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Nickel-based alloy/austenitic stainless steel dissimilar weld properties prediction on asymmetric distribution of laser energy

Siyu Zhou, Guangyi Ma*, Dongsheng Chai, Fangyong Niu, Jinfei Dong, Dongjiang Wu*, Helin Zou

Key Laboratory for Precision and Non-traditional Machining Technology of Ministry of Education, Dalian University of Technology, Dalian, Liaoning Province 116024, PR China

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ABSTRACT

A properties prediction method of Nickel-based alloy (C-276)/austenitic stainless steel (304) dissimilar weld was proposed and validated based on the asymmetric distribution of laser energy. Via the dilution level D_{C-276} (the ratio of the melted C-276 alloy), the relations between the weld properties and the energy offset ratio E_{C-276} (the ratio of the irradiated energy on the C-276 alloy) were built, and the effects of E_{C-276} on the microstructure, mechanical properties and corrosion resistance of dissimilar welds were analyzed. The element distribution C_{weld} and $E_{C\text{-}276}$ accorded with the lever rule due to the strong convention of the molten pool. Based on the lever rule, it could be predicted that the microstructure mostly consists of γ phase in each weld, the δ-ferrite phase formation was inhibited and the intermetallic phase (P, μ) formation was promoted with the increase of $E_{C\text{-}276}$. The ultimate tensile strength σ_b of the weld joint could be predicted by the monotonically increasing cubic polynomial model stemming from the strengthening of elements Mo and W. The corrosion potential U, corrosion current density I in the active region and $E_{C\text{-}276}$ also met the cubic polynomial equations, and the corrosion resistance of the dissimilar weld was enhanced with the increasing $E_{C\text{-}276}$, mainly because the element Mo could help form a steady passive film which will resist the Cl^- ingress.

1. Introduction

Compared with the traditional welding processes, laser welding has a number of key advantages, including the grain refinement and the lower residual stress, which could improve the weld quality [1–3]. Nickel-based alloy (C-276) and austenitic stainless steel (304) are extensively employed in the fabrication of components in the nuclear plants and chemical industries because of the high mechanical properties and corrosion resistances [4–7]. Laser dissimilar welding is inevitably applied for the joining of the two alloys [8], for example the seal welding of pump can and end cap in the nuclear reactor coolant pump.

In the laser welding, the extensive research has been conducted on the weld properties prediction based on the laser welding parameters with the energy symmetric distribution, the parameters usually included laser power, welding speed and focal point position. Anawa et al. evaluated the fusion zone area and shape of dissimilar welds as a function of the laser welding parameters by means of Taguchi approach [9]. Olabi et al. applied response surface methodology to investigate the effect of laser welding parameters on the mechanical properties of low carbon steel/austenitic stainless steel dissimilar weld joints [10]. Sathiya et al. established the relationship between the laser welding parameters and the tensile strength of austenitic stainless weld joints using artificial neural networks and genetic algorithm [11]. However, in the dissimilar welding, the asymmetric distribution of laser energy could change the dilution level (the fusion ratio of base metals), influence the element composition in the weld, and, further, impact the weld property accordingly. Hence, the energy offset ratio (the ratio of energy distribution on each base metal) is also an important parameter which could determine the dissimilar weld property. A few reports have investigated the qualitative influences of beam offset on the weld properties. Zhang et al. showed that the maximum microhardness of the BTi-6431S/TA15 dissimilar weld joint was achieved when the laser beam offsets towards the BTi-6431S alloy [12]. Lin et al. showed that as the electron beam shifted progressively toward the Alloy 690 base metal, the tensile strength of weld joint was reduced, and the corrosion resistance was enhanced in the Alloy 690/SUS 304L EBW welding [13]. The energy offset ratio should be correctly selected according to the different property demands, however, the quantitative relations between the weld properties and the energy

* Corresponding authors.
E-mail addresses: gyma@dlut.edu.cn (G. Ma), djwudut@dlut.edu.cn (D. Wu).

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offset ratio have not been built, and it is difficult to evaluate the weld quality accurately. Hence, the dissimilar weld property prediction model on asymmetric distribution of laser energy is necessary.

In this work, via the dilution level, the properties prediction method of the C-276/304 laser dissimilar welds on the energy asymmetric distribution was proposed, and the microstructure, mechanical properties and corrosion resistance of dissimilar welds were analyzed.

2. Experimental procedures

A pulsed Nd: YAG laser was used to join the C-276 alloy and 304 stainless steel plates with 0.5 mm thickness in the butt configuration, Table 1 shows the elements compositions of the base metals. The welding parameters included the single-pulse energy 1.5 J, the pulse duration 6 ms, the frequency 40 Hz and the welding velocity 150 mm/min. Argon gas was used as the shielding gas with the flow of 12 l/min. The diameter of laser beam focused on the upper surfaces of the specimens was approximately 0.6 mm, and the energy density is nearly uniform distribution. The asymmetric distribution of laser energy is achieved by offsetting the laser beam, and the offsets toward C-276 were defined as the positive and those toward 304 as the negative.

