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Ultrasonic vibration assisted laser welding of nickel-based alloy and Austenite stainless steel

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ABSTRACT

In the nuclear and petrochemical industries, there were still several problems in the dissimilar welding of nickel-based alloy and austenite stainless steel by laser welding (LW), such as the appearances of unmixed zone, secondary phase, and uneven element distribution. In this paper, 20 kHz ultrasonic vibration assisted laser welding (ULW) was used to solve these problems in laser welding of Hastelloy C-276 and austenite stainless steel 304 dissimilar materials. The analysis of morphology, microstructure, element distribution and microhardness were carried out to investigate the effect of ultrasonic vibration on the dissimilar weld. The results indicated that with the addition of ultrasonic vibration, the width of unmixed zone and the amount of secondary phase were reduced, and the element distribution was homogeneous. With the increase of ultrasonic intensity, penetration depth was slightly increased, and the dilution level of 304 base metal was correspondingly promoted. The width of unmixed zone was reduced due to the micro-turbulence formed near the fusion boundary caused by the cavitation effect. With the injection of ultrasonic energy, the main texture in the weld metal (WM) shifted from {211} <453> to {111} <213>, and the ratio of misorientation in the range of 55°~60° was significantly improved. The inter-granular secondary phase in the WM was confirmed to be *p* phase, and amount of which was decreased from 2.44% without ultrasonic vibration to 0.72% with ultrasonic output power of 500 W, because the segregation of element Mo was suppressed at higher ultrasonic intensity. The cavitation and acoustic streaming effects accelerated both the molten pool convection and element diffusion, and thus, with the increase of ultrasonic intensity, the element macro-distribution in the WM became more and more homogeneous. Because the grain size in the weld metal was not obviously refined, the microhardness value of the WM with ULW was not significantly enhanced.

1. Introduction

As a Ni-Cr-Mo-based superalloy with excellent corrosion resistance and mechanical strength at high temperature, Hastelloy C-276 has been widely used in the areas of petrochemical, oil, aerospace and nuclear industries [1–3]. There was much literature on the studies of Hatelloy alloys welding [4–6], the main problems were the precipitation of brittle phases such as *p* and *u* phases, because brittle phases will increase the sensitivity to hot cracking and decrease the plasticity of weld joints. Similarly, austenite stainless steel 304 is widely used in many applications because of its cheap price, excellent mechanical property and corrosion resistance [7–9]. During the manufacture of nuclear reactor coolant pump in the third generation plant, the seal welding is demanded to join the pump can (Hastelloy C-276 with 0.5 mm thickness) and end cap (304 stainless steel with much larger thickness) in an overlap configuration [10].

The welding of Nickel-based alloy and austenite stainless steel dissimilar materials were usually carried out using traditional arc welding processes. Sharma S et al. [11] joined Hastelloy C-276 and AISI 321 stainless steel using ERNiCrMo-4 filler, and the Mo-rich phase was found in the fusion zone and at the weld interface of Hastelloy C-276 side, the brittle phase constituted more potential sites for hot cracking. Dupont et al. [12] investigated the microstructural characterization and microsegregation potential in the dissimilar welding between a super austenite stainless steel (AL-6XN) and two Nickel-based alloys (IN625 and IN622) by gas tungsten arc welding (GTAW). The results indicated that the good cracking resistance of welds prepared with IN625 was attributed to the small amount of secondary phase. Prabaharan P et al. [13]

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addressed the weldability of Super Ni 718 alloy and 316L stainless steel by GTAW using three different filler wires, and the results indicated that the weldments using ERNiCrMo-4 filler exhibited lower impact energy because of the formation of undesired intermetallic compounds. Hosseini et al. [14] studied on the microstructure and mechanical properties of Inconel 617/310 austenitic stainless steel dissimilar welds, the unmixed zones were observed with three different fillers, and a number of cracks were initiated in the 310 SS unmixed zone when the 310 SS filler metal was used. The common problems in arc welding mainly included less stable process, wider HAZ, coarser grains, larger residual stress and deformation. In order to refine the microstructure and improve the welding quality, Zhou et al. used pulsed laser to weld the C-276/304 dissimilar materials, weld joint with finer microstructure and higher mechanical property was indeed achieved [15]. However, some of the problems still existed in the weld metal, including the appearances of unmixed zone, secondary phases, and uneven element distribution. Over all, the main problems involved in welding of nickel-based alloys and stainless steels were the precipitation of secondary phases, unmixed zone and uneven distribution of elements, these defects will lead to higher cracking sensitivity, lower impact toughness and poorer corrosion resistance of weld joint, impairing the properties of weld joint.

