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Article

Effect of Nano-Y₂O₃ on the Microstructure and Properties of Fe-Cr-C-N-Al Surfacing Alloy

Xingyu Ai, Zhengjun Liu * and Zongxuan Zou

Department of Materials Science and Engineering, Shenyang University of Technology, Shenyang 110870, China; 18809816959@163.com (X.A.); 15942492610@163.com (Z.Z.)

* Correspondence: liuzhengjun1962@163.com; Tel.: +86-138-0499-4179

Abstract: In this paper, Fe-Cr-C-N-Al-Y wear-resistant surfacing alloy was prepared by open arc surfacing with self-shielded flux-cored wire. The wear properties of the surfacing alloy were analyzed by MLS-23 rubber wheel wet sand wear tester. The phase composition and microstructure of the surfacing alloy were analyzed by XRD, SEM, EBSD and TEM, and the strengthening mechanism and wear mechanism of the alloy were discussed. The results show that the microstructure of Fe-Cr-C-N-Al-Y surfacing alloy is composed of M + γ -Fe + M₇C₃ + AlN. When the content of nano-Y₂O₃ is 0.456wt. %, the formability of the surfacing alloy is the best and the wetting angle is the smallest, which is 50.8°, AlN and M₇C₃ precipitate the most, and the microstructure grain is the smallest. At this time, the hardness value of the surfacing alloy is up to 62.3 HRC, which is 11.8 % higher than that of the unmodified surfacing alloy. The minimum wear weight loss is 0.125 g, and the wear resistance is increased by 41.86 %. The wear mechanism of surfacing alloy is mainly plastic deformation mechanism, and the material removal process is micro cutting and furrow wear.

Keywords: Fe-Cr-C; surfacing alloys; nanometer rare earth; hardening phase; abrasive wear

1. Introduction

With the continuous progress of industrial civilization and science and technology, higher requirements are put forward for the performance of materials. Wear, corrosion and fatigue constitute three forms of mechanical parts failure. The energy consumption and economic loss caused by the wear of mechanical parts are particularly serious [1–3]. With the rapid development of industry, how to improve the wear resistance of mechanical parts and increase the service life of parts is very important and of great economic significance [4–6]. Fe-Cr-C surfacing alloy will generate a large number of M₇C₃ primary carbides in the structure. This high hardness carbide can effectively improve the wear resistance of the surfacing layer and is very suitable for abrasive wear and erosion wear environment. However, large primary carbides are very easy to peel off, which greatly limits the application environment of Fe-Cr-C surfacing alloys. In recent years, many scholars have found that the use of cheap N elements instead of some C elements, the use of in-situ self-generating technology to form fine nitrides in the surfacing process. The formation of nitrides can effectively refine the microstructure, increase the hardness of the surfacing alloy, and effectively improve the wear resistance of the surfacing alloy [9,10]. In order to improve the wear resistance of Fe-Cr-C surfacing alloy, Wei et al. introduced titanium carbonitride in situ and deposited TiC-Ti_x(C, N)_y coating on the surface of ASTM G3101 steel by gas shielded welding [11]. The results show that the formation of Ti_x(C, N)_y carbonitride can effectively prevent the wear of the matrix and stop the dislocation sliding. Therefore, the titanium carbonitride reinforced coating has high hardness and excellent wear resistance under dry sliding wear test conditions.

In-situ synthesis technology is simple, which is of great help to improve the wear resistance of iron-based surfacing materials, and has been deeply concerned by domestic and foreign scholars [12–14]. Li et al. prepared an iron-based surfacing layer containing M₇C₃ and NbC in situ, and studied the effect of NbC content on the microstructure and wear resistance of iron-based composites [15]. It was found that α -(Fe, Cr), (Fe, Cr) C₃, NbC existed in all the surfacing layer. NbC are formed by the chemical reaction of Nb and C in the molten pool. With the increase of NbC content, the size and

quantity of NbC increase obviously. The shape of the hard phase also gradually changed from square to petal. In addition, with the increase of NbC content, the average microhardness increased from 819.3 HV_{0.2} (5 wt. %) to 900.5 HV_{0.2} (20 wt. %).

Nanometer rare earth oxide is a compound that is mainly used to improve the surface properties of materials. Because of its good physical and chemical properties, such as special electronic structure, good chemical activity and large ionic radius, it can be used as a grain refiner in surfacing alloys [16–22]. Adding an appropriate amount of nano rare earth oxide to the surfacing material may cause grain refinement and reduce crack sensitivity, thereby improving the hardness, wear resistance and corrosion resistance of the surfacing alloy surface. Chen et al. prepared TiC/Co-based coatings with different contents of nano-CeO₂ additives on ferritic steel by laser surface cladding technology [23]. It is reported that the addition of nano rare earth oxides creates new conditions for the nucleation of precipitated phases. Due to the uniform distribution of the precipitated phase, the coating with 1.5wt % CeO₂ exhibits high corrosion resistance, high microhardness and high wear resistance. Yun et al. prepared hypereutectic Fe-Cr-C surfacing layer by flux-cored wire arc surfacing, and studied the effect of different Y₂O₃ additives on the wear resistance of hypereutectic Fe-Cr-C surfacing layer [24]. The results show that the microstructure of the surfacing layer is composed of primary (Cr, Fe) γ C₃ and eutectic structure [A+ (Cr, Fe) γ C₃]. Y₂O₃ can refine M₇C₃ and significantly improve the wear resistance of the surfacing layer.

The addition of nano-Y₂O₃ in the surfacing alloy can be used as a heterogeneous nucleation particle of the hard phase to refine the M₇C₃ eutectic carbide. In this study, Fe-Cr-C-N-Al-Y wear-resistant surfacing alloys were prepared by open arc surfacing with self-shielded flux-cored wire. The effects of rare earth oxide Y₂O₃ on the microstructure and wear resistance of Fe-Cr-C-N surfacing alloys were studied.

2. Experimental Process

2.1. Preparation of Surfacing Alloy

The self-shielded flux-cored wire was used in the surfacing experiment, and the core composition was alloy powder and mineral powder. The core composition mainly includes high carbon ferrochrome, chromium nitride, graphite, aluminum powder, reduced iron powder (90-120 mesh) and spheroidized nano-Y₂O₃ powder (300-500 mesh, purity 99.9 %). The powder required for flux-cored wire is filtered through a sieve to remove large particles of powder and impurities. Put the filtered powder into the electrode drying furnace to dry, remove the moisture. After that, the filtered powder was placed in a planetary ball mill, 250rpm, running for 5 minutes, so that the powder was stirred evenly, which was conducive to maintaining welding stability and ensuring the homogenization of the microstructure of the surfacing layer. The outer skin of the flux-cored wire is H08A steel strip, and the base material is Q235 steel, composition is shown in Table 1. The production process of flux-cored wire is rolling-drawing method, which is simple in operation, high in production efficiency and good in wire forming quality. The diameter of the welding wire is reduced from Φ4.0mm to Φ3.2mm, Φ2.7mm and Φ2.4mm by four groups of reducing machines. The filling rate of the self-shielded wear-resistant surfacing flux-cored wire is about 38%. According to the preliminary experiment, the slag system of self-shielded welding wire for surfacing experiment was determined by considering the factors such as metal formability, splash, porosity and crack of surfacing layer. The specific composition is shown in Table 2.

