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Underwater laser cladding in full wet surroundings for fabrication of nickel aluminum bronze coatings

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A R T I C L E I N F O

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A B S T R A C T

Underwater laser repairing technology as a new type of on-line maintenance technology will promote the development of oceanographic engineering. However, there are many difficulties during the process of underwater laser repairing. In this paper, underwater laser cladding process in full wet surroundings (or WULC, for short) for fabrication of nickel aluminum bronze (or NAB, for short) has been reported, and laser cladding process in the air for fabricating NAB coatings was used for comparative study. The homemade protective covering was used to solve the problems of underwater laser repairing. For comprehending the effect of full wet surroundings and protective covering on microstructure and electrochemical performance of the NAB coatings, a series of characterization tests including SEM, EDS, XRD and TEM and a series of electrochemical measurements were carried out. The alloy coatings fabricated by WULC possess good formability through optimizing the processing parameters. The elements distribution of the coatings shows different patterns compared to conventional cast copper alloy and NAB coating fabricated by laser cladding in the air. In addition, the ordered solid solution and twinning structure have been observed in the WULC-NAB coatings. These unique microstructures and elements distribution patterns caused the better electrochemical performance of NAB coating fabricated by WULC. These findings suggest that the idea of using a protective layer in underwater laser cladding in full wet surroundings is feasible. The WULC process reported in this paper can provide some theoretical guidance for repairing damaged parts in full wet surroundings.

1. Introduction

Underwater repair and maintenance techniques have been paid extensive close attention recently for the reason of its convenience to repair the damaged parts in underwater environments [1]. Among those techniques, the underwater arc welding is the most extensively studied and widely used in the repair and maintenance of marine constructions [2]. However, underwater arc welding will become more and more difficult with the increase of water depth [3]. To be more specific, arc strike during wet-welding and establishment of pressure chamber for dry-welding are difficult because of ultrahigh hydraulic pressure. In recent years, underwater laser welding has become research focus, and the most representative research achievement is local-dry underwater laser cladding [4]. As well as the underwater arc welding, constructing the local-dry pressure chamber during underwater laser welding will become more and more difficult with increasing the water depth. Using wet-underwater laser repair techniques, by contrast, will not run into those problems. Recently, Ning Guo et al. have studied the effect of water depth on weld quality and welding process in underwater fiber laser welding. They pointed out that water has a strong hindering effect on ULBW [5]. Assuredly, underwater laser repair in full wet surroundings is a very complex process, including the interactions of laser-water, laser-metal and metal-water.

The interactions among laser, target metal and water must affect the surface nature of the workpiece. When the laser irradiates on the metal surface, the water close to the metal surface absorbs enormous amount of heat, and cavitation generates immediately. Once generated, the cavitation bubble grows to a maximum size and then implodes, because of the pressure gradient between the outside and inside of the bubble. In general, the cavitation bubble oscillates several times, emitting acoustic transients upon each collapse, until the bubble totally dissolves into the liquid. When the bubble collapses in the vicinity of a solid boundary, high-speed liquid jet forms and flows towards the surface of

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workpiece [6]. High-speed liquid jet will invade into the melting pool during underwater laser processing. Then, the melting pool will solidify quickly, and the water injected into melting pool will vaporize instantaneously. This series of reactions can fill the surface of metal workpiece with pores. Moreover, during the laser machining process, a metal plasma plume is generated on the target metal surface, because of the irradiation of high-energy laser [7]. The hot and dense plasma is important for laser processing especially for laser cladding to carry out successfully. In underwater environment (the water depth is over 8 mm), a kind of water vapor mixed with metal vapor plasma will be formed when the high-energy laser irritate onto the surface of the target metal. This plasma can attenuate the laser beam, and with the increase of the water vapor content in this plasma the attenuation of the laser beam will be seriously [8]. As a result, the absorbed laser energy by the workpiece is reduced severely. In another hand, the cavitation may affect the stability of the plasma, and then the stability of the beam channel will be influenced. The stability of beam channel have an important influence on the weld bead quality and the welding process stability [5]. In addition, the high-energy laser irritation can cause the water decompose into oxygen and hydrogen. The oxygen and hydrogen will influence the performance of the target metal [9]. In conclusion, the water has a strong hindering effect on the process of underwater laser processing. If we want to practice the underwater laser processing successfully, those problems mentioned above should be dissolved appropriate.

In this paper, the underwater laser cladding in full wet surroundings has been reported, which is a comparatively new conception. In this study, nickel aluminum bronze (NAB) was selected as the experimental material of substrate and coatings. It should be noted that the protective covering was used to ensure that the underwater laser cladding process can be carried out successfully. NAB is a popular choice for industrial applications [10] such as seawater lift pumps for the oil industry, hydraulic bushings for earth moving equipment, and hardware for the marine industry, due to its good combination of mechanical and physical properties [11]. However, there is a close relationship between properties of NAB and processing craft. For comprehending the effect of full wet surroundings and protective covering on NAB coatings, a series of characterization tests including SEM, EDS, XRD, TEM and electrochemical tests were carried out.

