Study on Cladding Performance, Coating Microstructure and Interfacial Bonding of Metal-base Coatings by Non-contact Cladding

Shibo Ma, Mingjie Shao, Shuangjie Zhang and Hongguo Wang

ABSTRACT

Coating material and its cladding performance is the key to the preparation of high quality coating. In this paper, cladding performance, cladding coating morphology, interface diffusion and microstructure of typical alloy powder material were studied, such as self-melting alloy powder, coated composite powder and mixture metal ceramic powder by experiment. The results show that self-melting alloy prepared by atomization technology has well cladding performance which coating with compact microstructure. Composite alloy powder prepared by chemical method technology has poor cladding performance which loose microstructure. Mixed metal ceramic powder has well cladding performance which homogeneous microstructure. Fe-base alloy and Co-base alloy can be achieved diffusion metallurgical combination with the steel substrate.

INTRODUCTION

Noncontact cladding coating technology is that preset alloy layer in workpiece surface, under the action of heat source non-contact (vacuum furnace,
induction, microwave, infrared) for the pre coating of cladding, the enough and concentrated heat effect on the surface of the matrix metal. In a very short time coated in the molten alloy coating on the surface of the substrate and infiltration substrate surface, cladding process similar to that of hard alloy sintering process, coating in the cladding have a certain degree of contraction, which conducive to the bond coat phase (self fluxing alloy) and between the matrix and the interface reaction and diffusion in miscible. The molten or semi molten material is coated on the surface of the workpiece, and then cooled to form a solid coating, and a diffusion metallurgy bonding between the coating and the base metal is formed [1].

Compared with the laser, plasma, such as welding contact cladding technology, non contact type cladding has the advantages of fast heating speed, energy saving, production efficiency high, the coating material without burning, easy to realize automation, energy is easy to control, the pre coating characteristics such as simple. The non contact cladding energy concentrates on the outer surface coating, the thermal effect of the base metal is small, and the thick coating (>1mm) can be prepared, and the process control is flexible and convenient. Non contact heating method is adopted, which is not easy to be mixed in the heating process. It is easy to realize the automation of heating process, and has great advantages in mass production of symmetrical parts. The cost of consumption in production is lower than that of laser and plasma cladding technology.

By changing the physical state and chemical properties of the strengthened material to enhance the performance of the workpiece, the composition of the cladding layer is mainly determined by the configuration of the cladding materials [2]. Therefore, the cladding material and its cladding properties are particularly important in a variety of factors affecting the performance and quality of the cladding layer. Cladding performance refers to the coating material by rapid heating, should have good heat transfer performance in cladding process. Molten or semi molten state of coating material should be with good spreading on the substrate properties and wettability, has good self slag performance and molten slag, gas coming to coating surface without obvious defects, which can obtain compact structure. The coating material applied to the cladding is mainly self fluxing alloy powder and composite powder and ceramic powder at present. Thus, the coating cladding properties and microstructure of the typical coating materials are studied in this paper.

COATING MATERIALS

In order to compare cladding performance, coating morphology, microstructure and interface combination of different powder material, Fe-based, Ni-based and Co-based self fluxing alloy powder and type corresponding coated composite powder and mixed ceramic powder (WC) were analyzed in this paper.
The grade and principal components as shown in TABLE I, TABLE II, TABLE III, in addition to the coated composite alloy powder are self configuring.

Figure.1 shows the three kinds of alloy powder SEM morphology. Self fluxing alloy and coated alloy powder have good sphere city, WC powder with polygonal shape. Self fluxing alloy powder prepared by melting-spray-drying-sieving process, coated composite powder [3] prepared by chemical plating process.