Ultrasonic vibration could influence the convection and solidification behaviors of molten pool due to the specific cavitation and acoustic streaming effects. Hence, ultrasonic vibration has been widely employed in many fields [16–18], such as casting, welding, cladding and additive manufacturing. Many investigations have been reported on the ultrasonic vibration assisted welding. Dai W studied the effect of ultrasonic emission waves on the weldability of aluminum alloy 7075-T6 during GTAW [19], and the relations between ultrasonic incident angle of ultrasonic emission wave and the thermal cycles were built. Cui Y et al. applied ultrasonic vibration in the shielded metal arc–welding of super-austenitic stainless [20]. It was observed that the width of unmixed zone in the WM was reduced by high-intensity ultrasonic vibrations. Sun Q et al. carried out the ultrasonic assisted tungsten inert gas ((U-TIG)) welding of AISI 304, the results showed that the penetration depth was increased up to 300% for the weld made with (U-TIG) welding compared with conventional TIG welding [21]. Lei Y et al. investigated the effects of arc-ultrasound on microstructures and mechanical properties of SiCp/6061Al MMCs joints produced by plasma arc "in-situ" alloy-welding with different excitation frequencies [22]. Krajewski A et al. analyzed the effect of ultrasonic vibration on the microstructure in the WM and heat-affected zone at various phases of the vibration wave [23]. Padhy G et al. conducted the ultrasonic vibration enhanced friction stir welding to examine the effects of ultrasonic vibration on the local microstructure evolution and microtexture of Al 6061-T6 weld nuggets [24]. Yuan T et al. studied the effect of ultrasonic assistance on grain refining in arc welds of Mg alloys, and the ultrasonic vibration was realized by dipping an ultrasonic probe in the weld pool to stir it at a distance behind the arc [25].

However, current welding methods were only involved in the ultrasonic vibration assisted arc welding, friction stir welding and braze welding, the ultrasonic vibration assisted pulsed laser welding was rarely involved. In addition, the research mainly focused on the effects of ultrasonic vibration on the weld shape, grain morphology, cracks, porosities and mechanical property. During laser welding of dissimilar materials, the effects of ultrasonic vibration on the secondary phases and micro and macro distributions of elements in the weld metal were rarely reported.

In this paper, the specific cavitation and acoustic streaming effects in weld molten caused by ultrasonic vibration were utilized to change the convection and solidification behaviors of molten pool and to eliminate the defects in welding of dissimilar materials, as illustrated above. The ultrasonic vibration was introduced to assist pulsed laser welding of Hastelloy C-276 and austenite stainless steel 304 dissimilar materials. The effects of ultrasonic vibration on the weld shape, unmixed zone, grain morphology and orientation, secondary phases, macro and micro distributions of elements and microhardness were systematically analyzed. The effect mechanism of ultrasonic vibration on pulsed laser dissimilar welding was explored.

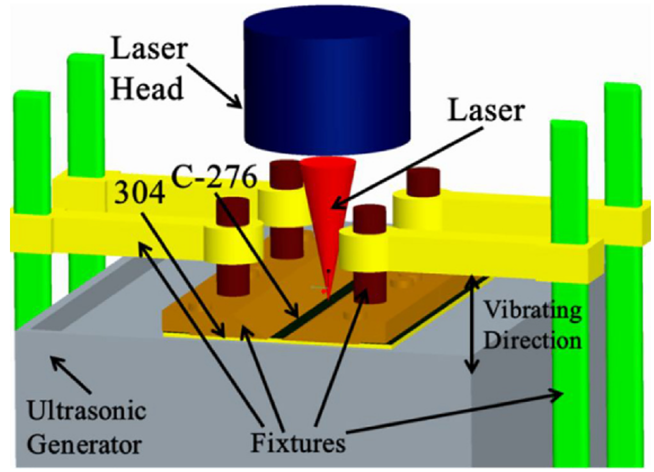

Fig. 1. Set-up for ultrasonic vibration-assisted pulsed laser dissimilar welding.

2. Experimental procedures

A schematic of the set-up for ultrasonic vibration assisted pulsed laser welding is shown in Fig. 1. The set-up consisted of an ultrasonic vibration platform and welding fixtures, and the work piece was fixed on the ultrasonic vibration board by fixtures. The maximum power of the ultrasonic generator was 500 W at a fixed frequency of 20 kHz. Laser welding with three different ultrasonic output powers of 0 W, 250 W and 500 W were conducted. The amplitude of ultrasonic vibration board was controlled by the ultrasonic output power. The output displacements with different output powers were measured by laser displacement sensor (Keyence, LK-H050) at sampling frequency of 392 kHz. The vibration waveforms of base metals were sine waves at 250 W and 500 W ultrasonic powers, and the amplitudes of which were 1.9 μm and 2.7 μm, respectively.

The base metals used in this study were Hastelloy C-276 and austenite stainless steel 304 sheets. The chemical compositions of base metals were listed in Table 1. The thickness of C-276 and 304 base metals were 0.5 mm and 2.0 mm, respectively. They were cut to a size of $40 \times 100\,mm^2$ and welded in an overlap configuration with C-276 placed on 304. A 500 W millisecond pulsed Nd:YAG laser system (GSI LUMONICS, JK701H, UK) with a 1064 nm wavelength and multimode beam was employed to perform dissimilar welding process. The collimated beam diameter was 23.5 mm. The focal length was 80 mm, and the focal beam diameter was approximately 0.6 mm. The incident direction of pulsed laser was perpendicular to the substrate surface. Pure argon gas was used as the shielding gas with a gas flow rate of 12 l/min. The optimized welding parameter was selected as pulse energy 4.0 J, pulse duration 6 ms, pulse repetition 30 Hz, welding velocity 150 mm/min and defocus distance 0 mm for both LW and ULW processes.

After laser welding, the metallographic samples of welded sheets were sectioned by wire electrical discharge machining. The samples were prepared by grinding using SiC papers, followed by the final polishing with 1.5 μm diamond powder. The electrolytic etching in a reagent of 10% oxalic acid was used to