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ARTICLE

Effect of Y_2O_3 on Microstructure and Properties of Fe-Al-Si-B Cladding by Plasma Transferred Arc

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Abstract: Fe-Al-Si-B in situ composite coating was prepared with plasma arc cladding on Q235 steel substrate. Moreover, rare earth oxide Y_2O_3 powder was added to the cladding powder in order to improve the microstructure and properties of the coating. The effect of Y_2O_3 on the microstructure and properties of the Fe-Al-Si-B cladding by plasma transferred arc was investigated. The microstructure, phase constituent, microhardness and wear property of the coating were examined by optical microscope (OM), scanning electron microscopy (SEM), X-ray diffraction (XRD), micro hardness tester, friction and wear tester, respectively. The result indicates that the addition of Y_2O_3 can purify the grain boundaries and homogenize the inclusions, and thus the shape and distribution of the inclusions are improved significantly. Furthermore, a dense, uniform, defect-free and significantly refined coating is then formed. When the content of Y_2O_3 reaches 0.9wt%, the hardness of the coating reaches 5.10 GPa, and the optimum wear resistance is obtained.

Key words: Y_2O_3; plasma transferred arc cladding; hardness; wear resistance

As one of the most common failure modes of mechanical parts, wear can seriously affect the operational life of the material, and in some severe cases it may cause equipment scrapping[1]. Therefore, various technologies of surface coatings aiming to enhance the wear resistance of materials have attracted extensive attention of many researchers. Among all of the technologies, the plasma transferred arc cladding technology, using plasma beam, can prepare a functional coating, which has a metallurgical bonding with the substrate, on the surface of a common metal material through melting the coating material and the thin layer on the surface of the substrate. It can significantly improve the substrate material's wear resistance, corrosion resistance, heat resistance, etc.[2-8]. Plasma transferred arc cladding technology is a very promising metal surface modification technology which has now been widely used in power, coal and machinery and other fields.

Recently, the application of rare earth elements in material surface engineering have been widely investigated[9]. Researches show that rare earth elements can improve the performances of the laser and plasma coating[10-12]; however, further studies especially on the analysis of rare earth elements oxide are still weak. At present, many researches have been carried out to clad aluminum coating on iron substrate by plasma[13], but researches of adding rare earth oxide Y_2O_3 in plasma cladding coating are rare.

In the present paper, Fe-Al-Si-B coating was prepared with plasma arc cladding on Q235 steel substrate and rare earth oxide Y_2O_3 powder was added to the cladding powder in order to improve the hardness and wear resistance of the steel. How Y_2O_3 affects the microstructure and properties of the coating was preliminarily analyzed.

1 Experiment

Q235 steel was used as the substrate. The cladding powder was Fe-based alloy powder mixed by ball-milling Fe, Al, Si, B, Y_2O_3 powder and its chemical composition is listed in Table 1.

The powder was evenly mixed according to Table 1. It was applied to the surface of the treated steel by an organic

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binder water glass and pressurized by mechanical force to form a layer of 2 mm in thickness. Cladding was automatically carried out by the plasma cladding equipment constituted by FRONIUS (MAGIC WAVE3000) welder and YASKAWA MOTOMAN (MA1400) arc welding robot. The plasma cladding process parameters are listed in Table 2.

The Fe-Al-Si-B cladding was cut along with the vertical scanning direct of the plasma beam and prepared into metallographic specimens, which were polished and etched using 4% nitric acid alcohol solution. OLYMPUS-BX60M upright metallurgical microscope and FEI Quanta 250F field emission-environment scanning electron microscope were used to observe and analyze the microstructure and composition of the coating. The phase constituent of the coating was identified by Bruker D8 X-ray diffractometer (working voltage: 30 kV, working current: 300 mA, working temperature: 21~25 °C, angle: 20°~100°, measurement speed: 8°/min). Furthermore, the hardness of the coating was measured by HVS-10002 microhardness tester (load: 1.96 N, load time: 10 s). Wear resistance test was conducted on the vertical shaft end face contact type pin-disk wear tester (Load: 20 N, Spindle speed: 300 r/min, Load time: 10 min).

2 Results and Discussion

2.1 Microstructure analysis

Fig.1 shows the optical microstructures of the coatings. As can be seen in Fig.1, microstructures of 1#~4# coatings all consist of white dendritic/columnar grains matrix which have a certain orientation and precipitated phase dispersedly distribute among them. Obviously, in the coating microstructure of sample 1 (Y_2O_3-free coating) larger-sized columnar grains can be seen. While in sample 2 (0.5 wt% Y_2O_3) which is constituted by columnar and dendritic grains that have secondary dendritic arms, compared with sample 1, the proportion of the black substances in grain boundaries declines and the grain size also significantly decreases. In sample 3 (0.9wt% Y_2O_3), the black substances in grain boundaries have completely disappeared, and the grain size is further refined.

