



Surface remanufacturing of ductile cast iron by laser cladding Ni-Cu alloy coatings

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ABSTRACT

Ductile cast iron is hard to be remanufactured without preheating and post heat treatment owing to the complicated phase evolution and a great tendency to form chilled structure during cladding process. Ni-Cu alloy shows great ability to obstruct the diffusion of carbon in the transition zone during the welding of cast iron due to the low solubility of carbon in nickel alloy. In the present study, different kinds of simulated grooves were devised to estimate the remanufacturing process of ductile cast iron by laser cladding. Ni-Cu alloy were used as the filling material. The microstructure and phase evolution in the transition zone were illustrated and mechanical properties have also been studied. Scanning electron microscopy (SEM), energy dispersive microanalysis (EDS), X-ray diffraction (XRD) and transmission electron microscope (TEM) were used to identify the microstructure and phase types of the claddings and transition regions. The result illustrated that various microstructures were formed during laser remanufacturing. Circular groove and cross cladding procedure were conducive to reduce residual stress. Microhardness decreased obviously after multi thermal cycles. The specimen shows ultimate strength of 502 MPa no less than that of the substrate.

1. Introduction

Ductile cast iron plays a significant role in many industry fields, such as ship engine, machine tool, pressure piping, industrial valves, etc. Ductile cast iron is mainly composed of graphite, pearlite and ferrite, and the graphite nodule is usually surrounded by ferrite to form “bovine eye” structure. Ductile cast iron can always be the alternatives of the steel in a lot of industry fields owing to its excellent cast characteristics, good property of shock absorption, well abrasive resistance and excellent toughness and strength. However, the surface of the ductile cast iron was often damaged due to strong wear and impact during service resulting in failure of the ductile cast iron. A variety of ways were used to remanufacture those damaged workpieces such as shielded metal arc welding [1,2] tungsten inert gas welding [3], powder welding [4], plasma beam treatment [5] and electron beam welding [6]. However, due to the poor weldability of ductile cast iron, lots of problems could not be solved using these methods, such as wide fusion region with high hardness, strong tendency of cracking and chilled structure, high heat input and large tendency of deformation. During remanufacturing process, it is a key problem to control the diffusion of carbon close to the interface region and control the precipitation of the brittle phases in partially melted zone (PMZ) and heat

affected zone (HAZ). Therefore, it is necessary to find some new ways to solve those problems.

Laser cladding was always to be chosen to repair damaged cast iron components. Laser cladding is a manufacturing method which could be used to generate compact and well metallurgical bonded coatings owing to its high energy density, little pollution, low element dilution and little thermal damage to the substrate [7–10]. However, heterogeneous composition between the cladding materials and the substrate always makes the laser cladding process on cast iron very difficult [11]. Various researchers have tried to repair ductile cast iron components using laser cladding process and enhance the performance of the surface of the ductile iron. Laser melting of nodular cast iron was generated by K.F. Alabeedi et al. [12], and the microstructure of the surface was modified and the hardness and erosion resistance of the surface were also improved. Hong Zhou et al. [13] obtained a new method of deep laser cladding on compact graphite cast iron and abrasive resistance was obviously enhanced. A. Fernández-Vicente et al. [14] obtained hardened layers on ductile cast iron and investigated the effects of laser treatment on the microstructure, cracks and stresses generated in the layers. Hao Liu et al. [15] got NiCoCr alloy coatings on compacted graphite cast iron by laser cladding, and the microstructure evolution and bonding characteristic in multi-layer were studied. The

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results showed that the width of the high micro-hardness zone decreased and the mechanical properties were improved under the thermal influence of multi-layer deposition method. Laser surface alloying with Cr or WC addition by different addition procedure on gray cast iron was completed by Zhi-kai Chen et al. [16], and the fatigue wear resistance was improved with appropriate Cr or WC addition.

However, cladding process was always generated on the flats, and the remanufacturing process on various simulated defects such as pits and grooves was hardly studied. Residual stress and cracks induced during the remanufacturing process were always hardly researched.

The aim of this work is to determine the residual stress, cracking sensitivity, mechanical properties and related microstructure evolution during laser remanufacturing process of ductile iron. Ni-Cu alloys have an outstanding wear and corrosion resistance, and it is a recommended filler alloy to weld cast iron. In the present study, a YAG laser with maximum power of 1200 W was chosen for the remanufacturing process. QT500-7 ductile cast iron and the Ni-Cu alloy powders were used as the base material and cladding material respectively. Experiments were focused on the residual stress and microstructure of the cladding layers and transition zone.

2. Experimental

This paper is organized as follows. The base material in this investigation was ductile cast iron QT500-7. This ductile cast iron has a yield strength of 320 MPa and ultimate strength of 500 MPa. Before laser cladding, various blocks were prepared by grinding and all the contaminants were removed from the surface. Microstructure of QT500-7 ductile cast iron consisted of pearlite and ferrite matrix with dispersed graphite nodules embedded in ferrite structure. Chemical composition of the ductile iron is shown in Table 1. Ni-Cu alloy powders with the particle size of 20–110 μm were used as the repairing material and chemical composition of the powders is shown in Table 2.

