OPTIMIZATION OF LASER BUTT WELDING OF STAINLESS STEEL 316L USING RESPONSE SURFACE METHODOLOGY

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Laser butt welding of stainless steel was investigated using a remote laser welding system. Weld width, weld area and tensile strength (Rm) were examined using response surface methodology (RSM), due to the process parameters being critical for the welding process. The objective was to determine the optimal processing parameters for the highest tensile strength. Numerical and graphical optimization techniques were used. In this study, optimal solutions were determined. These solutions improve weld quality, increase the strength and minimize the front weld width and back weld width in order to obtain a small heat affected zone.

Keywords: fiber laser; stainless steel; butt welding; weld strength; response surface methodology;

1. Introduction

In recent years, stainless steel light weight structures have attracted great interest in the industry because of energy efficiency, environmental protection and good corrosion resistance. This joining technology has some compelling advantages such as narrow heat-affected zone (HAZ), small deformation, deep penetration, no-contact, high joining speed, accuracy, flexibility and improved mechanical properties due to the high energy involved. An additional advantage is smaller and lighter structures. This is due to smaller flanges needed for making the joints. Considering all of the above, 3D structures, metallic and non-metallic materials, can be easily welded by laser technology. Those are the reasons why laser technology has been applied in the automotive, aerospace, energy, electronics, microelectronics, marine, and medical industries. Laser beams can be

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either continuous wave (CW) or pulsed wave (PW) and are used to achieve either deep welding penetration by keyhole welding or to join thin welding materials. Hao et al. [1] found that if the laser focal diameter is very small, as in the case of fibre lasers, precise preparation of the workpieces and proper clamping system of the specimens are crucial. Otherwise defects such as cracks and porosity can occur.

Jasbir [2] explained that one of the main points in laser welding technologies is to optimise the welding parameters. Laser power, welding speed and focus position play a major role in achieving the desired weld quality and maximum tensile strength.

In order to get a good weld joint, a set of welding tests were carried out to determine the optimal process conditions.

Bandyopadhyay et al. [3] have studied the effect of Yb fiber laser parameters with maximum 2 kW power and varying the laser speed between 1 and 5 m/min with the scope to achieve high strength dual-phase steels for the manufacture of the auto-frames. Kumar et al. [4] have reported a comparative study on laser welding of two types of stainless steels AISI 304 and 316 using a pulsed Nd: YAG laser of 600 W power. They used RSM to obtain optimal process parameters to maximize the tensile strength and minimize the weld width. Alcock and Baufeld [5] have done deep penetration welding of stainless steel 304L by utilizing a 15 kW diode laser on 10 mm thick sheets. They characterized at first the properties of the melt weld run, having the purpose to transfer the information in butt welding configuration. They first characterized the properties of the melt weld run, with the purpose of transfering the information in butt welding configuration. They concluded that a diode laser with high power can be capable to do deep penetration weld. Fabbro et al [6] found the variation in weld depth with respect to laser welding speed. They observed that the welding depth is dependent on the welding speed. Casalino et al [7] investigated the principal effects of laser processing parameters of welding 6 mm thick aluminium AA5754 in a butt configuration, by using Yb fiber laser in CW mode having 400 µm laser spot diameter. Experiments were realised at a constant power of 4 kW, while varying the welding speed between 2 and 3 m/min. They established the statistical relationship between welding parameters and welding geometry.

Gao et al. [8] studied weld geometry on stainless steel 316L and achieved optimal process parameters by combining Kriging model and Genetic algorithm. They saw that the micro-hardness is more uniform at the optimized weld than the one un-optimized. Jelokhani et al. [9] have determined the optimal process parameters of Inconel 625 with 0.5 mm thickness using a pulsed Nd: YAG with 400 W power. By using RSM to obtain the best combination laser power (Lp), spot size (SS) and welding speed (Ws) they obtained optimal weld strength of 1280 MPa. This represents 124 % of the strength of the base metal, when used Lp = 260 W, SS = 180 µm, Ws = 1.2 mm/s.

Khan et al. [10] demonstrated that to reach high quality welds in particular material and joint configuration, the combination of welding speed and focus position should be correctly selected for a given laser power and mode of operation. This is because it is very hard to get optimal results without optimization.

Muhammad et al. [11] used two methods of parameter optimization for resistance spot welding: multi-objective Taguchi method to calculate the total normalized quality loss and multi signal to noise ratio and Response Surface Methodology (RSM) to find the optimum process parameters.

Casalino et al. [12] investigated the power and speed of a hybrid laser welding of wrought to selective laser molten stainless steel using a high power fiber laser. The welds shows good tensile strength, but low elongation.