Because of a certain number of S and P elements in the substrate and the coating, it can be determined that the black substances are inclusions formed by these elements[14]. Thus, it can be confirmed that the Y_2O_3 addition can refine the grains, transform the grain growth orientation of the coating and reduce the number of grain boundary inclusions, all of which contribute to the purification of the grain boundaries.

With the increase of Y_2O_3 content, the grains of the coating microstructure are refined gradually; however, when the content of Y_2O_3 increases to 1.5% (shown in Fig.1d), the microstructure shows a clear deterioration that the grains are interlaced with each other, namely a slight mixed grain phenomenon appears. The reason is segregation of excessive Y_2O_3 particles in the grain boundaries. It can be found that the addition of rare earth element must have a certain limit in order to improve the coating microstructure.

Fig.2 is the OM and SEM micrographs of the coating bonding interface of sample 3#. The white band in Fig.2a with a 5~8 μm width is the bonding interface between the coating and the substrate. It is the single-phase region formed in the growth form of plane grain by the mixture

Table 1 Chemical composition of plasma cladding powder (wt%)

Serial number	Fe	Al	Si	B	Y_3O_2
1#	Bal.	12.46	5	5	0
2#	Bal.	12.58	5	5	0.5
3#	Bal.	12.13	5	5	0.9
4#	Bal.	11.55	5	5	1.5

Table 2 Process parameters of plasma cladding

Current/A	Shielding gas flow/ $L\cdot min^{-1}$	Ion gas flow/ $L\cdot min^{-1}$	Welding torch pendulum/mm	Cladding speed/ $cm\cdot min^{-1}$	Swinging frequency/Hz	Coating thickness/ mm
130	20	2.0	4	8	0.4	2.0

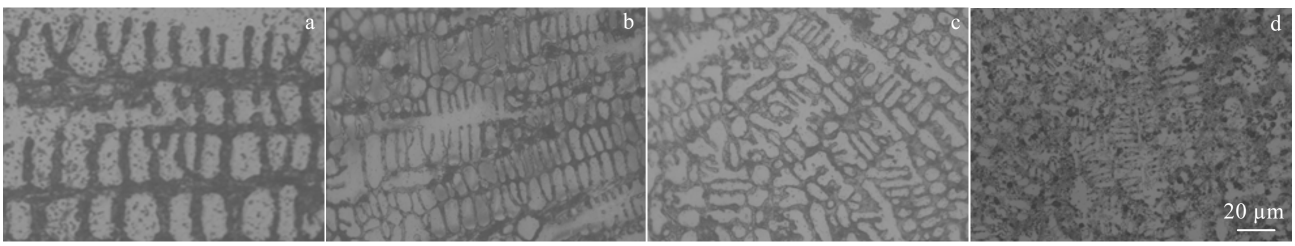

Fig.1 Microstructures of the samples with different Y_2O_3 contents: (a) 0wt% (1#), (b) 0.5wt% (2#), (c) 0.9wt% (3#), and (d) 1.5wt% (4#)

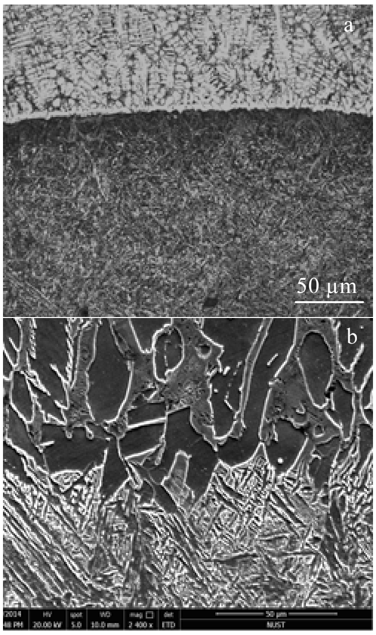

Fig.2 Junction interface microstructures of 3# sample: (a) OM image and (b) SEM image

of the micro-melting zone on the substrate surface and the powder melt. It is because the large temperature difference between the overheated melt and the unmelted substrate and the overall diffusion of the heat through the substrate under the interface released by the solidification that the solidification structure grows with a very low speed by means of planar extension. The formation of the plane grain is closely related to the stability of the solid-liquid interface, which can be determined by constitutional undercooling theory. Due to the positive temperature gradient at the interface, i.e. $dT/dx>0$, the flat solid-liquid interface remains relatively stable in a short time. As shown in Fig.2b, the interface is not flat, the coating metal transits to the substrate metal like a saw tooth, and a good metallurgical bonding forms.