![Figure 1. SEM morphology.](image)

(a) Self fluxing alloy  (b) Coated composite alloy  (c) WC

| TABLE I. CHEMICAL OF COMPOSITION OF FE-BASED ALLOY POWDER(WT%). |
|---------------------|---------------------|---------------------|---------------------|
| Name                | Main components (wt%) | Size (μm) | Melting point (℃) |
| Fe60                | >50Fe,3.5Si,3.5B     | 20–50      | 1080–1180          |
| Fe35WC (Coated)     | 65Fe,35WC           | 30–60      | 1120–1220          |
| Fe60 +WC50%(Mixed)  | 50Fe60,50WC         | WC40–80,Fe60 20–50 |

| TABLE II. CHEMICAL OF COMPOSITION OF NI-BASED ALLOY POWDER(WT%). |
|---------------------|---------------------|---------------------|---------------------|
| Name                | Main components (wt%) | Size (μm) | Melting point (℃) |
| Ni60                | >40Ni,4.0Si,4.0B    | 20–50      | 950–1000           |
| Ni35WC (Coated)     | 65Ni,35WC          | 30–30      | 1020–1140          |
| Ni60 WC50%(Mixed)   | 50Ni60,50WC        | WC40–80,Ni60 20–50 |

| TABLE III. CHEMICAL OF COMPOSITION OF CO-BASED ALLOY POWDER(WT%). |
|--------------------|---------------------|---------------------|---------------------|
| Name               | Main components (wt%) | Size (μm) | Melting point (℃) |
| Co50               | >30Co, 3.5Si,3.0B   | 20–50      | 1100–1200          |
| Haystellite40 (Coated) | 40Deloro60,60WC | 30–60      | 1010–1215          |
| Co50+WC50%(Mixed)  | 50Co50,50WC        | WC40–80,Co5020–50  |
COATING PREPARATION

Substrate and Pretreatment

The substrate material is alloy structure steel 4140, coating specimen preparation area with size 30mm×25mm. Sandblast the surface after machining, then, clean the surface with alcohol, blow it to make sure the surface clean completely without rust, oil, or other substances which could have poor influence.

Pre-placed Layer and Cladding Coating

Mix each experimental powder evenly, stir each of them with organic binder to make them pasty, coat the mixture on the surface of substrate, coating thickness is 1mm, put the specimens with the coating into drying machine, keeping dry for 2h at 200°C, make sure the organic substances of the powder volatilize completely, while effectively preheated sample.

The prefabricated powder layer samples implanted homemade cladding equipment after drying, and then open heating device, run cladding equipment. Test cladding temperature by high temperature infrared temperature tester, keep warm for 2 Min, and air cooling.

COATING ANALYSIS

Morphology Analysis

Compare the morphology of the Self fluxing alloy coating before and after sandblasting as shown in Figure.2. Slag precipitation of Ni60 coating for glassy, smooth surface, Fe60 and Co50 slag precipitation for slag, rough surface. So Ni60 self fluxing performance is better than that of Fe60 and Co50. The three self fluxing alloy coating on the surface of the state is not large difference after blasting, coating have different degrees of contraction, surface state of the Co50 slightly worse in Fe60 and Ni60.

Coated composite alloy such as Figure.3 shows after cladding, coating surface of Fe based and Ni based with the melting groove, crack and poor state. Analysis of its causes, coated powder is in carbide coating on the surface of the self fluxing alloy layer, alloy outer first heat melting, carbides of powder absorb heat energy below the surface, partial melting of fusible alloy capillary.
wetting carbide, part of the due to the difference in temperature between the alloy and carbide formation stratification cause melting groove in cladding process. Cobalt based commercial Stellite alloy [4] is actually a kind of self fluxing alloy with better self fluxing, preparation process the same as self fluxing alloy by atomization process, and different form coated composite alloy powder by chemical plating process.

Figure 4 shows self fluxing alloy mixed carbide tungsten cladding coating surface, same as single self fluxing alloy coating. Due to the high melting point of tungsten carbide powder, the cladding temperature of mixed powder coating significantly higher than that in the corresponding of self fluxing alloy powder. The surface state of mixing powder coating same as self fluxing alloy coating before and after the sandblasting, that the self fluxing performance of the mixing
powder based on self fluxing alloy powder mainly. Three kinds of powder have not greater difference. The oxidation degree of the matrix can be seen that the melting temperature of Fe based alloy is higher than that of Ni and Co based [5], the oxidation degree of nickel base alloy is the least, and the melting temperature is lower.