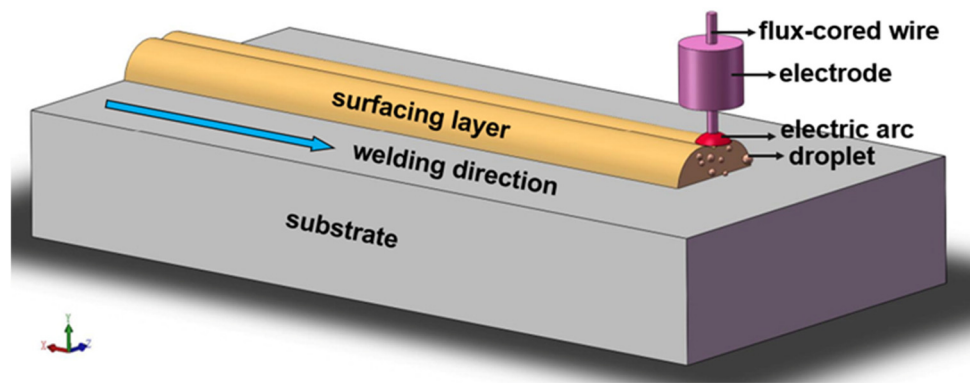
Table 1. Chemical composition of H08A steel strip and base metal (mass fraction, wt. %).

	C	Si	Mn	S	P	Fe
Q235	0.14-0.22	≤0.30	0.30-0.65	<0.045	<0.045	Bal
H08A	<0.01	≤0.03	0.30-0.55	≤0.03	≤0.03	Bal

Table 2. Slag system content of self-shielded flux-cored wires (mass fraction, wt.%).

	CaF ₂	SiO ₂	CaO	MgO	Al ₂ O ₃
Content	1.2-1.5	0.8-1.0	0.3-0.5	0.2-0.5	1.0-1.5

The open arc surfacing experiment was carried out on Q235 substrate by MZC-1250 AC automatic submerged arc welding machine to prepare surfacing alloys with different compositions. The welding diagram is shown in Figure 1, and the chemical composition of surfacing alloys is shown in Table 3. In order to reduce the dilution rate, a two-layer four-pass surfacing method was used to ensure that the microstructure of the top layer of the surfacing alloy was not affected by the substrate. After welding, enough cooling time should be maintained, and the interlayer temperature should be controlled at about 200 °C to prevent cracks. The overlap rate is between 35% and 50%. After machining, the microstructure and properties were tested. In this experiment, the content of nano-Y₂O₃ in self-shielded flux-cored wire was 0.114wt.%, 0.228wt.%, 0.342wt.%, 0.456wt.% and 0.570wt.%, respectively. Due to the low addition of nano-Y₂O₃ and the large heat input during the surfacing process, it is easy to cause some nano-Y₂O₃ to burn. This will lead to a deviation in the measurement of Y content in the surfacing alloy. Therefore, the Y content in the surfacing alloy is expressed by the amount of Y₂O₃ added in the flux-cored wire.

**Figure 1.** Schematic diagram of surfacing welding process.

Number	C	Cr	N	Al	Y	Fe
0	2.67	15.32	0.39	3.24	—	Bal.
1	2.43	13.85	0.39	3.63	<0.01	Bal.
2	2.66	13.61	0.41	3.69	<0.01	Bal.
3	2.58	15.31	0.45	3.84	0.02	Bal.
4	2.71	16.21	0.51	3.81	0.03	Bal.
5	2.57	14.87	0.48	3.79	0.04	Bal.

The surfacing alloy was machined to obtain the experimental specimens of microstructure characterization and mechanical properties. The position of the specimen is shown in Figure 2. The phase composition of the surfacing alloy was analyzed by Brooke D8 X-ray diffractometer. The test parameters: CuK_α target, tube voltage 50KV, scanning range 20° -100°, scanning speed 4° / min. The microstructure, phase distribution and wear morphology of the surfacing alloy were observed by OMLPUS BX-6 optical microscope and HITACHI S-3400 N scanning electron microscope, and the composition of the precipitated phase was analyzed by energy dispersive spectrometer equipped with scanning electron microscope.

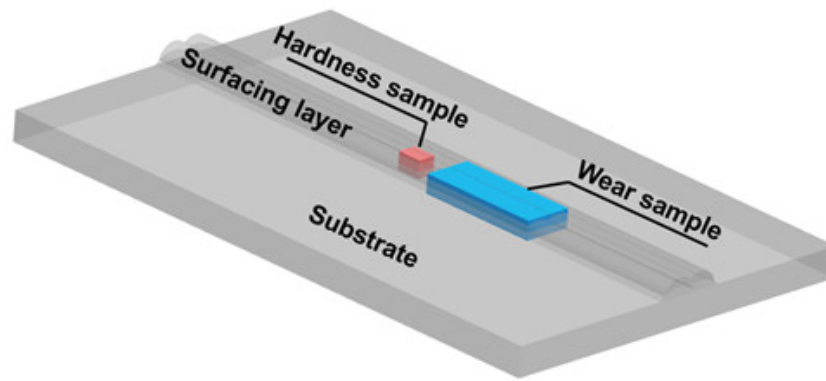


Figure 2. Schematic diagram of sampling location.

The ZEISS MERLIN Compact field emission scanning electron microscope equipped with Symmetry probe was used to analyze the samples by electron backscatter diffraction (EBSD) technique. The results were analyzed by Channel 5 software to analyze the grain size and volume fraction of precipitated phase in the surfacing alloy. The preparation method of EBSD sample is as follows: The polished sample is electropolished in 10 % perchloric acid alcohol solution with a voltage of 30V and a time of 30s.

The microstructure of the surfacing alloy samples was observed by FEI TalosF200 X transmission electron microscope (TEM). The type and structure of the precipitated phases in the surfacing alloy were determined by selected area electron diffraction (SAED), and the composition of the precipitated phases was determined by energy spectrometer.

The surface hardness of surfacing alloy was measured by HRC-150 Rockwell hardness tester. The microhardness of the side of the surfacing alloy was tested by Vickers hardness tester (TMVP-1T, Beijing, China) under the condition of loading 1 Kg and loading time 15 s. The abrasive wear experiment was carried out using MLS-23 rubber wheel wet sand wear tester, and the schematic diagram is shown in Figure 3. The experimental parameters are as follows: the number of rubber wheels is 240rpm, the wear time is 3min, and the maximum positive pressure of the rubber wheel is 23kg.

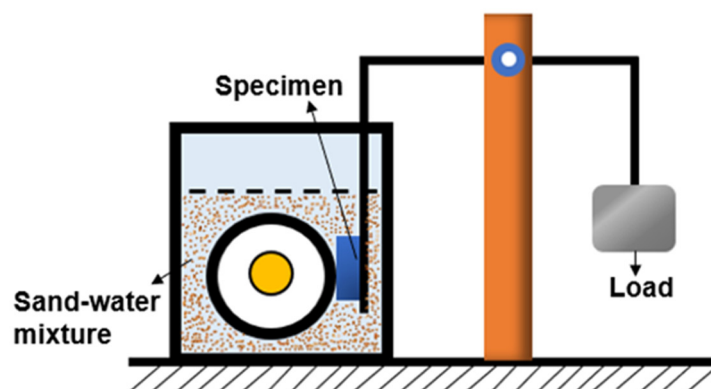


Figure 3. Schematic diagram of abrasion test.

