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Study on laser welding of austenitic stainless steel by varying incident angle of pulsed laser beam

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ABSTRACT

In the present work, AISI 304 stainless steel sheets are laser welded in butt joint configuration using a robotic control 600 W pulsed Nd:YAG laser system. The objective of the work is of twofold. Firstly, the study aims to find out the effect of incident angle on the weld pool geometry, microstructure and tensile property of the welded joints. Secondly, a set of experiments are conducted, according to response surface design, to investigate the effects of process parameters, namely, incident angle of laser beam, laser power and welding speed, on ultimate tensile strength by developing a second order polynomial equation. Study with three different incident angle of laser beam 89.7 deg, 85.5 deg and 83 deg has been presented in this work. It is observed that the weld pool geometry has been significantly altered with the deviation in incident angle. The weld pool shape at the top surface has been altered from semispherical or nearly spherical shape to tear drop shape with decrease in incident angle. Simultaneously, planer, fine columnar dendritic and coarse columnar dendritic structures have been observed at 89.7 deg, 85.5 deg and 83 deg incident angle respectively. Weld metals with 85.5 deg incident angle has higher fraction of carbide and δ-ferrite precipitation in the austenitic matrix compared to other weld conditions. Hence, weld metal of 85.5 deg incident angle achieved higher micro-hardness of ∼280 HV and tensile strength of 579.26 MPa followed by 89.7 deg and 83 deg incident angle welds. Furthermore, the predicted maximum value of ultimate tensile strength of 580.50 MPa has been achieved for 85.95 deg incident angle using the developed equation where other two optimum parameter settings have been obtained as laser power of 455.52 W and welding speed of 4.95 mm/s. This observation has been satisfactorily validated by three confirmatory tests.

1. Introduction

Austenitic stainless steel has a wide range of applications in nuclear structural fabrication, valve bodies and vessel internals because of their excellent mechanical properties. Joining process is required for this and laser welding is such a joining process. Laser welding has several advantages when compared to the conventional welding. It is non-contact type and its localized and narrow heat zone can create high quality result. Common re-working and after-work procedures are no more required. Laser welding has been widely applied in various industries including automotive, microelectronics, aerospace, medical, optoelectronics, microsystems etc. Kuryntsev and Gilmutdinov [1] have studied the laser welding of type 321 stainless steel and have found that the defocused laser beam has increased the volume of weld pool that in turn to reduce the requirement for preparation of edge and gap between workpieces. Yan et al. [2] have investigated the microstructure and mechanical properties of tungsten inert gas, laser and laser-TIG hybrid welded 304 stainless steel. They have found that laser welded sample has highest tensile strength and smallest dendrite size than all other. Experimental investigation on dissimilar pulsed Nd:YAG laser welding of AISI 420 stainless steel to kovar alloy has been reported in [3] and they have found that the start of solidification in the kovar side of weld zone has occurred by means of epitaxial growth. In the work of Ai et al. [4] a defect-responsive optimization method for the fiber laser butt welding of dissimilar materials has been investigated. The genetic algorithm (GA) is applied to solve the model. The dissimilar laser welding of AISI 316L stainless steel to Ti6-Al4-6V alloy via pure vanadium interlayer has been studied by Tomashchuk et al. [5]. The effects of laser power, scanning speed, defocus distance, beam incident angle and line energy on weld bead geometry and