**Microstructure Analysis**

Three kinds of self fluxing alloy powder cladding highest temperature are Fe-based (1215°C) > cobalt base (1172°C) > Ni base (1023°C), cladding temperature of Ni based coating is significantly lower than the other two kinds of coating. The cladding temperature of coated composite alloy coating is more than 1150°C, and the cladding temperature of mixing tungsten carbide coating is more than 1200°C.

(1) As shown in Figure.5-(a), the microstructure of Fe60 coating is divided into four parts, the matrix, the heat affected zone, the bonding layer and the cladding alloy [6]. There are obvious metallurgical binding characteristics between coating and substrate, which forming element concentration gradient distribution of transition layer [7] in the vicinity of the interface. Thus, establish the transition zone of the performance, avoid due to mutations in the composition and performance and weaken the binding between the coating and the substrate.

The microstructure of Fe based alloy coating is shown in Figure.5-(b) and (c), which is mainly composed of dendritic solid solution and eutectic structure distribution of the inter dendritic. Some B and Si of alloy float on the surface of the coatings by self-slagging with the form of borosilicate when cladding, another which solution in austenitic matrix. Fe and Cr of coating metal elements and C elements mainly formed (Fe, Cr)7C3 and (Fe, Cr)3C carbide hard phase. Figure.5-(c) shown the high magnification eutectic microstructure, and solid solution for the radial organization, the eutectic microstructure is stripy, block and granular distribution. Figure.6- (a) shows the phase analysis results of Fe60XRD. Ni elements are the main alloying elements in the formation and stability of gamma phase, Cr is the element to narrow the phase region, can increase strengthening effect of solid fusion, which makes the coating precipitation of the eutectic solid solution of Cr, Si, B and other elements during the coating cooling process, because of the composition of the alloy contains a lot of Ni, Cr. So get the cladding layer in austenite and martensite is given priority to, the coating microstructure is γ-(Ni,Fe,Cr) dendrite solid solution and distributing a strip, block and point to solid solution of (Fe,Cr)7C3, Cr7C3, Fe23(C,B)6 and that of carbide and intermetallic compounds precipitated phase formation of the eutectic structure.
(2) Ni60 alloy powder has a lower melting point and the cladding temperature is between 1000~1050°C. As shown in Figure 7-(a), there are not obvious metallurgical bonding-band between substrate and coatings. Figure 7-(a) shows microstructure of coating after cladding. According to Figure 6-(b) the analysis result of XRD, chromium can formed boride and carbide with boron, carbon at high temperatures for chromium dissolved in the nickel of alloy. Coating microstructure is (Ni, Cr) solid solution γ phase, point, block (Fe, Cr)7C3, Cr7C3 carbides and CrB, Cr2B, Ni3B and other boride distributed on matrix boride.

(3) Cobalt base self fluxing alloy is developed on the basis of Stellite alloys which main components are cobalt, chromium and tungsten, so known as Co-Cr-W alloy. In the Co-Cr-W alloy with boron, silicon, and the formation of cobalt
base self fluxing alloy. As shown in Figure 8-(a), there are obvious diffusion bonding between coating and substrate. Figure 8-(b), (c) shows the microstructure of Co based alloy coating, which is the dendrite and the eutectic structure. Figure 8-(c) is a typical fishbone eutectic structure of cobalt based alloy. Combined with the analysis results of XRD shown in Figure 6-(c), the matrix is \( \gamma \)-Co solid solution of Cr, Ni element, whose eutectic structure are \((Cr,Fe)C_3\), \(Cr_7C_3\), \(Cr_23C_6\), \(CrB\) and other boron carbon hard phase [8-9].

