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Microstructural evolution and characteristics of bonding zone in multilayer laser cladding of Fe-based coating

K.Y. Luo[a], X. Xu[a], Z. Zhao[a,b], S.S. Zhao[b,c], Z.G. Cheng[b], J.Z. Lu[a,*]

[a] School of Mechanical Engineering, Jiangsu University, Zhenjiang 212000, China
[b] Jiangsu ZKDG Laser Technology Co, Ltd, Zhenjiang 212000, China
[c] Laboratory of All-Solid-State Source, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

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ABSTRACT

Multilayer coatings were prepared on H13k steel substrate by laser cladding, and Fe-based powders mixed with different Mo and Ni contents were used. The microstructure change between layers in the multilayer deposit process was analyzed. The effects of Mo and Ni contents on the microstructure, phase transformation, element distribution, and microhardness were also systematically investigated. Results showed that dendrite matrix and interdendrite netlike eutectic structure were found in Fe-based cladding layers. Furthermore, the bonding zone was mainly composed of coarse dendrites because of remelting and reheating induced by secondary energy input. Due to the heat accumulation, relatively large dendrites in the bonding zone and thick bonding zone could be formed in the latter layers rather than in the early layers. The phases of sample 1 and sample 3 at room temperature are martensite, residual austenite, residual δ ferrite, M_2B and metal carbide ($M_{23}C_6$, and M_7C_3). The phases of sample 2 at room temperature are austenite, residual δ ferrite, M_2B and metallic carbide ($M_{23}C_6$, and M_7C_3) because more Ni content leads to the change of solidification mode. With increasing Ni content up to 8 wt %, the microhardness of laser cladding layer decreased from 600 $HV_{0.5}$ to 400 $HV_{0.5}$ but was distributed homogenously from the interior region to the bonding zone.

1. Introduction

Laser cladding (LC) is a new surface modification technology, and produces a surface strengthening layer on the metal substrate by rapid melting and freezing of the substrate and the coating when laser beam with high power density irradiates into the metal surface. The LC layer displays excellent wear resistance, corrosion resistance, and anti-oxidation properties. LC has achieved significant progress since it was developed by D. S. Gnanamuth in the United States in 1974. Since the early 1990s, LC technology has been extensively used in all fields of industrial production.

Fe-based coating is widely used in various aspects in manufacturing industries because of its low cost, high-abrasive resistance, and high hardness. A series of different elements or reinforced particles can be introduced into a Fe-based metal system to cause the improvement in the properties of Fe-based coating. Ramiro et al. (2018) proved that the crack free Fe-based coating by laser metal deposition could be produced without preheating the base material. Wang et al. (2014) added different kinds of Ni powder (Ni-based powder and pure Ni powder) into Fe-based coatings and reported that the number of microdefects in the coating increased upon the addition of pure Ni powder but not Ni-based powders. The crack tendency can be reduced by adding Ni-based powder. Chen et al. (2012) cladded a Fe-based cladding coating on the surface of pure titanium substrate, showing that the coating hardness can reach 800 $HV_{0.2}$ higher (four to five times) than that of the substrate. This finding could be due to the formation of hard particles, such as Fe_2Ti, Fe_2B, Fe_3Si, and Ti_2Ni. Fu et al. (2015) investigated the composition and formation mechanism of microstructures in Fe-based coatings and concluded that Fe-based cladding coating mainly contains dendrites and eutectic. At high solidification rates, dendrites are formed first, followed by the formation of eutectic by the unsolidified metallic liquid that nucleated among dendrites. The addition of La_2O_3 can refine crystals in the coating. Wang et al. (2018) added V8C7 particles into Fe-based coating system and got the pore-free coating, the microhardness and wear resistance of coating was improved. Gao et al. (2016) found three types of microstructures (planar, columnar dendrites, and equiaxed dendrites) under different solidification rates in different regions. The addition of Ti reduced the number of dendrite structures and increased the number of equiaxed grains, thereby improving the microstructure. However, the hardness decreased because the size of the

* Corresponding author at: Xuefu Road 301, Jingkou District, Zhenjiang 212013, China.
E-mail addresses: luoteacher@126.com (K.Y. Luo), blueesky2005@163.com (J.Z. Lu).

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crystal phases increased. Wang et al. (2010) demonstrated the formation of carbides based on the change of Mo content in the cladding layer. When the amount of Fe–Mo (wt.%) increased from 0% to 15%, the volume fraction of carbide gradually increased, whereas the primary carbide size decreased. This finding could be mainly attributed to the smaller size of (Ti/Mo) C hard particle than that of TiC, and that Mo can play fine grain role in the Fe–Ti–Mo—C system. Yang et al. (2007) concluded that Ni affected the microstructure of austenite phase in the Fe—Cr—Ni system and provided the opportunity for the formation of interdendritic regions with high Cr content. The microhardness decreased, but the electrochemical corrosion resistance improved with increasing Ni content. Lu et al. (2018) provided a 3-times laser scanning strategy to get the crack free Fe-based coating by laser cladding.