Electron probe microanalysis (EPMA) was used to analyze the elements compositions of the C-276/304 dissimilar welds. The tensile tests were carried out to evaluate the mechanical properties of the welding joints, and the welding joint tensile specimens were prepared according to ISO 4136-2001. The Knoop hardness tests were carried out across the welding joints using a DMH-2LS microhardness tester at a load of 100 g and dwell time of 15 s. The potentiodynamic tests were performed at room temperature to measure the corrosion resistance of the dissimilar welds, and the acidic solution (1 mol/L HCl) with a large quantity of chloride ion (5.5 wt% NaCl solution) was used as the corrosion solution.

3. Results and discussion

3.1. Dilution level

The energy offset ratio $E_{C\text{-}276}$ and E_{304} are defined as the ratios of the irradiated energy on the C-276 and 304 alloys to the total laser output energy, respectively. The $E_{C\text{-}276}$ and E_{304} could be evaluated by the irradiated area ratio, and $E_{C\text{-}276}+E_{304}=1$. The beam offset is selected from -0.3 mm to $+0.3$ mm with 0.1 mm increment, the corresponding E_{C-276} are 0, 0.11, 0.29, 0.50, 0.71, 0.89, and 1.00, respectively. When $E_{C-276}=0$, the two materials could not be joined well, so the test data at this point is ignored, just the welds with E_{C-276} from 0.11 to 1 are obtained. The effect of energy offset ratio on the upper surface morphology of dissimilar weld is given in Fig. 1 [14].

The dilution level D_{C-276} and D_{304} in the weld are defined as the ratios of the melted C-276 and 304 alloy area to the total melted area, respectively [15],

$$D_{C-276} = A_{C-276}/(A_{C-276} + A_{304}) \tag{1}$$

$$D_{304} = A_{304}/(A_{C-276} + A_{304}) \tag{2}$$

where A_{C-276} and A_{304} are the areas of melted C-276 and 304 alloys, respectively, which could be measured in Fig. 1. The dilution level D_{C-276} is directly determined by the energy offset ratio E_{C-276}, and the relation between D_{C-276} and E_{C-276} is given in Fig. 2.

The thermal property difference between the two alloys makes D_{C-276} and E_{C-276} unequal. The excellent linearity between D_{C-276} and E_{C-276} is achieved as given in Eq. (3), and the R-square value is greater than 0.99. The linear equation shows that the laser energy and the material melting mass satisfy the potential quantitative relation. Hence, by the laser energy, it is possible to predict the weld size in the laser welding.

$$D_{C-276} = 0.71E_{C-276} + 0.24 \tag{3}$$

3.2. Microstructure

Fig. 3 presents the images of the central region of the fusion zone (FZ) in the dissimilar weld formed with the different energy offset ratios. The solidification structure is predominantly the equiaxed grain, and the grain is refined compared with that in the base metal, which is due to the nature of rapid cooling in the laser welding.

According to the EPMA, the major elements present the macro uniform distribution in the weld, because the strong Marangoni convention in the molten pool is benefit for the uniform mixture of the dissimilar metals [16]. The relation between the major element composition C_{weld} in the weld and the dilution level D_{C-276} meets the lever rule, as given in Eq. (4). Eq. (3) substituted in Eq. (4), the relation between C_{weld} and E_{C-276} could be obtained in Eq. (5).

$$C_{C-276}D_{C-276} + C_{304}D_{304} = C_{weld} \tag{4}$$

$$C_{C-276}(0.71E_{C-276} + 0.24) + C_{304}(0.71E_{304} + 0.05) = C_{weld} \tag{5}$$

where C_{C-276} and C_{304} are the elements compositions of C-276 and 304 base metals, respectively. Eq. (5) shows that the C_{weld} and E_{C-276} are also in the form of the lever rule, and the C_{weld} is proportional to E_{C-276}. So the elements compositions of Ni, Fe, Cr and Mo in the weld could be predicted by the E_{C-276}, as given in Eq. (6), with the increase of E_{C-276}, the elements Ni, Mo and W gradually improve, the element Fe reduces, and the element Cr changes little.

$$\begin{bmatrix} \%Ni \\ \%Fe \\ \%Cr \\ \%Mo \\ \%W \end{bmatrix} = \begin{bmatrix} 34.8\% & 19.47\% \\ -47.22\% & 56.37\% \\ -1.56\% & 16.19\% \\ 11.37\% & 3.84\% \\ 2.66\% & 0.9\% \end{bmatrix} \begin{bmatrix} E_{c-276} \\ 1 \end{bmatrix} \tag{6}$$

During the welding of stainless steel, the Schaeffler diagram could be used to predict the microstructure in the weld. The

Table 1
Normal compositions of Hastelloy C-276 and 304 stainless steel (wt%).

Materials	Ni	Fe	Cr	Mo	W	Co	Mn	C	Si	P	S	V
304	8–10.5	Bal.	18–20	–	–	–	≤ 2	≤ 0.08	≤ 1.0	≤ 0.035	≤ 0.03	–
C-276	Bal.	4–7	14–16	15–17	3–4.5	≤ 2.5	≤ 1.0	≤ 0.01	≤ 0.08	≤ 0.04	≤ 0.03	≤ 0.035