3. Results and Discussion

3.1. Formability Analysis

Wetting refers to the process in which one fluid on the solid surface is replaced by another fluid. The schematic diagram is shown in Figure 4. The basic wetting can be expressed by Young Dupre equation [25]:

$$\cos\theta = (\sigma_{sg} - \sigma_{sl}) / \sigma_{lg}$$

In the formula, θ is the wetting angle; σ_{sg} is the surface tension of solid; σ_{sl} is the solid-liquid interfacial tension; σ_{lg} is the liquid surface tension. The smaller the θ , the better the wettability. The wettability depends on the surface tension of the solid, the solid-liquid interface tension and the liquid surface tension. For liquid, the lower the surface tension, the better the wettability [26,27].

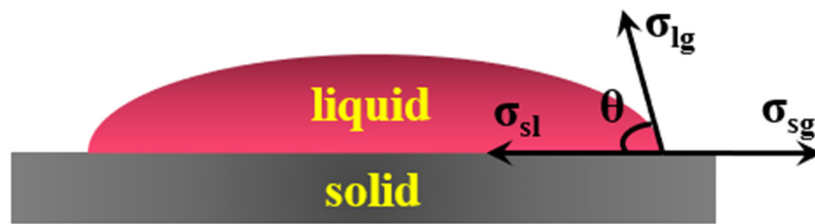


Figure 4. Schematic diagram of wetting.

The addition of rare earth elements in the surfacing alloy can also improve the fluidity and wettability of the metal-based composite powder, eliminate defects such as pores, and improve the macroscopic formability of the weld [28,29]. Figure 5 is the cross-section morphology of the surfacing alloy with different nano-Y₂O₃ content perpendicular to the welding direction.

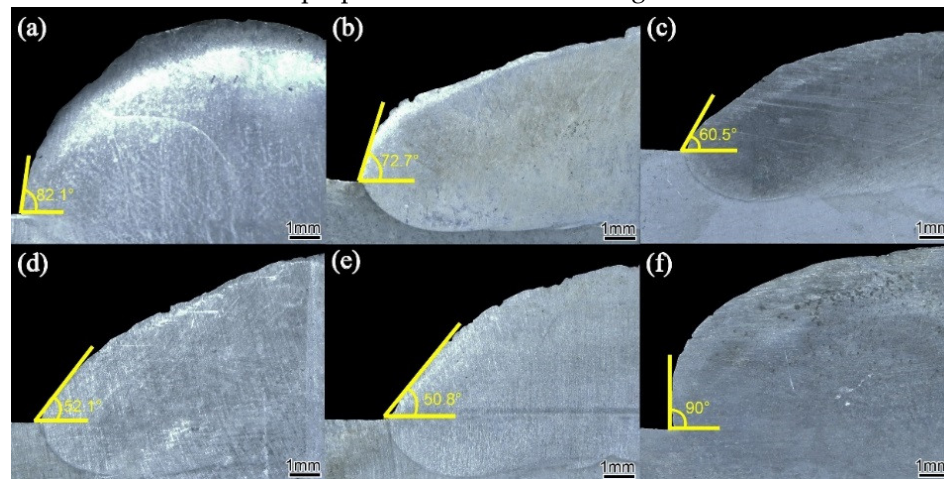


Figure 5. Cross-sectional morphology of surfacing alloy with different content of Y₂O₃.

With the increase of nano-Y₂O₃ addition from 0 wt. % to 0.456 wt. %, the wetting angle decreases to a minimum of 50.8°, and the formability of the surfacing alloy is good. When the addition of nano-Y₂O₃ is 0.570 wt. %, the wetting angle of the surfacing alloy increases to 90°, and the formability becomes worse. The reason is that nano-Y₂O₃ is added to the deposited metal as an oxide dispersion particle. With the increase of nano-Y₂O₃ content, the conductivity and thermal conductivity of the deposited metal decrease, thereby reducing the surface tension of the molten pool metal and reducing the wetting angle, which will lead to the improvement of the wettability between the molten pool metal and the base metal. Therefore, adding an appropriate amount of nano-Y₂O₃ can obtain a surfacing alloy with good forming quality.

3.2. Phase Analysis

Figure 6 is the XRD diffraction pattern of the surfacing alloy with different contents of nano-Y₂O₃. It can be found that the matrix structure of the surfacing alloy is composed of retained austenite (γ -Fe) and martensite M, and the hard phase is mainly composed of M₇C₃ eutectic carbide and AlN. It can be found that the base microstructure of the surfacing alloy is composed of retained austenite (γ -Fe) and M, and the hard phase is mainly composed of M₇C₃ and AlN. The addition of nano-Y₂O₃ has little effect on the phase composition of the surfacing alloy. However, compared with the surfacing alloy without nano-Y₂O₃ additive, the diffraction peaks of γ -Fe in the surfacing alloy with nano-Y₂O₃ additive shifted from 49.9° and 73.84° to 48.26° and 70.76°. According to Bragg's law:

$$2d\sin\theta=\lambda$$

In the formula: λ is the wavelength of X-ray, d is the interplanar spacing, and θ is the diffraction angle. In the experiment, the diffraction condition of X-ray diffraction experiment is constant. The decrease of diffraction angle leads to the increase of γ -Fe crystal plane spacing d , resulting in lattice distortion. Because the atomic radius of Y atom is 2.27Å. With the larger atomic radius Y occupying the γ -Fe lattice position, the lattice distortion energy increases significantly, the solid solution strengthening effect increases, and the strength of the surfacing alloy matrix is improved [30]. With the addition of nano- Y_2O_3 additive, M_7C_3 has an obvious diffraction peak at 41.5°. This shows that the addition of nano- Y_2O_3 changes the growth orientation of M_7C_3 . However, no diffraction peak of nano- Y_2O_3 was found in the X-ray diffraction pattern, which may be due to the fact that the content of rare earth elements added is lower than the limit value that XRD equipment can detect.

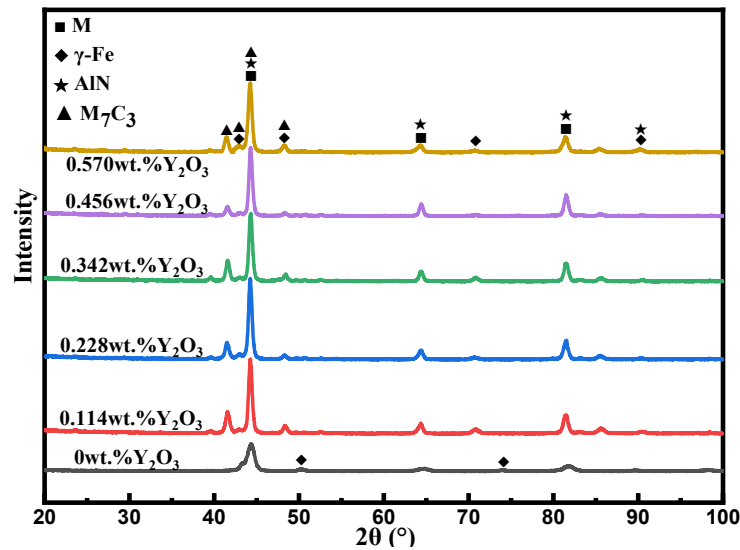


Figure 6. XRD diffraction pattern of the surfacing alloys with different content of nano- Y_2O_3 .