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shearing force of laser welded dissimilar AISI 304L and AISI 430 stainless steel has been investigated in [6]. An investigation has been made by Keskitalo et al. [7] to study the laser welding of duplex stainless steel with nitrogen gas as shielding gas. The result suggests that nitrogen increases austenite levels in the weld metal and improved toughness levels. A study of simulation of laser butt welding of AISI 316L stainless steel sheet using various heat sources has been performed and experimental validation also has been done in [8]. The simulated thermal cycles, residual stress and distortion has been validated by experiments. In the research of Chen et al. [9], the influence of processing parameters on the characteristic of stainless steel/copper laser welding has been studied. Hao et al. [10] have investigated the effects of beam oscillating parameters on the weld morphologies. They have found that the difference in cross-section width from top to the lower gradually has reduced to disappear with the increase in oscillating frequency. An attempt has been made to improve the quality of the weldment between nickel titanium (NiTi) and AISI 316L stainless steel wires in [11]. A pulsed wave Nd:YAG laser system has been used for the welding of CP Ti and stainless steel sheets and the effect of pulse profiles used in laser welding on weld appearance, weld geometry, microstructure, hardness variation, joint strength and failure mode of weld have been investigated in [12]. Tan and Shin [13] have studied the multi-scale modeling of solidification and microstructure development in laser keyhole welding process for austenitic stainless steel. The model predictions are validated with the experimental results and the effects of the welding parameters are analyzed based on numerical and experimental results. Optimization of CO_2 laser welding of DP/TRIP steel sheets using statistical approach has been conducted in [14]. In the article of Matsunawa et al. [15] the observation of keyhole as well as weld pool dynamics and their related phenomena to reveal the mechanism of porosity formation and its suppression methods have been studied. A numerical simulation model has been developed by Cho et al. [16] to study the temperature profile characteristics of weld bead and molten pool dynamics of high power disk laser welding process. Numerical and experimental study of molten pool formation during continuous laser welding of AZ91 magnesium alloy has been reported in [17]. A mathematical model has been developed by Zhou et al. [18] to analyze the heat transfer, fluid flow and keyhole dynamics during pulsed keyhole laser welding. A numerical and experimental investigation of laser welding of titanium alloy (Ti6Al4V) for modeling the temperature distribution to predict the heat affected zone, depth and width of the molten pool has been analyzed in [19]. Shanmugarajan et al. [20] have studied the effect of process parameters such as laser power, welding speed, shielding gas and laser beam mode on microstructure and mechanical properties of laser welded sample of type 304B4 borated stainless steel. Torkamany et al. [21] have analyzed the pulsed Nd:YAG laser welding of pure niobium plate to titanium alloy Ti-6AL-4V sheet in butt joint. The effect of pulsed Nd:YAG laser welding parameters and subsequent post-weld heat treatment on microstructure and hardness of AISI 420 stainless steel have been studied by Baghjari and Mousavi [22]. In the research of Chen et al. [23] the effect of laser-beam offsetting on microstructural characteristics and fracture behaviour of the laser butt joint of titanium alloy have been studied. An experimental procedure has been developed by Atabaki et al. [24] to join thick advance high strength steel plates by using the hybrid laser/arc welding (HLAW) process. An investigation has been made by Sun et al. [25] to analyze the laser butt joint of Al/steel dissimilar materials.

Within scope of literature review, it has been observed that almost limited or no information is available on the effect of laser incident angle on the mechanical and microstructural properties of pulsed laser welding of AISI 304 stainless steel sheets in a butt joint configuration. It is one of the important parameter that may be correlated with responses. This research aims to find the optimum incident angle for which the laser optic lens will be protected and also to understand the physical mechanisms responsible for the joint quality of the laser beam butt welding process of stainless steel plates. In the present work, 3 factors-5 levels experiments have been planned using response surface methodology (RSM) design matrix and analyzing the responses of interest by developed mathematical models based on experimental results. The second order mathematical equations have been developed for predicting the desired weld quality. In addition to statistical evaluation of the welded joints, metallurgical and mechanical analyses have been carried out on laser welded three specimens with incident angle 89.7 deg, 85.5 deg and 83 deg incident angle. A 3-D responses surface and contour plots have been developed to find the combined effect of input parameters on responses.

2. Response surface methodology

Response surface methodology is a useful design of experiment method that is gaining popularity. This includes a review of basic experimental designs for fitting linear response surface models, in addition to a description of methods for the determination of optimum operating conditions. The steps of response surface methodology are:

(i) Developing experimental strategy for selecting independent variables.
(ii) Statistical modeling to build an approximate relationship between the response and process variables.
(iii) Optimization for finding values of process variables producing desirable values of the response.

When all the independent variables are measurable, controllable and continuous during experiments, response surface, y can be expressed with negligible error by:

$$y = f'(x)\beta + \epsilon \tag{1}$$

where

$x = (x1, x2, \ldots, x_k)$.
$f'(x)$ = a vector function of p elements.
β = a vector of p unknown constant coefficients.
ϵ = a random experimental error assumed zero mean.

In RSM, an approximate model is needed to develop for the true response surface. The approximated model is constructed utilizing observed data from the process or system. Multiple regression analysis is commonly used for this. Usually, a second-order polynomial equation is used in RSM, which is given by

$$y = \beta_0 + \sum_{i=1}^{k}\beta_i x_i + \sum\sum \beta_{ij} x_i x_j + \sum_{i=1}^{k}\beta_{ii} x_i^2 + \varepsilon \tag{2}$$

where parameters β_0 β_i, β_{ij}, β_{ii} are called regression coefficient for $i = 0, 1, \ldots, k$ and $j = 0, 1\ldots k$.

2.1. Desirability function analysis

It is an approach in which, individual responses are transformed to corresponding desirability values. Desirability value depends on acceptable tolerance range as well as target of the response. Unity is assigned, as the response reaches its target value, which is most desired situation. Beyond acceptable limit, desirability value assumes zero. In this study, individual desirability function posses one of the following two characteristics: