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Friction and wear behavior of a Ni-based alloy coating fabricated using a multistep induction cladding technique

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ABSTRACT

A Ni-based alloy coating was fabricated on a gray cast iron surface using a multistep induction cladding technique. A scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS) and an X-ray diffractometer (XRD) were used to analyze the cross-sectional morphology, element distribution, and surface phase composition of the induction coating. The coating was metallurgically bonded to the substrate. There was a notable layered structure inside the coating. Element interdiffusion occurred at the interface between the coating and the substrate. The coating surface was composed primarily of γ-Ni solid solutions and Ni-Ni_3Si eutectic microstructures, in which hard strengthening phases, such as borides (Cr_2B and Ni_3B) and carbides ($Cr_{23}C_6$ and Cr_7C_3), were distributed. The microhardness and wear behavior were analyzed by Vicker indentation tester and the rectilinear reciprocating testing system, respectively. The microhardness at the interface of the coating and substrate increased significantly, and the average microhardness of the coating was approximately four to five times of the substrate. At room temperature and under dry sliding conditions, as the sliding distance increased, the coefficient of slowly. As the sliding load increased, the coefficient of friction of the coating changed insignificantly, but its wear loss increased. Abrasive and oxidation wear was the dominant wear mechanism of the coating.

A cylinder liner is an important but vulnerable part of a diesel engine, and its performance, to a large extent, determines the service life of the diesel engine [1]. The cylinder liner in a diesel engine operates in an extremely adverse working condition and is particularly subject to repeated friction from the piston ring. The friction loss of the cylinder liner-piston ring accounts for 6–7% of the total energy loss in a diesel engine. With the increasing technical performance requirements for diesel engines, cylinder liners suffer serve wear and consequently are discarded before reaching their normal service life. Therefore, remanufacturing cylinder liners and maximizing the use of retired ship and machine parts are of great practical significance to resource recycling [2].

Surface engineering techniques can be applied to recover dimensions and enhance performance, such as electroplating, thermal spraying, welding, laser cladding and induction cladding. It can be used to repair and remanufacture worn cylinder liners as well. Coatings remanufactured by electroplating and thermal spraying are mechanically bonded onto the substrates. The bonding between these coatings and the substrates are weak, and the coating thickness is limited. These coatings are prone to spalling under heavy loads. Coatings remanufactured by welding, laser cladding and induction cladding are metallurgically bonded to the substrates and have a dense structure. Of these processing techniques, induction cladding is an energy-saving, environmentally friendly, high-quality, low-cost, efficient and rapid surface remanufacturing technique [3–6].

To date, researchers have prepared Ni-[4], Fe-[5] and cobalt-[6] based alloy coatings on low carbon steel substrates using high frequency or supersonic frequency equipment, and prepared composite coatings by adding ceramic-phase elements into self-fluxing alloy powders [7]. In the study done by Chang et al. [4], a Ni-based alloy coating was fabricated on a steel substrate using vacuum induction melting, and the tribological property of the coating was analyzed on a ball-on-disc apparatus. According to Hu et al. [8], the dominant wear mechanism of the Ni-based alloy coating onto a medium carbon steel by induction cladding was mild adhesive wear. In our previous work [9], a comparative study on wear behavior of Ni-based alloy coating and HT 300 was carried out on a ball-on disc wear tester. Gray cast iron is a material commonly used in cylinder liners for diesel engines of ships. However, due to high carbon content of gray cast iron, white structures are easily formed at the coating-substrate interface, causing the coating to crack or spall. In addition, gray cast iron has a low melting point (1100 °C) close to that of the cladding material, causing difficulties in

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controlling the processing parameters. Hence, the research on preparation of coatings on gray cast iron by induction cladding is rare.

In this study, a Ni-based alloy coating was prepared on the surface of a gray cast iron substrate using a multistep induction cladding technique. The coating was then analyzed to determine its cross-sectional morphology, element distribution and microhardness as well as the phase composition of its surface. In addition, the friction and wear behavior of the coating under dry sliding conditions was studied on a self developed rectilinear reciprocating wear tester. This study provides a new technique for prolonging the service life of gray cast iron parts and improving their environmental benefits.

Experimental materials and methods

Materials and induction cladding technique

A gray cast iron HT 300 (ϕ 22 × 100 mm) was selected as the substrate. Its chemical composition is as follows (mass fraction, %): C (2.5–4.0), Si (1.0–2.5), Mn (0.5–1.4) and Fe (bal.). SH-Ni60A self-fluxing Ni-based alloy powder was selected as the cladding material. Its chemical composition is as follows (mass fraction, %): C (0.6–1.0), Cr (15–20), B (3.0–4.5), Si (4.0–5.5), Ni (bal.) and Fe ($\leq$5). Before induction cladding, a blasting machine was used to clean, coarsen and activate the substrate. Afterwards, the substrate was immersed in an ethanol solution and subjected to an ultrasonic cleaning treatment to remove grease impurities. Subsequently, the substrate was dried using a blower. The Ni-based alloy powder was homogenously mixed with a saturated sodium silicate solution. The mixture was then injected into a three-dimensional printing mold. A 3 mm thickness layer was then prepared on the substrate surface. After drying at room temperature, the substrate and the mold were heated in a furnace at 200 °C for 3 h and then cooled naturally in the furnace. Finally, the mold and the substrate with precoated layer (hereinafter the “specimen”) were separated (Fig. 1(a)).