(4) As shown in Figure 9-(a), a wide diffusion bonded zone can be formed between coating and substrate after Fe35WC powder cladding. Figure 9-(b), (c) shows that there are more pores, not infiltrate intergranular, and other defects in the coating which cladding performance is poor. According to the analysis result of XRD as shown in Figure 10-(a), the microstructure of the coating is mainly composite of \( \gamma \) solid solution, block WC, granular and strip \( M_7C_3 \) and \( Fe_6W_6C \) phase, which is the bright color and strip and block shaped distribution in coating under SEM.

(a) Interface                        (b) Coating                          (c) Coating
Figure 8. Microstructure of Co60 coating.

(a) Interface                        (b) Coating                          (c) Coating
Figure 9. Microstructure of Fe35WC coating.
(a) Fe35WC XRD  (b) Ni35WC XRD  (c) Stellite40 XRD
Figure 10. XRD of composite alloy coating.

(a) Interface  (b) Coating  (c) Coating
Figure 11. Microstructure of Ni35WC coating.

(5) Figure 11-(a) shows that the SEM photos of Ni35WC coating which has a wide bonding zone between coating and substrate. Figure 11-(b), (c) shown in microstructure of Ni35WC coating after cladding, slightly better than the Fe35WC, but also being some pores and non infiltration and so on defects. Analysis of XRD with the Figure 10-(b), the microstructure is \( \gamma \) solid solution with Cr, WC hard phase and distribution in the solid solution of carbide and boride hard phase.

(6) Figure 12-(a) shows the bonding status of stellite alloy between coating and substrate which is obvious diffusion bonding. The microstructure of coating shown in Figure 12-(b),(c), is compact and less defects, hard phase stripy and punctate distribution. As shown in Figure 10-(c), the coatings made of cobalt based chromium rich solid solution, WC, Cr23C6 and M7C3 hard phase composition.

(a) Interface  (b) Coating  (c) Coating
Figure 12. Microstructure of Stellite40 coating.
(7) As shown in Figure 13-(a), there is a wide diffusion bonding zone between coating and substrate after Fe60+50WC coating cladding. The melting point of the coating material is higher, and coating and substrate are fully diffused cause by the addition of tungsten carbide. As shown in Figure 13-(b), (c), a point, block tungsten carbide hard phase is dispersed in the Fe based bonded phase substrate with more pores and voids, which is not completely infiltration of tungsten carbide hard phase. According to the results of XRD analysis shown in Figure 14-(a), the microstructure of coating was Fe60 alloy solid solution and WC hard phase.

(8) In the previous paper, the melting point of Ni60 alloy powder was low, so the cladding coating was not able to form a sufficient diffusion bonding with the matrix. As shown in Figure 15-(a), the Ni60+50WC coating and the substrate formed a wide diffusion bonding zone, because of the addition of tungsten carbide to raise the melting point of the mixture. Figure 15-(b),
(c) shows that the nickel based alloy bonded phase is not completely infiltrated tungsten carbide hard phase in the coating, which has a lot of pores and voids. Combined with the results of XRD shown in Figure.14-(b), the microstructure of the coating is Ni60 alloy solid solution and WC hard phase.

(9) As shown in Figure.16-(a), cobalt based alloy mixed tungsten carbide coating and the substrate is also a better diffusion bonding the same as analysis of the above Fe60, Ni60 mixed tungsten carbide. The wettability of cobalt base alloy is better than that of iron base and nickel base in the liquid phase. As shown in Figure.16-(b), (c), cobalt based alloy mixed tungsten carbide coating, whose bonded phase is not completely coated tungsten carbide hard phase, have a certain porosity. Combined with the results of XRD shown in Figure.14-(c), the microstructure of the coating is Co50 alloy solid solution and WC hard phase.

**Interface Bonding Analysis**

There is no clear bonding interface between cladding coating and substrate, and a transition layer with a certain thickness is formed after cladding. The formation of the transition layer is due to the different concentration of each element in coating and substrate. Under the action of high temperature, wetting and concentration gradient, the elements of the high concentration state in the coating will diffuse to the surface of the substrate, and the high concentration of the substrate will diffuse to the coating[10].
In order to analyze the diffusion metallurgical bonding between the coating and the substrate, the EDS was used to analyze the element analysis of Fe-base, Ni-based and Co-based mixed tungsten carbide coating and matrix. Scanning bandwidth and element analysis results are shown in Figure.17 and Figure.18.