3.3. Microstructure Analysis

Figure 7 shows the metallographic structure of surfacing alloy with different nano- Y_2O_3 content. It can be found from the figure that the surfacing alloy is a typical hypoeutectic structure. The matrix is composed of γ -Fe and M, and the precipitated phase is composed of network M_7C_3 and black spotted AlN. When the addition amount of nano- Y_2O_3 is 0.456 wt. %, the microstructure of the surfacing alloy is the smallest, and the original coarse dendrites become equiaxed grains. The precipitation of M_7C_3 and AlN is the largest and evenly distributed. This is because the high melting point nano- Y_2O_3 is difficult to completely melt during the surfacing process. The incompletely melted Y_2O_3 in the surfacing alloy can easily become the core of heterogeneous nucleation, which can improve the nucleation rate and promote the formation of AlN. The large amount of dispersed AlN can effectively pin the grain boundary, hinder the grain boundary migration and refine the grain [31,32]. As the addition of nano- Y_2O_3 continues to increase to 0.570 wt. %, the structure becomes coarse dendrite crystals again. This is because the addition of excessive nano- Y_2O_3 leads to a decrease in the fluidity of the molten pool, slowing down the convection speed, slowing down the cooling of the molten pool, thereby increasing the time of dendrite growth [33,34]. This shows that adding an appropriate amount of nano- Y_2O_3 can play a role in grain refinement, and excessive nano- Y_2O_3 is not conducive to improving the microstructure of the surfacing alloy.

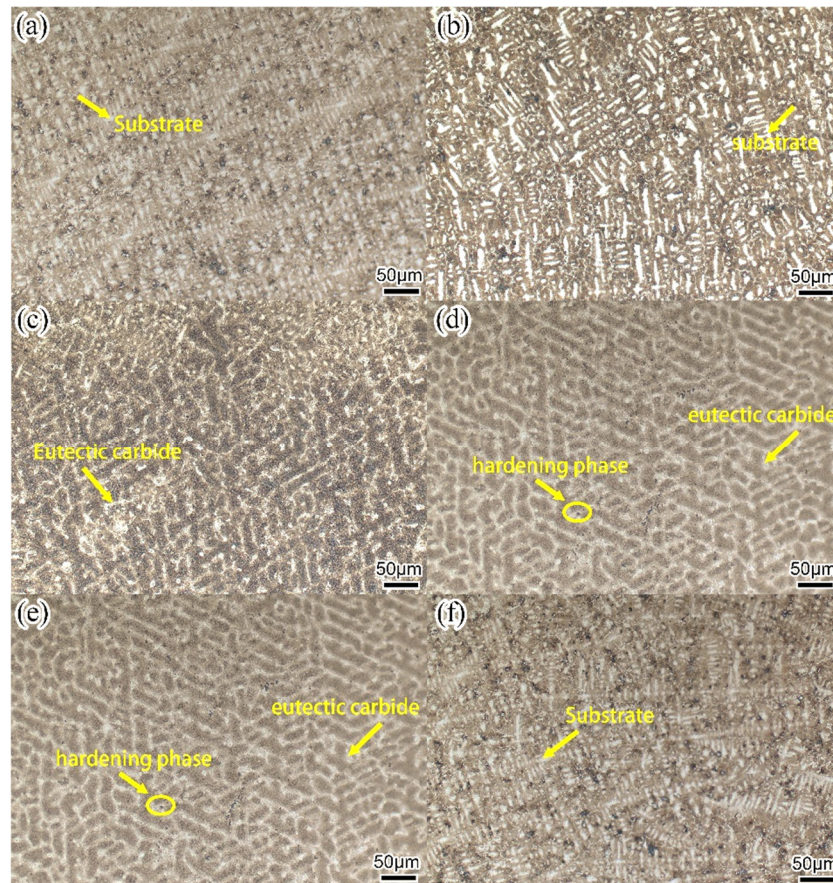


Figure 7. Microstructure metallographic diagram of surfacing alloy with different nano- Y_2O_3 content (a) 0 wt.% Y_2O_3 , (b) 0.114 wt.% Y_2O_3 , (c) 0.228 wt.% Y_2O_3 , (d) 0.342 wt.% Y_2O_3 , (e) 0.456 wt.% Y_2O_3 , (f) 0.570 wt.% Y_2O_3 .

In order to intuitively understand the element composition of each phase in the surfacing alloy structure. The EDS element distribution of the surfacing alloy with 0.456wt. % nano- Y_2O_3 was analyzed. The analysis results are shown in Figure 8. Figure 8a is the microstructure morphology of the surfacing alloy. Figure 8b–f are the element distribution maps of Fe, Cr, N, Al and Al / Cr, respectively. Due to the low content of Y and the small atomic radius of C, the element distribution of these two elements is not accurate and therefore not listed in the figure. The area with bright color in the figure is the element enrichment area, while the dark area represents the element depletion area. From the diagram, it can be clearly observed that the surfacing alloy is Fe matrix, and the network eutectic carbide is rich in Cr, and the content of Fe is lower than that of Cr. The hard phase particles are rich in Al and N. Combined with XRD analysis, M_7C_3 carbide is $(\text{Cr}, \text{Fe})_7\text{C}_3$. The black granular hard phase is AlN. Meanwhile, a small amount of Al, N and Cr are also distributed in the matrix. These alloying elements present in the matrix can play a role in solid solution strengthening of the surfacing alloy and play a positive role in improving the wear resistance of the surfacing alloy. In the analysis of the surface distribution of surfacing alloy elements, the presence of Y in AlN cannot be actually detected. In order to prove that nano Y_2O_3 can become the nucleation particle of AlN, the microstructure of surfacing alloy should be analyzed by TEM.

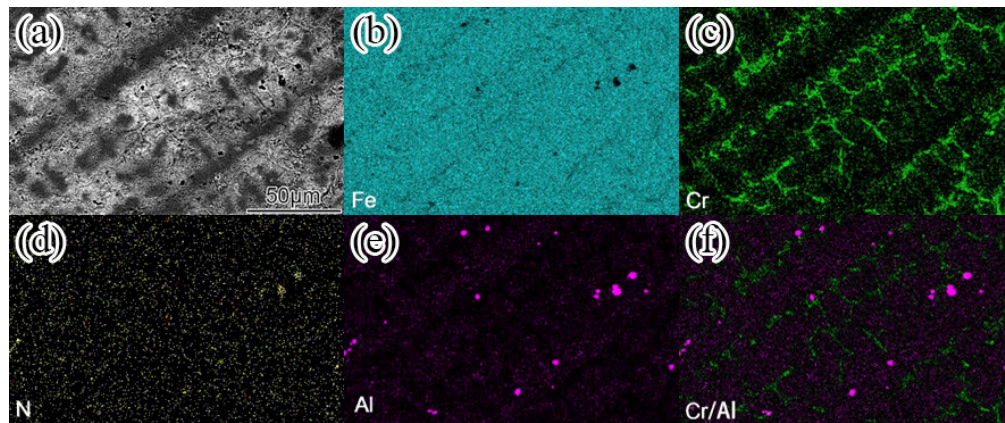


Figure 8. Microstructure of 0.456wt.%Y₂O₃ surfacing alloy and EDS element mapping analysis (a) morphology of microstructure, (b) Fe, (c) Cr, (d) N, (e) Al, (f) Cr/Al.

Figure 9 is the STEM-BF image and selected area electron diffraction pattern (SAED) of the surfacing alloy matrix with 0.456 wt. % nano-Y₂O₃ addition. From the electron diffraction pattern of Figure 9a, it can be analyzed that the matrix is austenite γ -Fe, face-centered cubic structure (fcc), crystal band axis is [112], lattice constant $a = 0.385$ nm. From the electron diffraction pattern of Figure 9b, it can be analyzed that the matrix is M, body-centered cubic structure (bcc), band axis [110], lattice constant $a = 0.293$, $c = 0.315$. Through TEM analysis, the matrix of the surfacing alloy is composed of retained austenite and martensite, which is consistent with the results of XRD analysis.