A self developed supersonic-frequency induction cladding experimental platform (Fig. 1(b)) (maximum current: 150 A; maximum frequency: 40 kHz) was used to prepare the coating. In the induction cladding process, the specimen was placed in a graphite sleeve to prevent the coating from oxidizing during the heating process and reduce the cooling rate. When the coating turned a bright red color, the heating process was terminated. From extensive experiments, it was found that a multistep with short duration heating at varying power increments could produce high-quality coatings (342 kJ for 90 s, then 684 kJ for 90 s, finally 125.4 kJ for 11 s). Fig. 2 shows the process optimization. When heated at a high power (11.4 kW) for a short duration (101 s), the substrate melted severely. When heated at a constant power (6 kW) for an intermediate duration (191 s), the Ni-based alloy powder was sintered but did not melt. When heated at a low power (3.8 kW) for a long duration (303 s), the coating presented flowing.

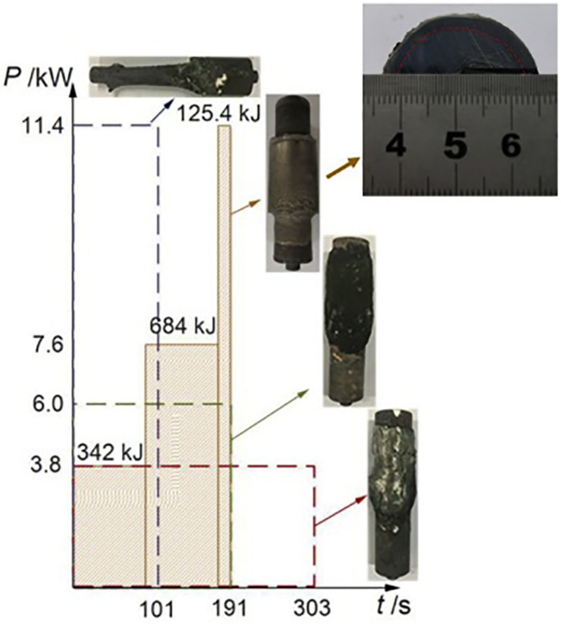

Fig. 2. Process optimization of the induction cladding.

Experimental methods

After cladding, each specimen was cut along the radial direction, which was then polished using emery paper ranging from #200 to #1,500 and finally polished using diamond powder with a particle diameter of 1 μm to a mirror finish. Before microstructural observation, the surface of the specimen was wiped with a solvent composed of hydrochloric acid (50 ml), water (50 ml) and copper sulfate (5 g) to increase its metallographic manifestation. A Supra 55 Sapphire scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS) was used to observe the cross-sectional morphology and element distribution of the coating. A PANalytical-Empyrean X-ray diffractometer (XRD) was used to analyze the phase composition of the coating surface.

An LW-HV 1000 Vicker indentation tester system was used to measure the microhardness along the substrate-coating direction (distance between adjacent measuring points is 200 μm; load is 200 g; load

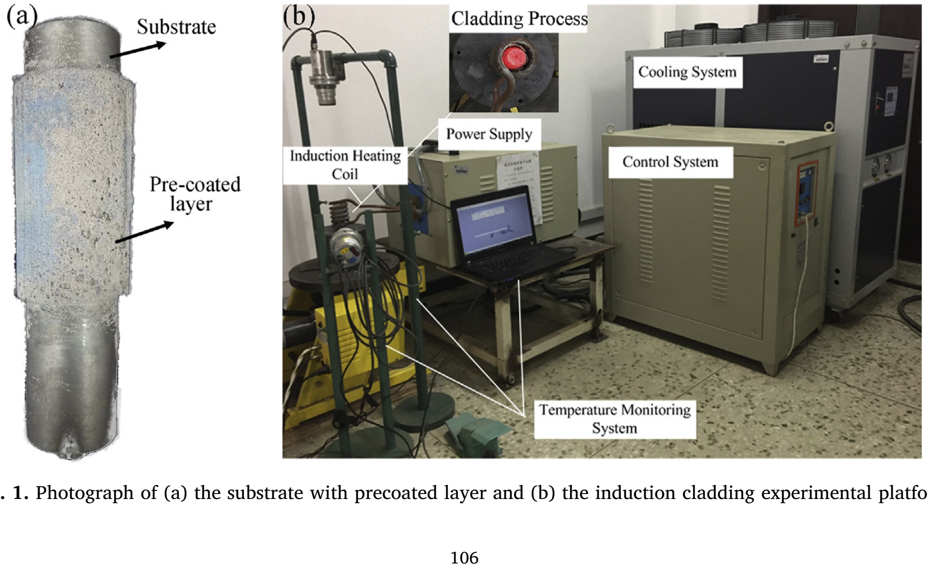

Fig. 1. Photograph of (a) the substrate with precoated layer and (b) the induction cladding experimental platform.