In this research, a YAG laser-based cladding system was used for the laser remanufacturing process, with a maximum power of 1200 W and 1064 nm wavelength. The off-axial auto powder feeding system was selected as the powder feeder and the powder nozzle was kept at an angle of 30° to the vertical. A 6-axis FANUC robot system was used to control the movement of the laser head and the nozzle. Inert Ar gas was chosen as powder carrier gas and the shielding gas, and N₂ gas was selected to protect the lens. The cladding region was machined and polished with sand paper and then cleaned with alcohol. Base metal specimens were prepared in dimension of 200 × 50 × 20 mm³ and the repairing zone was designed as different kinds of grooves up to 5 mm in depth. The groove shape and laser scanning methods were adopted as shown in Fig. 1. Table 3 provides a summary of these different process conditions. All the specimens were fixed in both sides during remanufacturing process to get close to the actual situation. Optimized processing parameters were used in this research. The optimized parameters included the following: laser power of 1000 W at the scanning speed of 3.3 mm/s and the powder delivery velocity 7.8 g/min. The laser spot diameter and the overlapping were kept constant at 3 mm and 47% respectively.

The specimens were machined into various samples by wire-electrode cutting, and analysis was performed on transverse cross section and longitudinal section of those samples. The section planes were polished by sand paper and polishing cloth. After polishing, 4% Nital solution and aqua regia were used to etch the interface zone and cladding zone respectively. Optical microscope (OLYMPUS MPG3) was

Table 2

Chemical composition of Ni-Cu powders (wt%).

C	Si	Fe	B	Cu	Fe
0.04	2.2	0.6	1.2	21	Bal.

used for the analysis of the morphology. Scanning electron microscopy (SEM, Quanta 200 with EDS analysis system) was used to examine the cross-sectional microstructure as well as the fracture. Transmission electron microscope (TEM) was used to identify the phase structure. The element distribution was determined via Energy-dispersive X-ray spectroscopy (EDS). X-ray diffraction analysis was carried out by means of X-ray diffraction technology using Cu-K α radiation (X-350A). Microhardness was measured using a Vickers tester (DSZF-1), and a load of 1.96 N was applied during a dwell time of 10 s. Tensile tests were carried out on an Instron5569 testing machine. A representative groove was applied on the ductile cast plate. The depth of the groove was 3.5 mm with a width of 15 mm as it was shown in Fig. 2a. Overlapping cladding tracks were adopted to fill the groove area. After cladding, the top surface of the cladding was removed to ensure the test section of the plate was completely flat as it was shown in Fig. 2b. At last, the plate was machined into a dog-bone specimen for tensile testing as Fig. 2c shows.

3. Results and discussion

3.1. The effect of groove design and cladding procedure on cracks

Fig. 3 shows the dye penetrant testing results and the crack morphology in the cladding layers. As Fig. 3a shows, the cracks of sample B1 and B3 mainly occurred at the interface between the cladding layers and substrate, which indicates that the groove design of B1 and B3 are easy to cause strong stress concentration. The crack of the sample B5 occurred at the center line of the cladding layer, indicating that the stress is also concentrated in the center line. Generally, the tensile stress is not high enough to cause the cracking of the cladding layer, but there are some defects such as bad fusion in the cladding layers and these defects always cause cracks. Differences in coefficient of thermal expansion often cause stress concentration in the laser cladding process. Zhang [17] studied the thermal welding process of pearlitic ductile iron and suggested that crack initiation and propagation in pearlitic ductile iron are the results of the difference in mechanical properties of the base metal from those of the fill materials. Rasch [18] found that Ni-Cu deposit had limited use for welding of pearlitic ductile iron because of the hot-cracking sensitivity with the coexistence of high carbon contents. Fig. 3b and Fig. 3c show the dye penetrant testing results and cross section morphology of sample B2, B4 and B6. It can be seen that almost no cracks could be found in those samples except that there is a small amount of crack in the sharp corner position in the sample B4, which meaning that the cracking tendency is significantly reduced by cross scanning procedure. Similar results could be found in Fig. 3d. The cladding layers almost broke away from the substrate in sample B7, while the layers combined well with the substrate and no cracks could be found in B8. The results also indicate that the stress caused during cladding process by cross scanning procedure is also significantly reduced.

Residual stresses were always caused by the thermal expansion mismatch between the substrate and the cladding materials during the cooled process of the claddings. Compared with the substrate, the expansion process of the cladding layer is more obvious. Therefore, fracture always occurred in the interface zone and cladding layers if the residual stress was high enough. For laser cladding process, there are many defects like undercut in the surface of the cladding layers. Therefore, even if the residual stress is less than the strength of the cladding layer, the crack may occur at the undercut region. The residual

Table 1

Chemical composition of ductile cast iron (wt%).

C	Si	Mn	P	S	Mg	Cu	Fe
3.3	3.5	0.28	≤0.05	≤0.02	0.035	≤0.1	Bal.

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