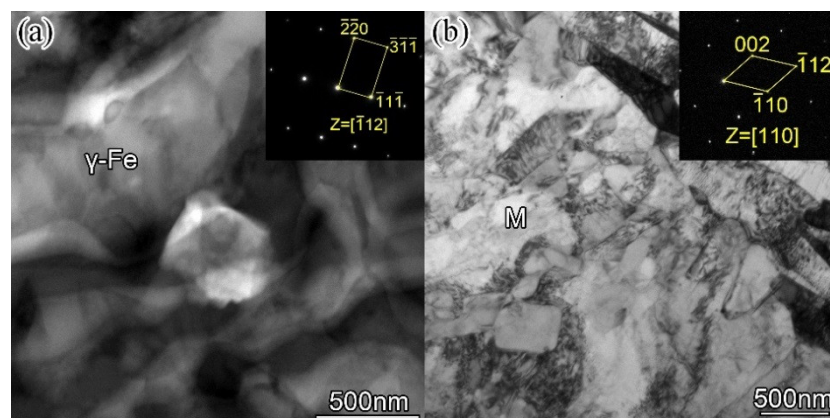


Figure 9. STEM image and selected area electron diffraction pattern of 0.456wt. % Y₂O₃ surfacing alloy matrix microstructure (a) γ -Fe, (b) M.

Figure 10 is the STEM-BF and the corresponding STEM-EDS of eutectic carbides in the surfacing alloy with 0.456 wt. % nano-Y₂O₃ addition. From Figure 10a, it can be seen that the dark irregular area is eutectic carbide, and the light area is surfacing alloy iron matrix. From the STEM-EDS corresponding to Figure 10a (Figure 5.11b–f), it can be found that the eutectic carbide region is poor in N and Al. The enrichment area of Cr and C corresponds to the shape of eutectic carbides. Combined with the electron diffraction pattern of eutectic carbide in Figure 10a, it can be seen that the eutectic carbide is face-centered cubic structure (fcc) and the crystal band axis is [001]. The lattice constants are $a = 4.53\text{\AA}$, $b = 7.01\text{\AA}$, $c = 12.2\text{\AA}$. This is consistent with the M_7C_3 structure. When the Fe atom replaces the Cr atom in Cr_7C_3 , because the difference between the radius of Fe atom and the radius of Cr atom is very small, the crystal structure of the formed $(Cr, Fe)_7C_3$ eutectic carbide does not undergo large lattice distortion, and the final eutectic carbide structure is orthogonal.

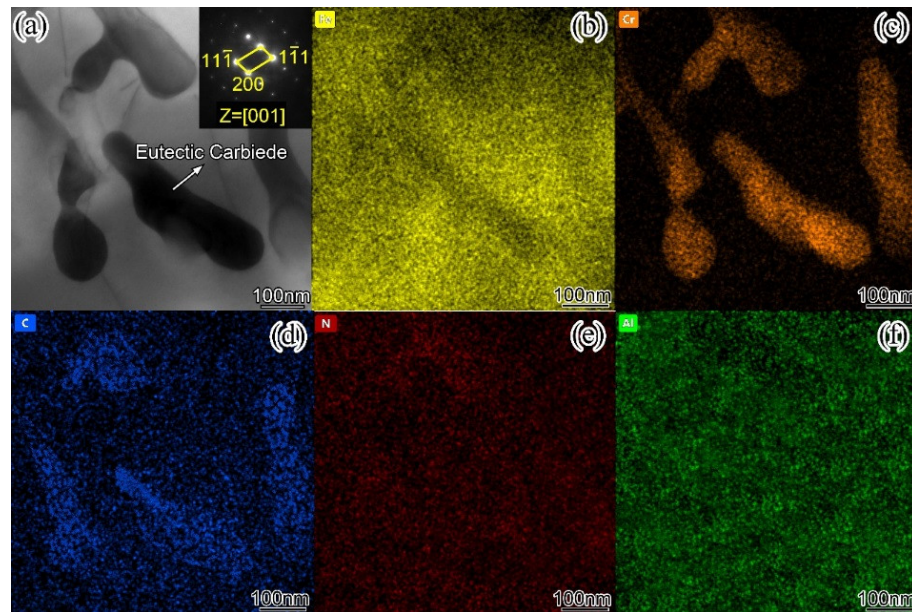


Figure 10. STEM-BF image of 0.456wt. % Y_2O_3 surfacing alloy eutectic carbide and STEM-EDS maps (a) Morphology of eutectic carbide and SAED patterns, (b)-(f) STEM-EDS maps corresponding to (a).

Figure 11 is the STEM image of the hard phase of the surfacing alloy with 0.456 wt. % nano- Y_2O_3 addition. It can be found from Figure 11a that the hard phase is an irregular hexagon, and there are dark strip particles in the middle area of the hard phase. The corresponding electron diffraction patterns were obtained by selecting electron diffraction in A and B regions. In Figure 11b, it can be known from the calibration of the diffraction pattern that the A region is a typical face-centered cubic structure (fcc), the crystal band axis is $[011]$, and the lattice constant is $a = 4.1\text{\AA}$. By comparing with the PDF card, it is determined that the hard phase is AlN and the space group is Fm-3m (225). In Figure 11c, it was found to be a face-centered cubic structure, $a = 10.554\text{\AA}$, and it can be determined to be Y_2O_3 after comparing the PDF card. From Figure 5.12a, it can be clearly seen that the AlN hard phase grows around Y_2O_3 , and the two are closely combined. This confirms from the experimental results that AlN and Y_2O_3 can form a heterogeneous nucleation interface. Y_2O_3 can be used as a nucleation particle to effectively promote the formation of AlN , refine the grains and promote the precipitation of eutectic carbides, and the wear resistance of the surfacing alloy is significantly improved.

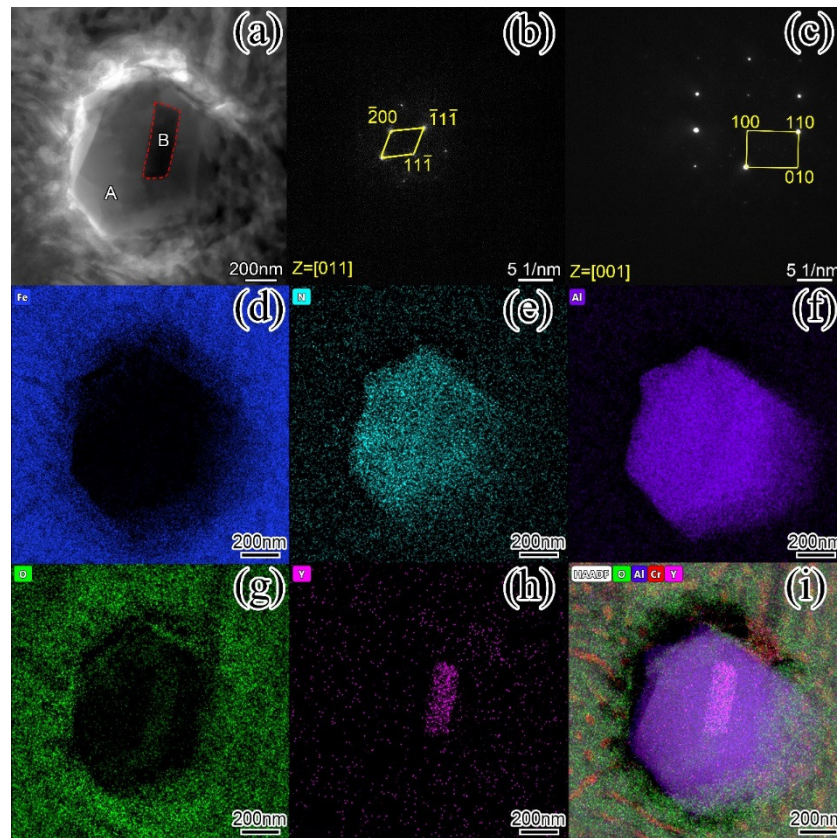


Figure 11. STEM-BF image of 0.456wt. % Y_2O_3 surfacing alloy hardening phase and STEM-EDS maps (a) Morphology of hardening phase, (b) SAED patterns of A, (c) SAED patterns of B, (d)-(i) STEM-EDS maps corresponding to (a).