Fe-based coating powder material as shown in TABLE I, the main elements of C, Fe, W, Cr, Ni, Si, B, the matrix is 4010, the main elements are Mo, Cr, C. The results can be seen from the

![Figure 17. Scanning area.](image1)

(a) Fe60+WC50% coating     (b) Ni60+WC50% coating          (c) Co50+WC50% coating

![Figure 18. Element diffusion concentration.](image2)

(a) Fe60+WC50% coating     (b) Ni60+WC50% coating          (c) Co50+WC50% coating

results of Figure.18-(a), the red curve is the element content of Fe element on the scanning line, yellow is Cr element, blue is the Ni element, the purple is the Mo element, and the blue is the W element. The Si, C, and other content of the small element concentration are negligible. The main elements of the coating are Fe, Cr, Ni, from one side of the cladding layer to one side of the substrate, which is continuous transition trend, not the change of the element concentration.

Ni-based coating powder material as shown in TABLE II, the main elements of C, Ni, Cr, Fe, Si, B, the matrix is 4140, the main elements of Mo, Cr, C. The
results can be seen from the results of Figure.18-(b), the yellow curve is the element content of Ni element in the scanning line, red is the Fe element, the green is the Cr element, the purple is the Si element, the blue is the Mn element, and the blue is the C element. The Si, C, Mn and other content of the small element concentration are negligible. Although there is a continuous transition trend, which the main elements of the coating Cr, Fe from the side of the cladding layer to the substrate side. But there is a change of the concentration of the element between coating and substrate junction, and the concentration of Fe is more obvious, and the Ni elements are the trend of continuous transition. It shows that only Ni elements can diffuse in the interface, the other elements cannot form a full diffusion.

Co-based coating powder materials as shown in TABLE III, the main elements of C, Cr, Ni, Fe, Mo, Si, B, Co, matrix for 4140, the main elements for Mo, Cr, C. The results can be seen from the results of Figure.18-(c), the yellow curve is the element content of Co element in the scanning line, red is the Fe element, the green is the Cr element, the purple is the Si element, the blue is the Mn element, and the blue is the W element. The same with the previous analysis, Co, Cr, Fe elements of coating can diffuse with matrix.

CONCLUSIONS

Through to analyze cladding coating morphology, microstructure and its combination with matrix of three self fluxing alloy powder, coated composite powder and mixed tungsten carbide powder, draw conclusions as follows:

(1) Ni-base alloy have the best self fluxing performance in the self fluxing alloy, Fe-based and Co-based alloy take second place. Self fluxing alloy coating are compact, without obvious defects. Fe and Co-base self fluxing alloy can form complete diffusion bonding with matrix, Ni-base cannot. The microstructure of Fe-base coating are eutectic structure which consist of γ-(Ni, Fe, Cr) dendrite solid solution and strip, block or punctate distribution in solid solution of (Fe, Cr)7C3, Cr7C3, Fe23(C,B)6 and other intermetallic compound. The microstructure of Ni-base coating are γ-(Ni, Fe, Cr) solid solution, and punctuate, block (Cr, Fe)7C3, Cr7C3, Cr2B, Ni3B and CrB carbides and borides distribute in the solid solution.

(2) The cladding performance of self fluxing alloy and coated composite alloy prepared by atomized process are better. The cladding performance of coated composite alloy prepared by chemical process is poor, which not easy to prepare the coating with good surface and defect-free. The microstructure characteristics of coated composite alloy are γ-solid solution, WC and boride (carbide).

(3) The cladding performance of Co-base, Fe-base and Ni-base with WC powder coatings are better, whose microstructure characteristics are bond phase solid solution of self fluxing alloy and WC hard phase. Fe and Co-base mix
powder coating can form a complete diffusion metallurgical bonding with the substrate.

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REFERENCES