2. Experimental

In this study, preplaced layer of NAB powder and protective covering were used. The substrate material is as-cast NAB, and the compositions of as-cast NAB are listed in Table.1. The NAB powder was mixed using elemental powders, and the composition of NAB powder was designed as the same as as-cast NAB. The protective covering is semi-volatile, and its compositions are shown in Table. 2. The function of CaF_2 is to remove the hydrogen produced by water decomposition. Adding $CaCO_3$ is to create the atmosphere for the formation of metal plasma. Cu, Al, Fe, Ni, Mn and Cr are the supplementary elements, meanwhile, they can also prevent oxygen from damaging the coating. The function of TiO_2 and Si are slagging. $C_6H_7NO_2$ in the protective covering acts as gas-forming constituents and binder. In this study, the NAB powder and protective covering were preplaced in the air before the process of WULC. The thickness of NAB powder is 1.5–1.8 mm, and the thickness of protective covering is 0.5–0.8 mm.

NAB coatings were fabricated underwater by laser cladding system, and the process of the underwater laser cladding in full wet surroundings is shown in Fig.1 schematically. In addition, the video which shows the process of WULC has been included in supplementary data, and Fig.1 b was captured from the video. The laser system are equipped with ytterbium laser device (IPG Photonics Corporation), programmable manipulator (KUKA) and cladding head YC52 (Precitec). In order to find the instructive maintenance methods for underwater damaged parts, a series of parameters of the WULC process have been studied in this paper. Those parameters are as follows: water depth, power density, the application of protective covering and processing craft. First of all, the effect of water depth on formability of NAB coatings with protective covering and without protective covering in full wet surroundings were studied. After this experiment, we can make a progress on the water depth of underwater laser processing. In this study, the water depth of underwater laser processing will get up to 10 mm.Then, single track NAB coatings were manufactured with different power density under the water depth of 10 mm for studying the effect of power density on formability of NAB coatings. So far, the optimal parameters for fabricating NAB single-track coatings underwater in this paper were obtained. Then, multi-track NAB coatings with different processing crafts were fabricated. The first processing method is shown in Fig.2 a, and another method is shown in Fig.2 b schematically. The method shown in Fig.2 a is a kind of continuous process, and is called method A. NAB powder layer and protective covering were preplaced on the whole surface of substrate NAB plate, and then, WULC process was carried out underwater until multi-track NAB coating was finished. Another method shown in Fig.2 b is not continuous, and is called method B. The whole NAB coating was finished track by track. In other words, when a single track of NAB coating was finished, laser beam would be removed until the second preplaced layer was prepared. This method is an imitation of the synchronous feeding system. Through rational design, the synchronization of laying materials and laser irradiation can be achieved, and the repair efficiency will be improved for underwater laser processing in the future. In order to contrast, the NAB coatings were also fabricated in the air with the same parameters as NAB coating fabricated by underwater laser cladding except for the full wet environment.

After fabricating NAB coatings, the microstructure characterization including SEM, EDS, XRD and TEM were carried out to understand the process of WULC. Scanning electron microscopy (SEM, FEI Quanta 200, Netherlands) with an acceleration voltage of 20 kV was utilized to observe the microstructure of WULC-NAB. An energy-dispersive X-ray spectroscopy (EDS) was used to understand the elements distribution mechanism of the WULC process. The phase-analysis of the different portions in WULC-NAB coatings were performed on PANalytical X'Pert Pro MPD X-ray diffraction with Cu Kα radiation, and the parameters used in this test are as follows: the tube voltage of 40 kV, the tube current of 40 mA and the scanning speed of 2°/min. JEM-2010 transmission electron microscopy (TEM) was utilized to observe the microstructure further. Electrochemical testing of the substrate, NAB coating fabricated in the air and NAB coating fabricated underwater were studied on individual samples (with surface area of 1 cm^2) for assessing the corrosion properties. The surface of the samples are all polished, without any scratches. Aerated 3.5 wt% sodium chloride solution with pH of 6.8 was applied to this whole electrochemical experiment at room temperature. For electrochemical measurements, a three electrode configuration was employed using platinum plate as the counter, saturated calomel as the reference and prepared specimens as the working electrodes, respectively. All electrochemical measurements were performed using a CHI600E electrochemical workstation (CHINSTRUMENTS Inc. China). Each of the corrosion tests was repeated three times for checking the reproducibility of the electrochemical experiments, and the most representative data that was closest to average values was selected for plotting.

Table 1
Compositions of NAB.

Element	*Cu*	*Al*	*Fe*	*Ni*	*Mn*	*C*	*Cr*	*The balance*
Wt%	78.7	9.6	4.3	4.8	1.25	0.8	0.45	0.1