Raymond and Montgomery [13] explained the importance of using RSM. They said that it is one of the techniques used to model and analyse engineering problems in order to optimize the process parameters aiming to obtain the optimal weld quality. In this case, the model that specifies the relationships between measured response and input factors can be developed, which is crucial to RSM investigations.

In this study, the main objective is to identify the optimal process parameter that can increase the shear strength when using the micro-spot welding process, by using RSM Design Expert.

2. Materials and methods

The experiment was done using a laser remote welding system, schematically shown in figure 1. A single mode fiber laser (IPG Photonics, model YLR-400-AC, wavelength1070 nm) with a maximal power of 400 W CW was used. The laser beam was focused and guided by a three-dimensional scanning head (HighYAG, RLSK) which was attached to a six-axis robot arm (Motoman MC2000). The scanning head deflects the laser beam in lateral directions by two galvanometric driven mirrors and control the vertical focal position with a motor driven collimating lens. The focus diameter was 54 µm at nominal working distance of 510 mm from the scanning head. Argon was used for shielding above and below the welds. The system allows welding speed up to 60 m/min with positional accuracy of ±0. 07 mm.

Rectangular specimens with dimensions 40 mm × 120 mm × 1 mm were clamped onto a welding table (Figs. 2-3). Under the butt joint, the table had a 10 mm wide and 10 mm deep grooves to prevent clamping lining evaporation which would influence on the welding process dynamics.

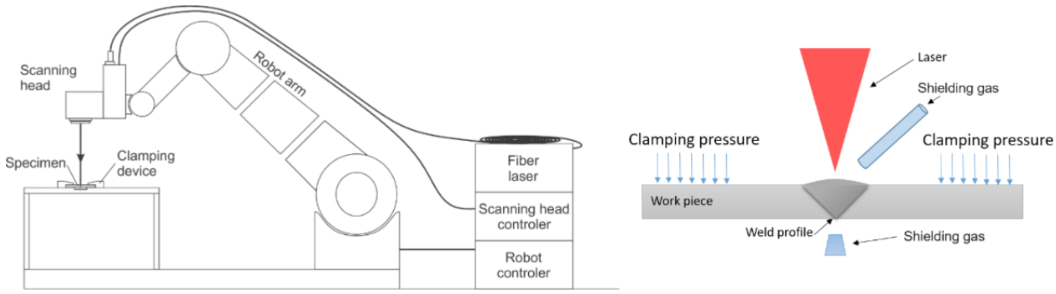

Fig. 1. Schematic representation of the setup based on laser remote welding system.

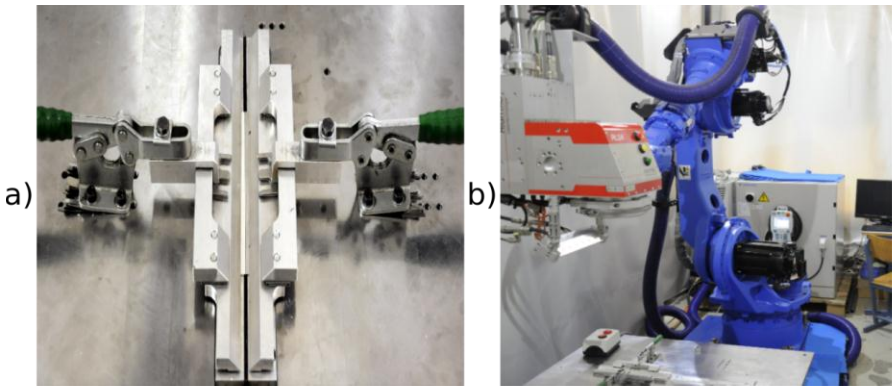

Fig. 2. Clamping system used for securing samples (a); robotic setup used for welding (b).

The welding speed, focus position, power and trajectory of the laser beam were set on the robot controller. The movement was done only by the robot arm in order to provide a constant angle of incidence of the laser beam. The laser was switched on only between the second and third point, while the moving speed was kept constant.

2.1 Materials

A 1 mm thick austenitic stainless steel EN 1.4404 (AISI 316L) plates were used in the experiment.

Stainless steel AISI 316L is an extra-low carbon version of Type 316 that minimizes harmful carbide precipitation due to welding. Typical uses include exhaust manifolds, furnace parts, heat exchangers, jet engine parts, pharmaceutical and photographic equipment, valve and pump trim, chemical equipment, digests, tanks, evaporators, paper and textile processing equipment, parts exposed to marine atmospheres and tubing. AISI 316L is used extensively for welds where its immunity to carbide precipitation due to welding assures optimal corrosion resistance.