Figure 12 is the EBSD inverse pole figure (IPF) and grain size statistics of nano- Y_2O_3 surfacing alloys with different contents. It can be seen from the figure that with the increase of nano- Y_2O_3 content to 0.456 wt. % Y_2O_3 , the grain refinement of the surfacing alloy is obvious, the average grain equivalent diameter is reduced from $3.35\mu\text{m}$ to $2.96\mu\text{m}$, and the grain size distribution is more uniform. As the content of nano- Y_2O_3 continues to increase to 0.570 wt. %, the grain size of the surfacing alloy increases to $4.03\mu\text{m}$ and the grain size varies.

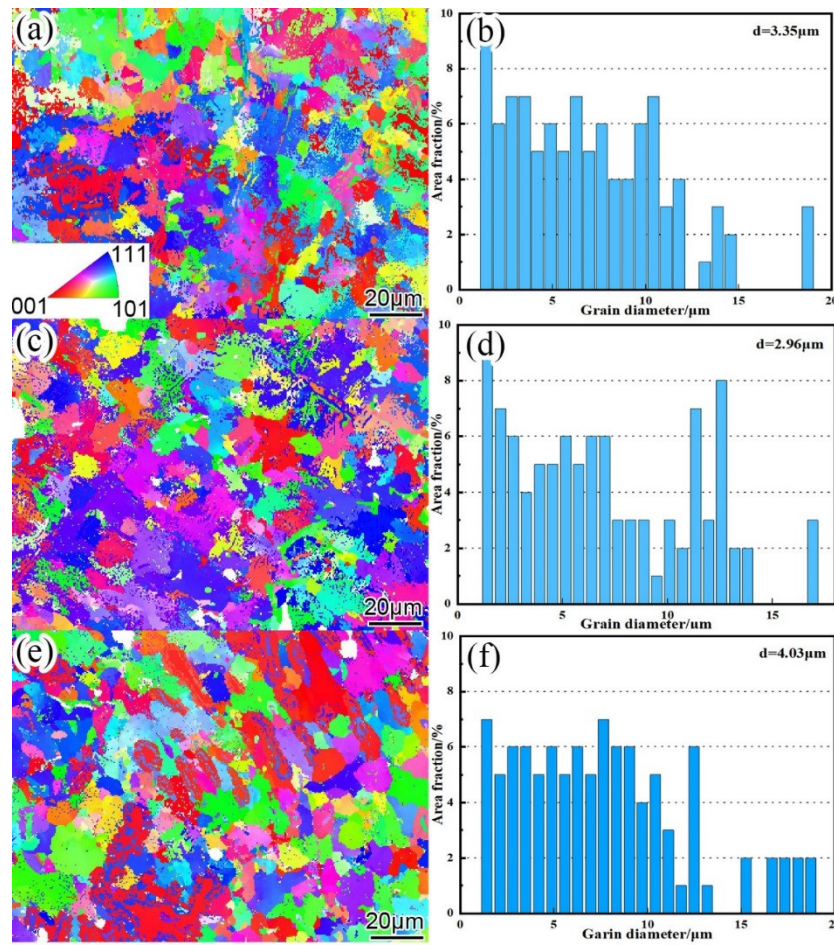


Figure 12. IPF diagram and grain size statistics of surfacing alloy with different nano-Y₂O₃ contents (a) 0 wt.% Y₂O₃ IPF diagram, (b) grain size statistics to (a), (c) 0.456 wt.% Y₂O₃ IPF diagram, (d) grain size statistics to (c), (e) 0.570 wt.% Y₂O₃ IPF diagram, (f) grain size statistics to (e).

The decrease of grain size will increase the hardness of surfacing alloy. The relationship between yield strength and grain size can be expressed by Hall-Petch [35]:

$$\sigma_s = \sigma_i + k d^{1/2}$$

In the formula: σ_s represents the yield limit of the material; σ_i represents the lattice friction resistance generated by moving a single dislocation; k represents the correlation constant; d represents the grain size. It can be found that the yield strength increases with the decrease of grain size. Generally, the hardness of the material increases with the increase of strength. With the addition of nano-Y₂O₃, the grains are refined, which increases the hardness of the surfacing alloy. When the nano-Y₂O₃ is added too much, the microstructure of the surfacing alloy is gradually coarse, which in turn reduces the hardness.

Figure 13 is the variation trend of the volume fraction of each phase of EBSD with the content of nano-Y₂O₃ additive. It can be seen from the figure that with the increase of nano-Y₂O₃ additive content, the volume fraction of ϵ -M₇C₃ and AlN in the surfacing alloy increases first and then decreases. When the content of nano-Y₂O₃ is 0.456 wt. %, the volume fractions of M₇C₃ and AlN are 35.34 % and 3.87 %, respectively. The volume fraction of M₇C₃ and AlN increased by 5.7 % and 2.52 % compared with that without nano-Y₂O₃. With the increase of nano-Y₂O₃ content, the volume fraction of M₇C₃ and AlN changes little.

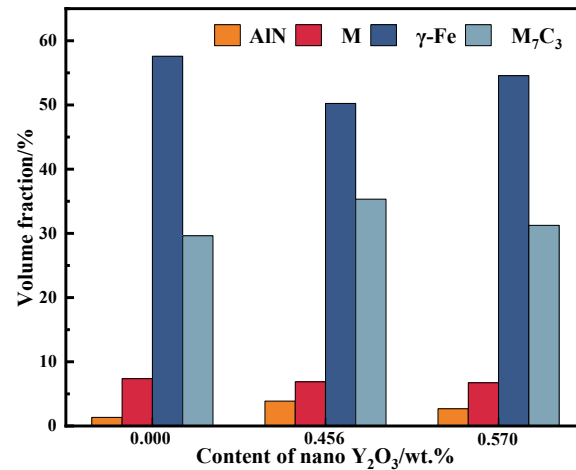


Figure 13. Effect of different nano- Y_2O_3 content on the volume fraction of the phase in surfacing alloy.

This indicates that the addition of appropriate nano- Y_2O_3 can effectively act as heterogeneous nucleation particles, increase the precipitation amount of AlN and increase the volume fraction of M_7C_3 . The matrix of surfacing alloy is mostly retained austenite, the volume fraction of martensite is less and the change of nano- Y_2O_3 content has little effect on the volume fraction of martensite. The surfacing alloy matrix is mainly composed of retained austenite and a small amount of martensite, which ensures that the surfacing alloy matrix has good strength and toughness.