The XRD pattern of the coating of sample 3# is shown in Fig.3. It can be seen that the coating is mainly composed of α-Fe phase and Fe_3Al intermetallic compounds; furthermore, a SiC ceramic phase and eutectic structure Fe_3Si, FeB form. Due to the low content of rare earth element, no diffraction peak can be formed[15,16].

The distribution of elements in the coating and the precipitated phases were analyzed by scanning electron microscope (Fig.4), and SEM-EDS results of the A, B, C areas' marked in Fig.4 are shown in Table 3. It can be observed that there exist Si and B elements in A, B and C areas, in which certain lattice distortion formes due to interstitial solid solution of a part of the Si and B. This leads to the increase of deformation resistance, which has a positive effect on the hardness and wear resistance of the coating. While the SiC ceramic phase with high hardness

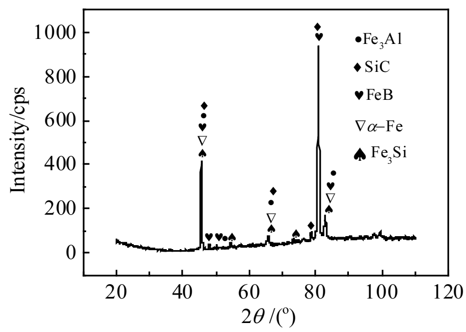

Fig.3 XRD pattern of 3# sample

and Fe_3Si, FeB eutectic structure form by the other part of Si and B. They distribute in the grain boundary, which have anchoring effect on dislocation, and thus the strength and wear resistance of the coating are improved[17].

Fig.4 and Table 3 show that Y element exists in both B and C areas. It indicates that the precipitation of Y element in the grain boundary replaces the original low melting point inclusions that are unevenly distributed, which contributes to the refinement and dispersed distribution of the inclusions, namely modification occurred[10]. In addition, the precipitation of Y element in area C is attached to the surface of the intermetallic compounds, which produces a certain anchoring effect on the dislocation. With the addition of element Y, the composition of coating becomes more uniform, the matrix and the grain boundaries are purified, and meanwhile the grains are refined.

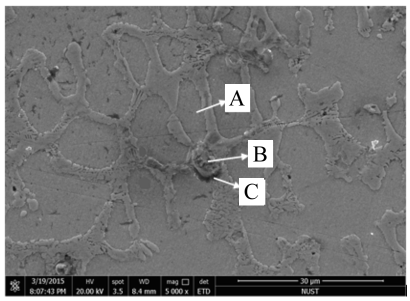

Fig.4 SEM micrograph of the microstructure of 3# sample

Table 3 SEM-EDS analysis results of areas marked in Fig.4 (wt%)

Element	Area marked		
	A	B	C
Al	4.00	9.34	9.01
Si	3.23	3.67	2.98
B	3.98	3.41	4.03
Fe	88.7	83.47	83.87
Y	0.00	0.11	0.09
Total	100.00	100.00	100.00

Functioning together with the other intermetallic compounds, the addition of element Y can enhance the mechanical properties of the coating.

2.2 Microhardness analysis

Fig.5 shows the microhardness distribution of the 1#~4# samples. It can be observed that the microhardness of the coating is distinctly higher than that of the substrate. The highest microhardness value of 1# sample is up to 4 GPa. The addition of Y_2O_3 into the cladding powder significantly improves the microhardness. With the increase of Y_2O_3 content, the hardness of the coating first increases and then decreases. The microhardness of 3# sample is up to 5.1 GPa.

There are mainly three reasons for the increase of the microhardness of the coating. Firstly, the addition of Y_2O_3 significantly refines the grains. It is mainly due to the segregation of the compounds' tiny solid particles on the interface, which helps to reduce the grain boundary energy, and hinder the growth of the unit cell. Secondly, the brittle and hard Fe_3Al intermetallic compound forms in the coating precipitated irregularly in the grain, enhancing the hardness and wear resistance of the coating. Thirdly, SiC ceramics with high hardness and Fe_3Si, FeB eutectic structure formed in the coating disperse in the grain boundary to impede dislocation motion. Si and B with the form of interstitial solid solution, can cause lattice distortion that can improve deformation resistance, which increases the hardness and wear resistance of the coating.

