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Effects of laser remelting on microstructures and immersion corrosion performance of arc sprayed Al coating in 3.5% NaCl solution

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ABSTRACT

An arc sprayed aluminum (Al) coating on S355 steel was processed using a laser remelting (LR). The microstructures, chemical element composition, and phases of the obtained Al coating were analyzed using a field mission scanning electronic microscope (FESEM), energy dispersive spectrometer (EDS), and X-ray diffractometer (XRD), respectively, and the residual stresses were measured using an X-ray diffraction stress tester. The immersion corrosion tests and potentiodynamic polarization of Al coating in 3.5% NaCl solution were performed to investigate the effects of LR on its immersion corrosion behaviors, and the corrosion mechanism of Al coating was also discussed. The results show that the arc sprayed Al coating is composed of Al phase, while that by LR is composed of Al-Fe and AlO_4FeO_6 phases, and the porosities and cracks in the arc sprayed Al coating are eliminated by LR, The residual stress of arc sprayed Al coating is -5.6 ± 18 MPa, while that after LR is 137.9 ± 12 MPa, which deduces the immersion corrosion resistance of Al coating. The corrosion mechanism of arc sprayed Al coating is pitting corrosion and crevice corrosion, while that by LR is uniform corrosion and pitting corrosion. The corrosion potential of arc sprayed Al coating by LR shifts positively, which improves its immersion corrosion resistance.

1. Introduction

Coating technology is widely applied on the surface modification of steel, magnesium (Mg) alloy, titanium (Ti) alloy and etc. due to its convenient preparation, flexible processing and low cost [1,2], which effectively improves abrasion resistance, oxidation resistance and corrosion resistance of the above substrates [3,4]. Al coating is usually introduced as barrier layer in the marine circumstance or humid atmosphere to resist electrochemical corrosion, which not only isolates the corrosive medium, but also preserves the substrates by consuming itself as the anode materials [5]. Generally speaking, the Al coating has corrosion resistant in neutral aqueous solutions owing to the passive oxide film, which is rapidly formed on the substrate [6]. The thicknesses of Al_2O_3 on the Al coating increase with the immersion time, while the corrosion resistance of Al coating decreases with the corrosion period [7]. In fact, the Al coating is sprayed on naval architecture and ocean engineering using an arc spraying, which is modified by the molten or partially molten particles with high speed to obtain the needed performances [8]. Even through the Al particle surface is easily oxidized in the arc spraying process, the subsequent particles with the high speed impact the oxide layer, and the dense oxidation film is formed on the Al coating, which effectively prevents the corrosion media from diffusing into the substrate, and improves the corrosion performance of Al coating [9,10]. However, there are some porosities and cracks in the Al coating, which affect its corrosion performance.

LR is a new method of improving the qualities of Al coating, which can eliminate the internal porosities of the Al coating, and refine the coating structures to improve the bonding strength between the coating and the substrate, enhancing the power of corrosion resistance [11]. Compared with the traditional remelting processing, the arc sprayed Al coating is more dense by LR, the micro–defects are smaller, and the effects on the substrate are slight [2,12,13]. In recent years, with development of laser processing, the LR technology has received more and more attentions.

At present, the researches are focused on surface treatment of pre-existing coating using a LR. The laser remelted Al_2O_3-13% TiO_2 coatings were fabricated on a Ti–6Al–4 V alloy, the results showed that the metastable γ-Al_2O_3 phase was transformed to the stable α-Al_2O_3 by LR, which increased the coating hardness [14]. The laser remelted Inconel 625 coatings decreased the porosities, roughness and hardness, and the columnar dendritic microstructure of Al coating was formed after LR [15]. When the

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Fe-based amorphous and nano-crystalline coatings were fabricated using a LR, the results demonstrated that the laser-remelted coating obtained the denser structures than the as-sprayed coating and achieved high corrosion resistance performance [16]. LR improved the corrosion performance of plasma-sprayed Al–Si coating, the corrosion mechanism was converted from crevice corrosion to pitting corrosion and preferential galvanic corrosion [17]. The Ni-based amorphous composite coating including a small number of crystal phases was prepared using a laser processing. It was reported that the laser remelted coatings represented dense amorphous structure, which were embedded by some crystal phases, the corrosion resistance was enhanced by LR and did not interfere with the forming of passive film [18]. However, so far the evaluations of LR on corrosion performance are little reported.