3.4. Analysis of Hardness and Wear Resistance

Figure 14 is the histogram of Rockwell hardness change of surfacing alloy with different content of nano- Y_2O_3 . From the diagram, it can be found that with the increase of nano- Y_2O_3 content, the hardness of the surfacing alloy increases first and then decreases. When nano- Y_2O_3 is not added, the Rockwell hardness of the surfacing alloy is 55.7 HRC. When the addition amount of nano- Y_2O_3 is 0.456%, the Rockwell hardness of the surfacing alloy reaches 62.3HRC, and the Rockwell hardness increases by 11.8 %. From the above volume fraction analysis results, it can be seen that with the increase of nano- Y_2O_3 content, the volume fraction of martensite and retained austenite in the surfacing alloy matrix does not change much, while the volume fraction of M_7C_3 and AlN precipitates increases significantly. However, the content of nano- Y_2O_3 in the surfacing alloy continues to increase, which will lead to the weakening of the fluidity of the surfacing alloy molten pool, the difficulty of slag and gas discharge, the slow cooling rate of the surfacing alloy molten pool, the long growth time of the surfacing alloy structure, and the coarse structure, which will reduce the hardness of the surfacing alloy [36].

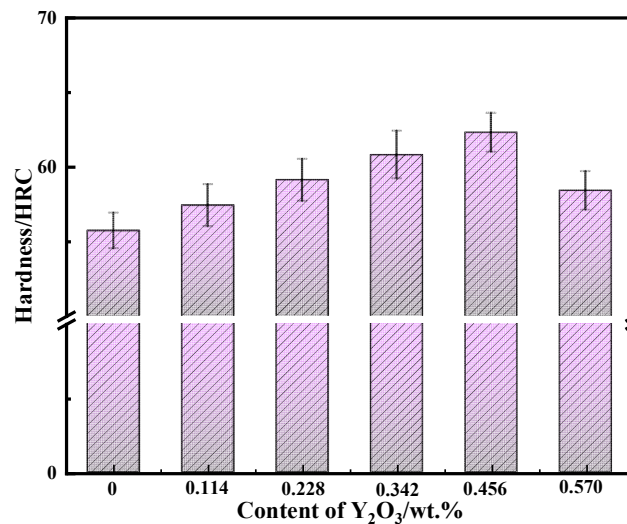


Figure 14. Rockwell hardness curve of surfacing alloy with different Y_2O_3 content.

Figure 15 is the lateral microhardness distribution map of surfacing alloy with different nano- Y_2O_3 content. It can be found from the figure that with the increase of nano Y_2O_3 content, the hardness of surfacing alloy increases first and then decreases. When the content of nano- Y_2O_3 reaches 0.456wt. %, the microhardness of the surfacing alloy reaches the maximum value of 688HV_{0.5}, which is 23 % higher than that without nano- Y_2O_3 . Due to the low hardness of the base metal Q235 itself, it is generally around 330 HV, as the distance from the surface of the surfacing alloy is closer, the microhardness gradually increases. This is due to the dilution effect of the base metal on the surfacing alloy. The eutectic carbide M_7C_3 of the surfacing alloy is small and the hardness is low.

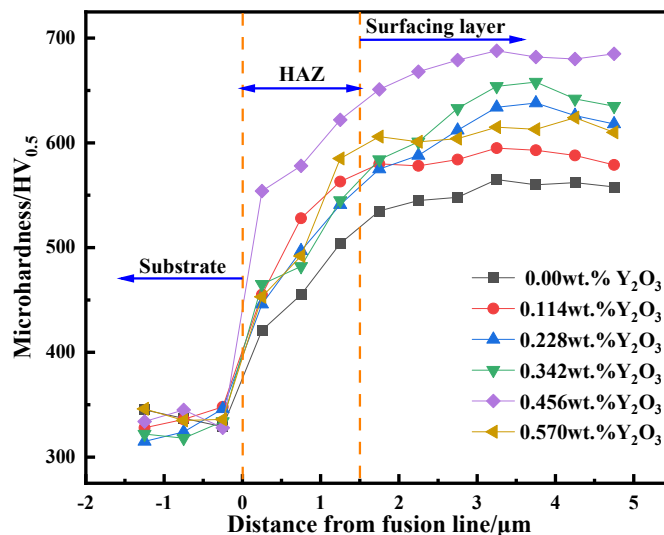


Figure 15. Microhardness across the vertical section of surfacing layer with different Y_2O_3 content.

Figure 16 is the change of wear weight loss of surfacing alloy with different content of nano- Y_2O_3 . It can be seen from the diagram that with the increase of nano- Y_2O_3 additive content, the wear weight loss of the surfacing alloy decreases first and then increases. When the addition of nano- Y_2O_3 is 0.456wt. %, the wear resistance of the surfacing alloy is the best, and the minimum wear loss is 0.125g. Compared with the surfacing alloy without nano- Y_2O_3 , the wear resistance is increased by 41.86 %. As the content of nano- Y_2O_3 additive continues to increase to 0.570 wt. %, the wear loss increases and the wear rate decreases. The change trend of wear resistance of surfacing alloy with the content of nano Y_2O_3 additive is basically consistent with the change of hardness. Adding an

appropriate amount of nano- Y_2O_3 will increase the precipitation of AlN hard phase with small size and uniform distribution. The increase of AlN hard phase can further improve the distribution and precipitation of M_7C_3 . The increase of hard phase will inevitably lead to the increase of hardness and wear resistance. The austenitic matrix has the ability of work hardening. When under the action of abrasive wear load, the surface of the surfacing alloy will undergo work hardening, which hinders the expansion of microcracks and improves the wear resistance of the surfacing alloy. When excessive nano- Y_2O_3 is added, the microstructure of the surfacing alloy will be coarse, which will reduce the wear resistance of the surfacing alloy.

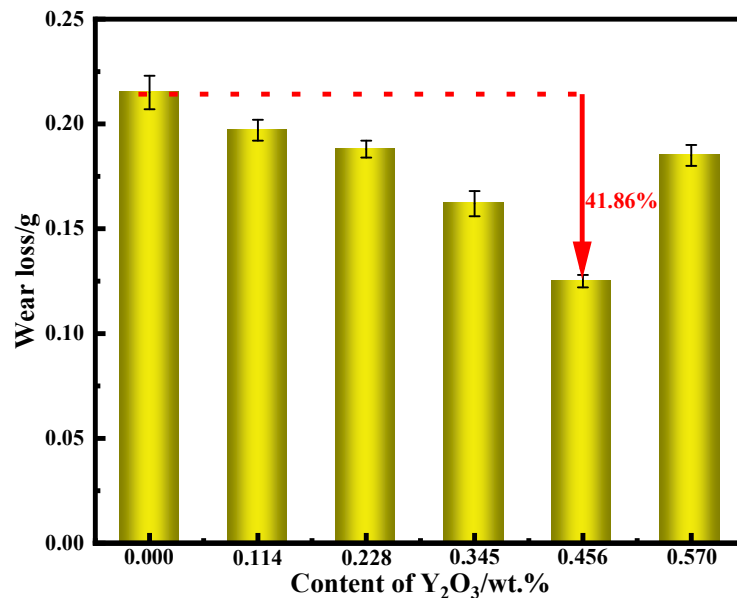


Figure 16. Abrasion weight loss of surfacing alloys with different Y_2O_3 content.