Multilayer cladding is widely used in some cases, such as roller repair and piston repair. Scholars have explored the coating performance. Bykovskiy et al. (2015) investigated composition and hardness distribution in bilayer coating with different second-layer track direction (at angles of 0°, 45°, and 90° than in the first case). The elemental composition and equal microhardness were similar between the two cases, but the microhardness distribution along depth direction was homogeneous at an angle of 0° in the direction of the second cladding layer. Xu et al. (2006) discussed the effect of cladding method on crack sensitivity. Constant chemical composition and gradient chemical composition during laser multilayer cladding process were used in this study. The crack sensitivity when getting gradient material distribution is lower than that of constant chemical composition distribution because of the gradual distribution of WC particles.

Studies have focused on the change of microstructure and properties of cladding layers with the different element content and parameters. The properties of cladding coating applied with different cladding methods have been extensively studied. However, few scholars have investigated the bonding zone between cladding layers; as such, the properties of the bonding zone should be studied deeply.

This study aims to investigate the microstructure revolution, phase solidification and bonding characteristics in multilayer coating. The strategy of reciprocated deposition, namely, multilayer LC, was applied considering the material properties of the elements added. The microstructural revolution and element distribution in the cladding layer and in the bonding zone were investigated. The hardness distribution in the coating layer was also examined.

2. Experimental procedures

2.1. Experimental materials

Three different samples (X431, X431 + 8%Ni45, X431 + 1.5%Mo) using three kinds of powders were built for LC experiment. The Fe-based alloy was X431 stainless steel alloy powder manufactured by Höganäs Corporation. Ltd. H13 K was the substrate, and the Ni-based alloy material Ni45 and the Molybdenum powder were used. The particle size of the powder was within an range of 45–106 μm, and the element content of samples are shown in Table 1.

2.2. Experimental process

The deposition approach is shown in Fig. 1a. After LC process beginning, the laser beam and powder nozzle traveled along the length direction, and the powder was sent into the melt pool instantaneously. When one cladding path was finished, the laser beam without energy output and side powder nozzle moved to the start point of the following layer and traveled in the same direction along the path to deposit the following layer. In width direction, five to seven cladding tracks should be deposited to obtain a wide cladding surface. In thickness direction, 10 layers should be deposited for observation and further tests. After the deposition, the samples were cooled under the condition of air cooling. For each sample, the processing parameters did not change.

The powder was dried to remove moisture before cladding, uniformly mixed, and placed in the powder feeder. The substrate surface was polished and cleaned by acetone. An IPG 4000 W ytterbium fiber laser system was used in this experiment. The beam spot was round, and the energy presented a nearly Gaussian distribution. A method of positive defocus distance was used to obtain an adjustable focal length. Thus, the interaction between laser beam and powder can be improved through side feeding. After optimization, the laser power was 1.7 kW, and the diameter of laser spot was 5 mm. The overlapping rate was 60%, and the speed in laser scanning was 5 mm/s. Pure shield argon was served as shielding gas and its flow rate was 30 L/min. The feeding speed of powder was 10–15 g/min.

Three kinds of powders were employed for LC experiments. After cladding, the cladding samples were sectioned by line cutting, mounted by abrasive paper, and polished by grinder for metallographic examination. Chloroauric acid (HCl: HNO3 = 3: 1) was used as metallographic etchant. As shown in Fig. 1b, the bottom of the layer was on the X—O—Y plane, the precipitation direction was along the Z-axis, and the observation area was selected from the Y—O—Z plane (longitudinal cross section). The macroscopic morphology and the observation area of the experimental sample can be seen in Fig. 2. The morphology and the microstructure were observed using microscope and scanning electron microscopy (SEM) (JSM-6480, JEOL, Japan) with region elemental analysis using energy-dispersive X-ray spectroscopy (EDS) (Naron System Six, Thermo Electron Corporation, USA). Microhardness ($HV_{0.5}$) was obtained by Vickers hardness tester with a 0.5 kgf loading and 15 s dwell time.

3. Results and discussion

3.1. Microstructure analysis

In this research, 10 layers coating was deposited. Planar and cellular crystals only exist between substrate and coating, but not between layers. Fig. 3a shows the optical micrograph of fifth to seventh layers in sample 1, and two types of microstructures are distinguished in the coating. Optical microscopic image of bonding zone between layers (Fig. 3b) showed that a white-bright “band” which mainly contained with incorporated equiaxial dendrites could be found. The columnar dendrites occurred within short distance from the bonding zone (Fig. 3b). In the interior region of each layer, small and refined equiaxial dendrites could be found (Fig. 3c). But steering dendrites also occurred at the top of early layers (Fig. 4). Fully-grown columnar dendrites were also easier to be found in the early layers than those in the latter layers (Fig. 4).

Two main parameters (the growth rate R and the temperature gradient G) are introduced to describe the microstructural evolvement. According to the research by Kou (2003), the change of G/R ratio might

Table 1
Main chemical composition of three samples (wt%).

Sample	Materials	Fe	Ni	Cr	C	Si	B	Mo	Mn
1	431	Balance	2.36	18.1	0.17	0.90	0.60	0.05	0.17
2	431 + 8%Ni45	Balance	7.97	17.7	0.16	1.07	0.75	0.05	0.16
3	431 + 1.5%Mo	Balance	2.32	17.8	0.17	0.89	0.59	1.55	0.17