-based coatings with 5 wt% WC, the wear morphology of coating under low load presents a large number of adhesion phenomena, indicating that the main wear type is adhesive wear (figure 4(d)). The adhesion phenomenon of coating in the wear morphology under medium load reduces obvious plough cutting marks, indicating that the type of wear is the coexistence of adhesion wear and plough.
cutting wear (figure 4(e)). The wear morphology of coating under high load shows the adhesion phenomenon of furrow and small area, indicating that the main wear type is plough wear (figure 4(f)). Similarly, the wear property of cladding coating increases with the increase of load in the process of wear. Adhesion and peeling gradually decrease, constantly turning to plough wear. For Fe-based coatings with 10 wt% nano-WC, the wear morphology of coating under low load shows slight furrow and a small amount of debris, indicating that the main wear type is micro-furrow (figure 4(g)). The adhesion phenomenon of coating decreases in the wear morphology under medium load and there are obvious plough cutting marks (figure 4(h)). There are a large amount of accumulated debris and marks of rolling plastic deformation of the debris, indicating that the wear type is plough cutting wear. Wear resistance under high load wear morphology plough cutting trace is more obvious, grinding spot becomes smooth, further to plough wear transformation (figure 4(i)). Similarly, in the process of wear resistance, gradually decreases adhesion and peeling phenomenon along with the continuous increase of load, and constantly changes to plough wear. In general, the wear resistance is more obviously influenced by the hardness of materials [22]. Consequently, the higher the hardness of material has, the better of the wear resistance of material is became. The adhesion phenomenon in the material wear morphological diagram decreases and obvious plough cutting marks appear with the increase of WC. This is because there are a certain number of micro-bumps on the surface of Fe-based coatings with nano-WC [23]. As a result, it can be
obtained that the unmelted nano-WC particles dispersed distribution in the worn surface of the Fe-based cladding coatings, and the strengthen and hard phase can enhance the wear resistance of the Fe-based cladding coatings.

3.1.2. Effect of nano-WC contents on the wear behavior
The relationship between the load \((P)\) and the friction coefficient \((f_c)\) for different material coatings is shown in Figure 5. For Fe-based coatings, it can be found that the friction coefficient was small and fluctuated greatly before the time of 10 min. It is because that the steel ball was in point contact and the contact surface was a mirror. The lubrication was large, the friction was small, and the friction coefficient was unstable. The fluctuation range of the coefficient of friction decreases gradually with the increase of the load, and the coefficient of friction is all high (between 0.6 and 0.7) in the range of the load from 20 N to 60 N (Figure 5(a)). The friction coefficient (between 0.5 and 0.65) is stable and small under the low load of 20 N. For medium load, \(f_c\) was stable before 35 min and then jumped to a wide range under the medium load of 40 N, and the friction coefficient was mainly around 0.6. For medium and heavy loads, \(f_c\) increases slowly with the increase of time, but the corresponding \(f_c\) growth rate is small (Figure 5(a)).

For Fe-based coatings with 5 wt% WC, \(f_c\) is slowly increasing with the increase of time, the fluctuation range of \(f_c\) is larger, and the interference of abrasive debris affects the numerical jump of \(f_c\). Meanwhile, it can be seen that the fluctuation range of \(f_c\) decreases (between 0.6 and 0.75) gradually with the increase of \(P\). It meant that the addition of nano WC makes the coefficient of friction become unstable. This is because the microstructure distribution of cladding layer is uneven with addition of nano WC. On the other hand, the composition changes greatly which affects the \(f_c\) value in the process of wear (Figure 5(b)). Especially for Fe-based coatings with 10 wt% WC, the range of friction coefficients is larger as the load changes from 20 N to 60 N (Figure 5(c)). The \(f_c\) is highly unstable and fluctuates in a large range under the low load of 20 N, \(f_c\) tends to be stable with the increase of \(P\). These small amount of unmelted nano WC particles can easy leads to the severe abrasive wear, besides, the laser cladding process is rapid solidification process which tends to produce large temperature gradients. It well known that the addition of carbide and the high solidification rate are conducive to the generation of cracks and uneven microstructure as a consequence is harmful to the stability of wear coefficient.
Wear loss weight can effectively characterize the wear property of the material. In order to further determine the actual wear amount of the material, the wear capacity was analyzed under the difference load testing conditions (low load 20 N, medium load 40 N and high load 60 N) in figure 6. The wear capacity under heavy load of the same coating is twice as much as that of the under medium load, and the wear capacity under medium load is about four times as much as that under low load. The wear capacity gradually increases with the increase of the load. According to the comparison of the wear capacity of Fe-based coatings with the addition of nano-WC, the improvement of wear ability is significant influenced by the addition of nano-WC especially under high load testing conditions. The wear capacity increase more than 10–20 times with the addition of nano-WC from 5%WC to 10%WC under high load testing conditions. The wear capacity of cladding coating can be improved by adding nano-WC, due to the formation of Cr23C6, W2C and WC hard phases as the laser cladding solidification process. Besides, the microhardness of Fe-based/WC composite coating is higher than the Fe-based coating, which is attributed to the formation of WC and W2C hard ceramic phases in the cladding coating [24].

