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Optimization of pulsed laser welding process parameters in order to attain minimum underfill and undercut defects in thin 316L stainless steel foils

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ABSTRACT

In this study, the optimization of pulsed Nd:YAG laser welding parameters was done on the lap-joint of a 316L stainless steel foil with the aim of reducing weld defects through response surface methodology. For this purpose, the effects of peak power, pulse-duration, and frequency were investigated. The most important weld defects seen in this method include underfill and undercut. By presenting a second-order polynomial, the above-mentioned statistical method was managed to be well employed to balance the welding parameters. The results showed that underfill increased with the increased power and reduced frequency, it first increased and then decreased with the increased pulse-duration; and the most important parameter affecting it was the power, whose effect was 65%. The undercut increased with the increased power, pulse-duration, and frequency; and the most important parameter affecting it was the power, whose effect was 64%. Finally, by superimposing different responses, improved conditions were presented to attain a weld with no defects.

1. Introduction

Using thin 316L stainless steel foils has found new applications in various industries such as bipolar plates in polymer electrolyte membrane fuel cells. In fuel cells, bipolar plates are placed at the anode and cathode sides, and they distribute reactive gases; namely, hydrogen and oxygen, on the electrode surface. Bipolar plates made of AISI 316L austenitic stainless steel thin foil have attracted much attention in comparison to conventional graphite bipolar plates due to all of the following properties: good corrosion resistance, high mechanical strength, ease of providing flow distribution channels, decreased weight, and reasonable prices [1,2]. To join thin stainless steel foils with a thickness of 100 μm in the previously mentioned application, one of the common methods is using adhesives; however, adhesive joints have limited joint durability and are lacking in complete electrical conductivity between the foils at the joint [3]. One of the other methods put forward in this regard is resistance seam welding. However, this method also has defects including distortion, porosity, and cracks in the weld. Due to these limitations, laser welding is a promising method to join these foils [4,5]. A low heat input (HI), a narrow weld zone and heat-affected zone (HAZ), low distortion, high welding speed, ease of automation, and the possibility of autogenous welding are some advantages of using laser welding in comparison to other alternative processes [6]. Using Nd:YAG laser, due to its shorter wavelength than those of other conventional laser sources, and using pulsed stimulation rather than continuous laser, due to a lower average power required, and thus a lower HI and shorter solidification time, are the best choices to join thin 316L steel foils [7,8].

The present study is needed for observing defects such as undercut and underfill in the pulsed Nd:YAG laser welding of a thin 316L steel foil. The undercut is a defect, characterized by the formation of a groove-like hollow near the weld, and the underfill defect is defined as a longitudinal superficial channel in the middle of the weld. The mechanism of these defects in laser welding is complex, and many studies have been conducted in this regard, but so far, no thoroughly satisfying results have been reported [9]. Research shows that the most important factors involved in the formation of the undercut in a laser welding process include excessive heat at the edge of the base metal [10,11], the amount of shear stress resulting from the surface tension gradient in the molten metal [12], high speed welding [9,13], poor wetting properties [14] and the presence of surface oxide shells [13]. Another factor affecting the undercut is the amount of filler metal. When no changes occur in other conditions, the undercut depth decreases with the increased amount of filler metal. The addition of filler

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metal causes the molten metal flow to decrease from the edges towards the center of the weld pool [11]. With regard to the underfill, studies show that the main reasons for its formation in the laser welding can be considered to be more input energy than necessary for a full penetration [15], an inappropriate focus position [16], and evaporation and spattering of the weld metal due to the extreme turbulence of molten metal in the weld pool [15,17]. In pulsed laser welding, the selection of the input parameters of the process is an important issue in order to achieve a joint with a desirable quality. In recent years, various researchers have optimized the similar aspects of this process through design of experiment (DOE) [18–20]. One of the methods applied in DOE is the response surface methodology (RSM), which is based on statistical and mathematical techniques to apply purposive changes to the input parameters, and to investigate its effect on the response. Among the advantages of using this method are determining the degree of main, interactive, and second-order effects of the input parameters, developing mathematical functions to achieve an effective relationship between the input parameters and responses, and performing the minimum number of logical experiments. This method has different techniques, and the central composite design (CCD) technique is of the highest validity [21]. For the first time, the RSM with a CCD technique was used in this study to optimize the parameters affecting the weld defects in the process of pulsed Nd:YAG laser welding on a thin 316L steel foil.

