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Effects of heating time on the microstructure and properties of an induction cladding coating

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ABSTRACT

A Ni-based alloy coating was prepared on the surface of grey cast iron via a multi-step induction cladding method, and the effects of the heating time on the porosity, elemental distribution, microhardness and corrosion resistance of the coating were studied. The microstructure and elemental distribution of the cross-section of coating and the phase composition of the coating surface were analysed by scanning electron microscopy (SEM) coupled with energy-dispersive spectroscopy (EDS) and X-ray diffractometry (XRD), respectively. The results revealed that the cross-section of the coating apparently consisted of different zones and was metallurgically bonded to the substrate, and that the quality of the interface was excellent. Clusters of fine graphite appeared in the lower part of the coating near the substrate, and needle-like structures and a few pores were found in the middle and upper part of the coating. The coating was composed of γ-Ni solid solution, the Ni_3Si eutectic structure, an intermetallic compound ($Cr_{1.12}Ni_{2.88}$) and hard phase structures, such as boride (Ni_3B) and carbide ($Cr_{15.58}Fe_{7.42}C_6$). Prolonged heating time reduced the porosity but increased the melting depth of the substrate surface, resulting in an increase in the width of the interdiffusion zone and severe dilution of the coating. As a result, the microhardness was significantly reduced, while the corrosion resistance was not improved as the heating time increased. After immersion corrosion, pitting and selective corrosion appeared on the surface of the coating. The corrosion products mainly included $NiSO_4(H_2O)$, NiO_2 and SiO_2. By selecting a suitable heating time, it could control the melting depth of the substrate, reduce the dilution rate and retain the hardness and corrosion resistance of the coating.

Owing to advantages such as excellent machinability, castability, thermal conductivity, shock absorption, a self-lubricating property and low cost, grey cast iron is widely used in the manufacture of marine and auxiliary diesel engines, machine tools, automobiles, construction equipment as well as other large equipment parts [1]. Grey cast iron is prone to the formation of shrinkage cavities and shrinkage porosity defects in the casting process, and these defects are the cause of failure during operation [2]. Application of an alloy coating, such as via high-velocity oxygen-fuel (HVOF) spraying, plasma surfacing, or laser cladding, to the surface of grey cast iron is often used to improve its wear resistance and corrosion resistance. In addition, laser induction hybrid cladding (LIHC) is a promising surface modification technology to produce Ni- and Fe-based WC coatings on the low and mild steel [3,4]. The coating prepared by HVOF spraying is mechanically bonded to the substrate; such a coating has a weak bonding force and limited coating thickness and is prone to flaking off under heavy load conditions. The coatings prepared from plasma surfacing and laser cladding can form a metallurgical bond and possess a compact structure. Induction cladding is a new surface cladding technology that combines the advantages of induction heating and surface coating techniques. Based on the electromagnetic induction effect, the thermal effect and the skin effect, the self-fluxing alloy and metal cermet is coated on the surface of the substrate. Induction cladding can be used to prepare large-area coatings with uniform thickness, wear resistance and corrosion resistance in an energy efficient, environmentally friendly and low-cost manner [5].

To date, researchers have used medium-, high-, or ultrasonic-frequency equipment to prepare Ni-based, Fe-based and Co-based alloy coatings and composite coatings (by adding ceramic composite to self-fluxing alloy powders) on medium- and low-carbon steel substrates and studied the wear resistance and corrosion resistance of the coatings [6–9]. However, studies on the effects of processing parameters on the properties of coatings have rarely been reported. Chang et al. [8] studied the effect of the heating temperature on the microstructure and hardness of the layer prepared using vacuum induction cladding. Liu et al. [10] studied the effects of the heating time on the microstructure and elements distribution of the coating formed by a high-frequency

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induction cladding method. It was revealed that as the heating increased, the microstructure and Cr distribution became uniform in the coating, and the impurities and pores floated upward in the upper part of the coating. Due to the high carbon content of grey cast iron and the inhomogeneous heat distribution and rapid cooling during the cladding, the white structure resulting in the spallation of the coating occurs at the interface between the coating and the substrate. In addition, grey cast iron possesses a low melting point (1100 °C) that is close to that of the cladding material, so the processing parameters are difficult to control. Therefore, there have been few studies on the preparation of coatings on grey cast iron substrates using induction cladding technology [11].

In this paper, a Ni-based alloy coating was prepared on a grey cast iron substrate via a multi-step induction cladding method. The effects of the heating time on the microstructure and properties of the coating were studied. This study provides new processes to improve the properties of grey cast iron parts and experimental evidence for the industry application of induction cladding.