The wear rates of the three types of laser cladding coatings (Fe-based, Fe-based + 5%WC and Fe-based + 10%WC) are shown in figure 7. The wear rates decrease more than 2–3 times with the addition of nano-WC from 5%WC to 10%WC under the medium load of 40 N. The wear rates decrease more than 4–6 times with the addition of nano-WC from 5%WC to 10%WC under the high load of 60 N. The gap of the wear rates of the three types laser cladding also increased with the load condition increases. It can be found the wear rates of the coatings with the addition of 5%WC and 10%WC is smaller than the Fe-based coatings, indicating that the addition nano-WC is beneficial for improvement the wear resistance. Besides, Fe-based/WC composite coating has better high temperature wear property than Fe-based coating, because the formation of hard and high temperature WC particles has better wear resistance which is good for higher surface hardness [25].

In order to get a deeper analysis for underlying wear mechanism, the surface morphology 3D characterizations were measured by microxam-800 contact-free optical profiler, and 3D wear morphology of Fe-based coatings with the addition of nano-WC (Fe-based, Fe-based + 5%WC and Fe-based + 10%WC) under high load (60 N) were compared, as shown in figure 8. It can be found that the worn surface of the Fe-based coating has the abrasive and adhesion wear phenomenon and obvious plastic deformation on the edges wear testing (figures 4(c) and 8(a)). The wear morphology of Fe-based coating is narrow and deep and the 3D wear morphology displays V-shaped. According to the quantitative calculation, the surface wear area is
0.749 mm², the area at the wear peak is 0.0753 mm², the wear volume is 2787572 μm³, the wear volume at the wear peak is 12776 μm³, the maximum wear depth is 15.2 μm, and the average wear depth at the wear peak is 0.369 μm.

According to the above Fe-based coating, there is no obvious sign of plastic deformation and only shallow grooves on the worn surfaces of coating with Fe-based + 5%WC (figures 4(f) and 7(b)); and. Furthermore, the grooves in the surface of Fe-based + 5%WC coating are shallower than that of Fe-based coating. This result is well consistent with the wear resistance of Fe-based + 5%WC coating. According to the quantitative calculation, the surface wear area is 0.727 mm², the wear peak area is 0.0805 mm², the wear volume is 1343167 μm³, the wear peak volume is 8056 μm³, the maximum wear depth is 12.3 μm, and the average wear depth at the wear peak is
0.100 μm. The surface morphology of Fe-based + 5%WC coating is wider and lighter than those on the worn surface of Fe-based coating, and the wear peak becomes lower, but the appearance of two peaks are shown in figure 8(b), which resulting in a slight increase in the overall wear amount of the coating.

The wear morphology becomes shallower and wider with the increase of the content carbon, as shown in figure 8(c). According to the quantitative calculation, the surface wear area is 1.03 mm², the area at the wear peak is 0.0468 mm², the wear volume is 3176719 μm³, the volume at the wear peak is 5292 μmm³, the maximum wear depth is 8.51 μm, and the average wear depth at the wear peak is 0.113 μm. This shows that the laser cladding Fe-based coatings can easily lead to the severe wear of counterparts and the addition of nano-WC of laser cladding coating have better wear property than that the Fe-based substrate [26]. Thus, it is necessary to make a proper choice for strengthening and hard phase which is applicated in the laser cladding of Fe-alloy based composite coating.

4. Conclusion

It has been found that the addition nano-WC 5 wt%WC and 10 wt%WC have better wear resistance than that of the Fe-based coating, which is contribute to the exist of hard WC phase during laser cladding solidification. Among the key findings are the following:

(1) In the Fe-based coatings, the dendrite has less directional with the addition of nano-WC in the Fe-based coating. For Fe-based with 5.0 wt% nano-WC coatings, the grains of the coatings are composed of fine grains the obvious polygon dendrites.

(2) There is a large area ploughing and a seriously adhesive wear in the Fe-based coatings. The undecomposed nano-WC particles embed in the Fe-based matrix on the surface of the coatings, and the formation of strengthen and hard phase is beneficial to improve the wear resistance of the Fe-based coating.

(3) The wear morphology changes from V-shape to concave type, the wear marks are wider and shallower, and the wear depth is significantly reduced with the addition of nano-WC ranges from 5%WC to 10%WC.

![Figure 8. 3D non-contact surface mapping of the wear scars under high load: (a) Fe-based coating, (b) Fe-based coating with 5%WC, (c) Fe-based coating with 10%WC.](image-url)
Meanwhile, wear volume of Fe-based with 5% nano-WC is about 65% of Fe-based coating, and wear volume of Fe based with 10% nano-WC is about 80% of Fe-based coating.

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