In this study, an Al coating was sprayed on S355 steel using an arc spraying, which was processed using a laser remelting (LR). The microstructures, chemical element compositions and phases of the obtained Al coatings were analyzed using a field emission scanning electronic microscope (FESEM), energy dispersive spectrometer (EDS) and X-ray diffractometer (XRD), respectively, the residual stresses were measured using an X-ray diffraction stress tester. The corrosion performance and electrochemical curves of Al coatings were tested in 3.5% NaCl solution, the effects of LR on the corrosion performance of Al coating were discussed, which provided an experimental base for arc sprayed Al coating by LR on the ocean engineering.

2. Experimental

The experimental material was S355 mild steel with the chemical element composition (mass, %): C $\leq$0.17, Si $\leq$0.55, Mn $\leq$0.94, P $\leq$0.035, Cr $\leq$0.065, S $\leq$0.035, Ni $\leq$ 0.065, Mo $\leq$0.30, Zr $\leq$0.15, and the remainder was Fe. The process of arc spraying was shown as follows: mechanical polishing → chemical deoiling → rust cleaning → washing and drying → arc spraying → cooling → surface cleaning. The arc spraying test was conducted on an AS400 type intelligent digital arc spraying machine, the technological parameters of arc sprayed Al coating are shown in Table 1. After arc spraying twice, the thickness of Al coating was ~300 μm. The LR test was conducted using a ZKSX-2008 type all-solid state optical fiber coupled transmission laser system, the technological parameters of LR are shown in Table 2. After LR, the surface-interface morphologies and the element distributions of the obtained coating were analyzed using a JSUPRA55 type FESEM and its configured EDS, respectively. The phases and residual stresses of Al coatings were detected using a D/max2500 type X-ray diffractometer (XRD) and X350-A type X-ray diffraction stress tester, respectively. The immersion corrosion was performed in a YQW-250 type immersion corrosion test chamber in accordance with the GB 6458-86 (NSS) protocol, 3.5% NaCl solution was used to simulate the immersion corrosion in sea water. The technological parameters of immersion corrosion are shown in Table 3. The morphologies, chemical element distributions and phases of Al coatings after immersion corrosion were analyzed using a FESEM, EDS, and XRD, respectively. The electrochemical test was conducted on a CS350 type electrochemical workstation, the technological parameters of electrochemical corrosion are shown in Table 4, and the polarization curves from the test were achieved using a fitting.

Table 1
Technological parameters of arc sprayed Al coating.

Item	Parameter
Diameter of Al wire/mm	2
Spraying voltage/V	30–32
Spraying current/A	160
Spraying distance/mm	150
Spraying angle/°	80
Spraying pressure/MPa	0.6
Overlap ratio/%	35

Table 2
Technological parameters of LR.

Item	Parameter
Protective gas	Ar
Output power/W	1200
Spot diameter/mm	4
Scanning speed/mm/s	15
Overlap ratio/%	50

Table 3
Technological parameters of immersion corrosion.

Item	Parameter
Corrosion solution	3.5 ± 0.5% NaCl
pH	6.5–7.2
Temperature/°C	26 ± 7
Immersion time/h	720

3. Analysis and discussion

3.1. Morphologies and EDS analysis of Al coating surface

Fig. 1(a) shows the surface morphology of arc sprayed Al coating. When the Al particles parallelly impacted on the substrate at the same direction, the porosities were generated by the uncompleted accumulation of the Al particles or the interference of residual gas in the pits on the substrate, called “shadow effect” [19]. There were stacked state of molten drops in the arc spraying test, the island-like and carinate shapes were unevenly distributed. In addition, large areas of pits and crevice existed among the irregular weaves. The plane scan analysis result of the surface is shown in Fig. 1(b). The mass fractions of chemical elements (mass, %): Al 51.48, O 11.79, C 36.72; and the corresponding atom fractions (at, %): Al 31.14, O 13.38, C 55.49. The Al atom-rich zones were formed on the Al coating, as shown Fig. 1(c). There were some shadows, which displayed the uniform variation from the atom-rich zones to the atom-poor zones gradually. Fig. 1(d) shows the O distribution. There were relatively approximate proportions of atom-rich zones and shadows, even though the former occupied more. Compared with the Al distribution, the O represented less atom-rich zones. Besides, the Al and O were similarly distributed between the atom-rich zones and atom-poor zones. Furthermore, there were the oxide films on account of arc sprayed defects and the explosion in the air. The existence of C was the pollution in the air, as shown in Fig. 1(e).

Fig. 2(a) shows the surface morphology of arc sprayed Al coating by LR. The island-like and carinate shapes disappeared, and the pits and crevice in the superficial surface were flattened. The reconstruction of Al coating produced low surface roughness. In addition, the minimized ripples and slight wrinkles appeared on

Table 4
Technological parameters of electrochemical corrosion.

Item	Parameter
Corrosion solution	3.5 ± 0.5% NaCl
Working temperature/°	25 ± 1

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