Figure 17 is the wear morphology of the surfacing alloy with different content of nano- Y_2O_3 . Figure 17a shows the wear morphology of the surfacing alloy without nano- Y_2O_3 . At this time, the furrow is deep and there are plough wrinkles and spalling pits, and no obvious cracks are observed on the surface. It can be seen from Figure 17b–e that after adding nano- Y_2O_3 to the surfacing alloy, the plough wrinkles and peeling pits on the surface of the surfacing alloy are reduced, and the furrows become shallow. It can be found from Figure 17e that when the content of nano- Y_2O_3 reaches 0.456 wt. %, the depth of wear marks on the surface of the surfacing alloy is the shallowest and evenly distributed, and the spalling pits disappear. At this time, the wear resistance of surfacing alloy is the best. With the further increase of nano- Y_2O_3 content, the surface wear scar of the surfacing alloy becomes deeper, the surface appears abrasive dust and furrows, and the wear resistance of the surfacing alloy becomes worse. Appropriate amount of nano- Y_2O_3 can increase the precipitation of AlN, change the distribution of M_7C_3 , and significantly improve the wear resistance of surfacing alloy.

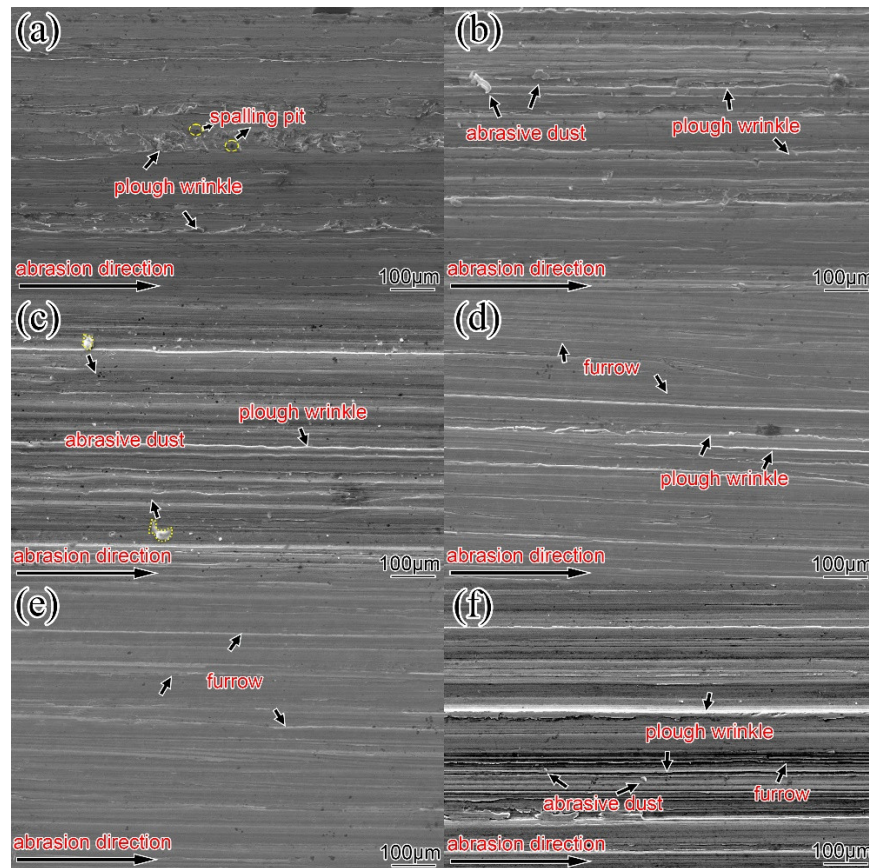


Figure 17. Abrasion morphology of surfacing alloy with different Y_2O_3 content: (a) 0 wt.% Y_2O_3 , (b) 0.114 wt.% Y_2O_3 , (c) 0.228 wt.% Y_2O_3 , (d) 0.342 wt.% Y_2O_3 , (e) 0.456 wt.% Y_2O_3 , (f) 0.570 wt.% Y_2O_3 .

Figure 18 shows the effect of AlN on abrasive wear. In this study, the hard phase of the surfacing alloy is mainly AlN particles + M_7C_3 . Among them, M_7C_3 has high hardness and is distributed in the matrix in a grid shape, playing the role of wear-resistant skeleton. A large number of dispersed AlN particles also play a positive role in the wear resistance of surfacing alloy. When nano- Y_2O_3 is not added to the surfacing alloy, the amount of AlN precipitation is less, so that the wear resistance can not be effectively exerted. When an appropriate amount of nano- Y_2O_3 is added to the surfacing alloy, the amount of AlN precipitates is large, the hard phase is evenly distributed and the interval between them is small, which makes the abrasive unable to continuously cut the matrix, thus obtaining higher wear resistance.

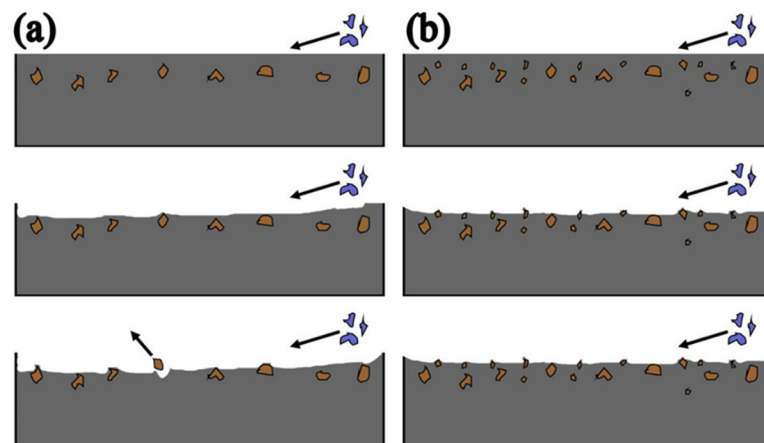


Figure 18. Schematic diagram of the effect of AlN hardening phase on abrasive wear: (a) small amount of AlN, (b) large amount of AlN.

4. Conclusions

Different contents of nano-Y₂O₃ were added to Fe-Cr-C-N-Al surfacing alloy. The microstructure and mechanical properties of the modified surfacing alloy were analyzed. The evolution of microstructure and properties of nano-Y₂O₃ was studied. The mechanism of abrasive wear of surfacing alloy was discussed in detail. The conclusions are as follows:

(1) The formability of surfacing alloy with different content of nano-Y₂O₃ was analyzed. It was found that adding an appropriate amount of nano-Y₂O₃ can obtain a surfacing alloy with good forming quality. When the nano-Y₂O₃ content is 0.456wt. %, the formability of the surfacing alloy is the best and the wetting angle is the smallest, which is 50.8 °.

(2) The addition of nano-Y₂O₃ does not change the phase composition of the surfacing alloy. The microstructure of the alloy is still M + γ -Fe + M₇C₃ + AlN. When the content of nano-Y₂O₃ is 0.456wt. %, the precipitation of AlN and M₇C₃ is the most and the grain size is the smallest.

(3) Compared with no nano-Y₂O₃, the hardness and wear resistance of the surfacing alloy modified by nano-Y₂O₃ were significantly improved. When the nano-Y₂O₃ content is 0.456wt. %, the hardness of the surfacing alloy is 62.3HRC, and the Rockwell hardness is increased by 11.8 %. The minimum wear weight loss is 0.125 g, and the wear resistance is increased by 41.86 %. The wear mechanism of surfacing alloy is mainly plastic deformation mechanism, and the material removal process is micro cutting and furrow wear.

(4) After studying the abrasive wear mechanism, it is found that the wear resistance of the surfacing layer is not only affected by the hardness when the external conditions are constant. The size, quantity and distribution of the second phase precipitated in the surfacing alloy play a decisive role in the wear resistance of the surfacing alloy.

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