2. Material and methods

2.1. Laser welding

The 316L steel being used has the chemical composition presented in Table 1, and is in the form of a thin foil with a thickness of 100 μm. The pulsed laser welding process with the laser source of Nd:YAG, with a maximum average power of 160 W and a laser focus diameter of 0.2–2.0 mm was used in order to join the foils. This device is equipped with a 15x magnifying stereomicroscope for the careful observation of the welding point, and has a CNC table to move the Workpiece at a constant speed. Considering their application as bipolar plates, lap-joint was adopted for joining the foils. In order to fasten the foils at the joint firmly, a fixture was designed as shown in Fig. 1(a). In the fixture being used, first, four slots were created with different widths; and after a few preliminary welding operations and checking the weldment appearance, the welding process was carried out at the optimal slot width (five millimeters). Surveys showed that the presence of any air gaps of more than 10 μm between the joint members would cause perforation and even cutting instead of welding in similar parameters. Fig. 1(b) and (c) shows an actual image of welding system and schematic images of how the foils have been placed in the fixtures, the distance of the laser beam and shielding gas nozzle from the workpiece, and the welding direction. According to the investigations conducted, the scope of the process input parameters was obtained as shown in Table 2.

2.2. Testing specimens

To assess the weld defects, according to the statistical design used, foils with dimensions of $20 \times 60\ mm^2$ were cut by paper-cutting machine. For each parameter, two lap-joint foils were fixed in the fixture shown in Fig. 1(a) and the welding process was done in a way that all the welds were situated in the direction of the roll-

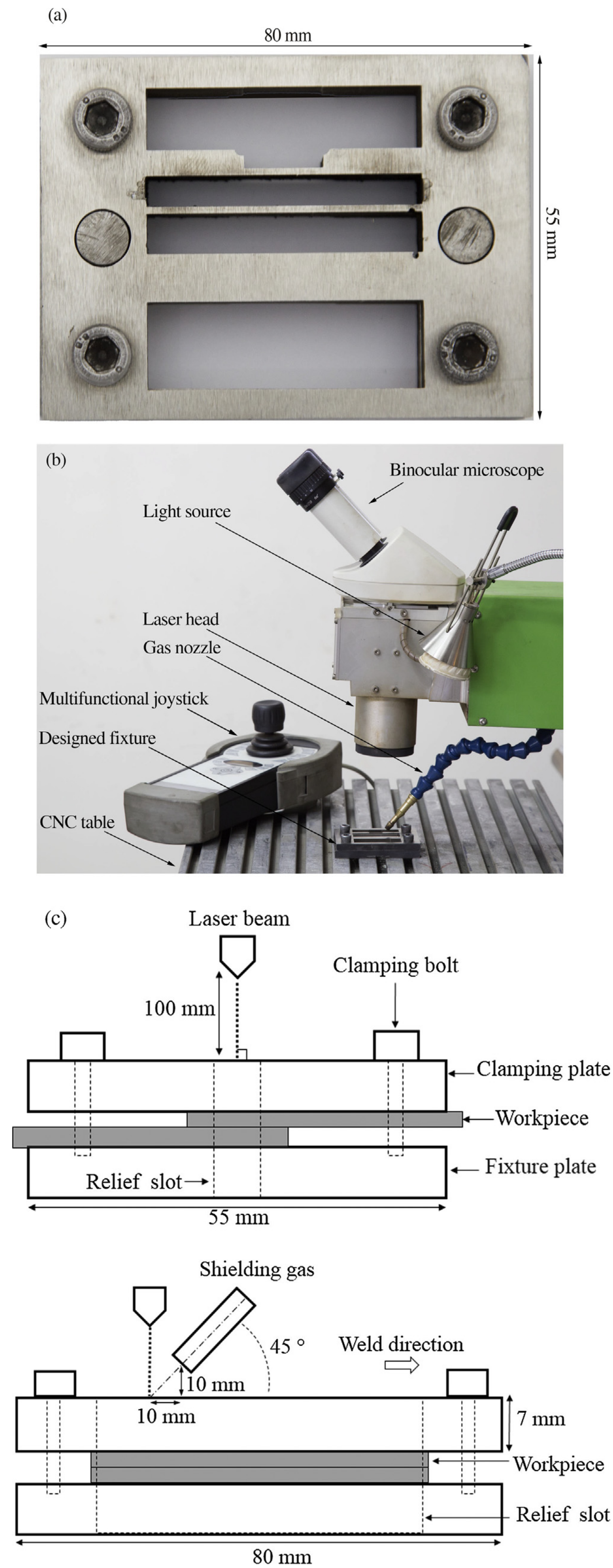

Fig. 1. (a) Designed fixture, (b) and (c) actual image and schematic images of laser welding process.

Table 1
Typical chemical analysis of the base metal used (wt%).

Cr	Ni	Mo	Mn	Si	C	S	P	Co	V	W	Fe
17.35	9.93	2.10	1.64	0.49	0.03	0.01	0.03	0.16	0.06	0.04	Bal.