Experimental materials and methods

Materials and test procedures

The material used for the substrate was HT 300 grey cast iron (*Φ*22 mm × 100 mm), and its elemental composition (mass%) was C (2.5–4.0), Si (1.0–2.5), Mn (0.5–1.4), and Fe (balance). The cladding material was the self-fluxing Ni-based alloy powder SH-Ni60A (particle size: 150–320 mesh), and its elemental composition (mass%) was C (0.6–1.0), Cr (15–20), B (3.0–4.5), Si (4.0–5.5), Fe (≤5), and Ni (balance). The surface of the substrate was cleaned, roughened, and activated by sandblasting, and then, the substrate was placed in an alcohol solution, degreased with an ultrasonic cleaner and dried with a dryer. A homogeneous mixture of the Ni-based alloy powder and a saturated sodium silicate solution was placed in a three-dimensional (3D)-printed mould to form a pre-coated layer on the substrate surface with a thickness of 1 mm, as shown in Fig. 1(a). After the substrate, together with the mould, was cured at room temperature, the substrate and the mould were heated in a dryer oven at 200 °C for 3 h and then naturally cooled in the oven to separate the pre-coated layer from the mould.

The experimental device was a self-developed GGC120A ultrasonic-frequency induction cladding test platform (maximum current = 150 A, and maximum frequency = 40 kHz) with a vertical rotary table and an infrared temperature measurement system (as shown in Fig. 1(b)). In the induction cladding process, the workpiece was placed in a graphite sleeve to prevent oxidation of the coating during heating and to reduce the cooling rate. The heating was stopped when the coating was glowing bright red. After induction cladding, the thickness of the coating was approximately 0.8 mm. Extensive experiments showed that a high-quality coating could be obtained by the equivalent increment of current and short duration heating processes. The process parameters for different heating time are shown in Table 1.

Table 1
Process parameters for the induction cladding.

Samples	Heating current/A		
	10	20	30
Ni-2	90 s	90 s	7 s
Ni-3	90 s	90 s	9 s
Ni-4	90 s	90 s	11 s

Analysis of the characteristics of the coating

After cladding, the workpiece was cut in the radial direction, polished with emery paper (particle sizes from #200 to #1500) and finally polished to a mirror finish with diamond powder (diameter = 1 μm). Before the microstructure observation, the surface of the sample was wiped with a corrosive solution prepared from 50 mL of hydrochloric acid (HCl), 50 mL of water (H_2O) and 5 g of copper sulfate ($CuSO_4$) to increase the metallographic contrast. The microstructure and elemental distribution of the cross-section of the coating were observed using a TESCAN-VEGA 3 scanning electron microscope (SEM) coupled with an energy dispersive spectrometer (EDS). The phase composition of the coating surface was analysed by a PANalytical-Empyrean X-ray diffractometer (XRD). The microhardness of the cross-section of the coating was measured along the direction from the substrate to the coating using an HX-200 Vickers microhardness tester with a load of 200 g, a load holding time of 20 s and a distance of 50 μm between adjacent test points.

Porosity measurement

The porosity of the coating was measured by image analysis. First, the morphology of the coating was collected by an OLYMPUS GX 51 metallographic microscope (Fig. 2(a)–(c)). Subsequently, the image was processed by the software Image J, and the profile of the pores was obtained after abstraction (Fig. 2(d)). The porosity of the coating was calculated using the Eq. (1) [12]:

$$R_p = \frac{S_1}{S_2} \times 100\% \quad (1)$$

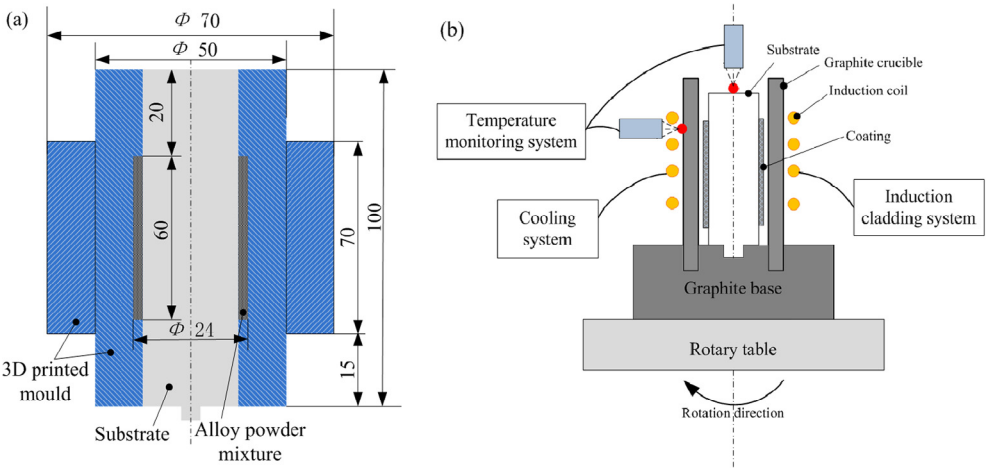

Fig. 1. Schematic diagrams of (a) the coating deposition mould/mm and (b) the experimental device.