C element and Fe element transit to the coating during cladding, so that the coating contains SiC ceramic phase and Fe phase (Fig.3 shows), and in the region near the interface, the concentration is larger. In coating of adding of Y_2O_3 particles, the combined effect of SiC and Y_2O_3 to increase the hardness of the interface is greater than effect of dilution of Fe to decrease hardness, so from Fig.5, it can be seen after the addition of Y_2O_3, near the interface of coating, hardness value reaches the maximum. In the coating without Y_2O_3 particles, the dilution effect of Fe is greater than enhancement effect of SiC ceramic phase. Therefore, the hardness of the coating near the interface is relatively low, and the hardness of the whole coating decreases gradually from the surface to the substrate.

2.3 Wear resistance analysis

The amount of the coating's wear extent per unit area is used to represent the wear resistance of the coating metal, and the smaller the value is, the better the wear resistance of the coating is. Fig.6 shows the wear test results of the coatings with different Y_2O_3 contents. As it can be seen from Fig.6, the wear resistance of the coating is better than that of the substrate metal. With the increase of the cladding powder's rare earth oxide Y_2O_3 content, the wear resistance of the coating increases first and then decreases. These results are similar to the results of hardness analysis. The wear resistance of the coating is up to triple that of the substrate when the Y_2O_3 content is 0.5wt%, and when the content of Y_2O_3 is 1.5wt%, the wear resistance of the coating declines to double that of the substrate. When the content of Y_2O_3 is too low, the grains can't be sufficiently refined, and thus it is very easy to fall off when rub against the roller, resulting in low wear resistance of the coating. However, when the content of Y_2O_3 is too high, the undissolved Y_2O_3 particles segregate at the grain boundary, which causes the coarse microstructure, and thus the wear resistance decreases again rather than increases.

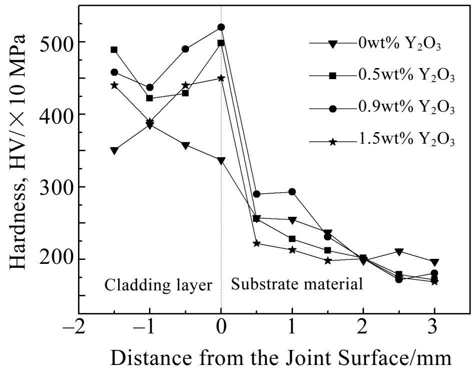

Fig.5 Microhardness distribution of different coatings

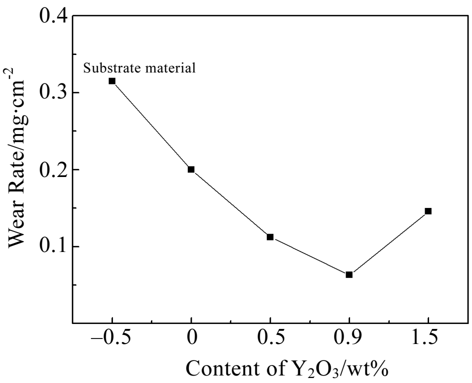

Fig.6 Wear resistance of the Fe-Al-Si-Y coating

When the content of Y_2O_3 is 0.9wt%, the wear resistance is the best which is five times as high as the substrate. The analyses on how the rare earth element improves the wear resistance and the hardness of the coating are similar.

3 Conclusions

1) The addition of rare earth oxide Y_2O_3 can refine the grains and change the growth direction of the dendritic crystals, which make the microstructure uniform and form a

compact and defect-free coating. Meanwhile, suitable content of Y_2O_3 can change the morphology of inclusions and reduce the amount of harmful inclusions at the grain boundary, which can purify the grain boundary.

2) When the content of Y_2O_3 is 0.9wt%, the hardness of the coating is as high as 5.1 GPa and the wear resistance reaches its best which is up to five times as much as the substrate.

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Y_2O_3对 Fe-Al-Si-B 等离子熔覆层组织与性能的影响

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摘 要：采用等离子弧熔覆技术，在 Q235 钢板基体表面熔覆了一层 Fe-Al-Si-B 原位复合涂层，并通过在熔覆粉末中添加稀土氧化物 Y_2O_3改善熔覆层的组织与性能。利用光学显微镜(OM) 、扫描电镜(SEM) 、X 射线衍射仪(XRD)、显微硬度仪、摩擦磨损试验机对熔覆层的组织、相组成、显微硬度及磨损性能进行了表征。结果表明：Y_2O_3的加入净化了晶界，使得晶界处夹杂物均匀化，明显改善了晶界处夹杂物的形态，形成了致密均匀、无缺陷且显著细化的熔覆层组织。当稀土氧化物 Y_2O_3质量分数为 0.9%时，熔覆层的硬度达到 5.10 GPa，耐磨性能达到最佳。

关键词：Y_2O_3；等离子熔覆；硬度；耐磨性

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