RSM based on preliminary investigation was used to develop the welding plan. A central composite design of factor variables was chosen for preparation of experimental plans. The selected input variables were the laser welding speed and the vertical position of laser focus regarding the upper surface of the welding sample. In order to find the optimal range of each input parameter, 16 experimental runs were executed according to RSM by changing one of the process parameters. The objective was to obtain the fastest possible welding, therefore laser power was kept constant at the maximal value of 400 W. During the experiments, welding speed varied between 0.5-2.9 m/min while the vertical position of the focus point changed from -2 to 2 mm, with respect to the upper surface of the sample. Argon gas (5.0 purity) with 7.5 l/min flow rate was used during the welding to shield the top and back side of the weld (Fig.1).

2.2 Test procedures

After the laser welding tests, each specimen was first visually inspected and then cut perpendicularly to the weld direction. The objective of the cut is to obtain a transverse section of the welds for different welding parameters (Fig 4). Cutting was done using a Struers cutter. The cut surfaces were prepared for metallographic inspection by grinding and polishing. After polishing, carpenter 300 series stainless steel etchant was used to show the bead shape. The welding shape, size, penetration depth and the heat affected zone (HAZ) were examined using an optical microscope (Olympus Inverted Metallurgical Microscope GX 51, connected to a camera, Leica DFC 295).

Tensile strength testing was done using the Zwick Z250 testing machine, at the room temperature 23 °C, under the following conditions: preload force 100 N, speed in the yield range 0.0025 1/s and test speed 0.008 1/s. Three samples were prepared for tensile tests, for each welding sample. Image J [14] software was used to measure the front weld width, middle weld width, back weld width and for assessing welding thickness and weld area.

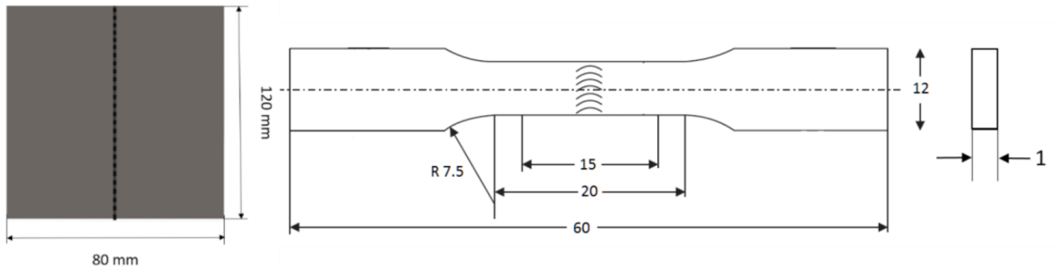

Fig. 3. Schematic representation of the specimens prepared for tensile tests.

Design Expert v10 trial [15] was used to determine the mathematical models with best fits and measured responses. The software finds combinations of factor levels in order to optimize the process for each response and process input factors.

The suitability of the model is tested using the sequential *f* test, *lack-of-fit* testing and analysis-a-variance (ANOVA) technique using the same software to get the best-fit model [15].

3. Results and discussion

Macro-samples obtained at optical microscopy for all 16 different welding combinations of process factors are presented in Fig.5.

According to the design matrix shown in Table 1, the results of the weld-bead profile were measured using the transverse sectioned specimens and the optical microscope.

Table 1

Design Matrix for process factors and response

Process factors			Process response					
No.	Welding speed [m/min]	Focus position [mm]	Front weld width [mm]	Middle weld width [mm]	Opposite weld width [mm]	Weld thickness [mm]	Area [mm²]	Tensile strength [MPa]
1	1.5	0	0.644	0.395	0.47	1.111	0.49	-
2	0.5	0.5	1.108	1.122	1.114	0.972	1.121	-
3	1.5	0	0.644	0.477	0.47	1.111	0.512	474
4	1.5	0.7	0.729	0.437	0.538	1.178	0.601	568
5	2.9	0	0.602	0.242	0.212	1.028	0.297	403
6	0.5	0	2.012	1.803	1.305	1.066	1.821	558
7	2.5	0.5	0.532	0.275	0.314	1.048	0.345	-

8	0.5	-0.5	0.848	0.838	1.051	1.045	0.93	560
9	2.5	-0.5	0.445	0.267	0.276	1.051	0.31	-
10	1.5	-0.7	0.519	0.317	0.413	0.969	0.364	465
11	1.5	2	0.577	0.385	0.409	1.069	0.45	-
12	0.5	2	0.967	1.08	1.26	1.13	1.2	561
13	2.9	2	0.489	0.222	0.215	1.104	0.301	493
14	1.5	-2	0.377	0.336	-	0.461	0.143	-
15	0.5	-2	1.215	0.979	1.124	1.159	1.142	556
16	2.9	-2	0.455	0.422	-	0.545	0.209	-

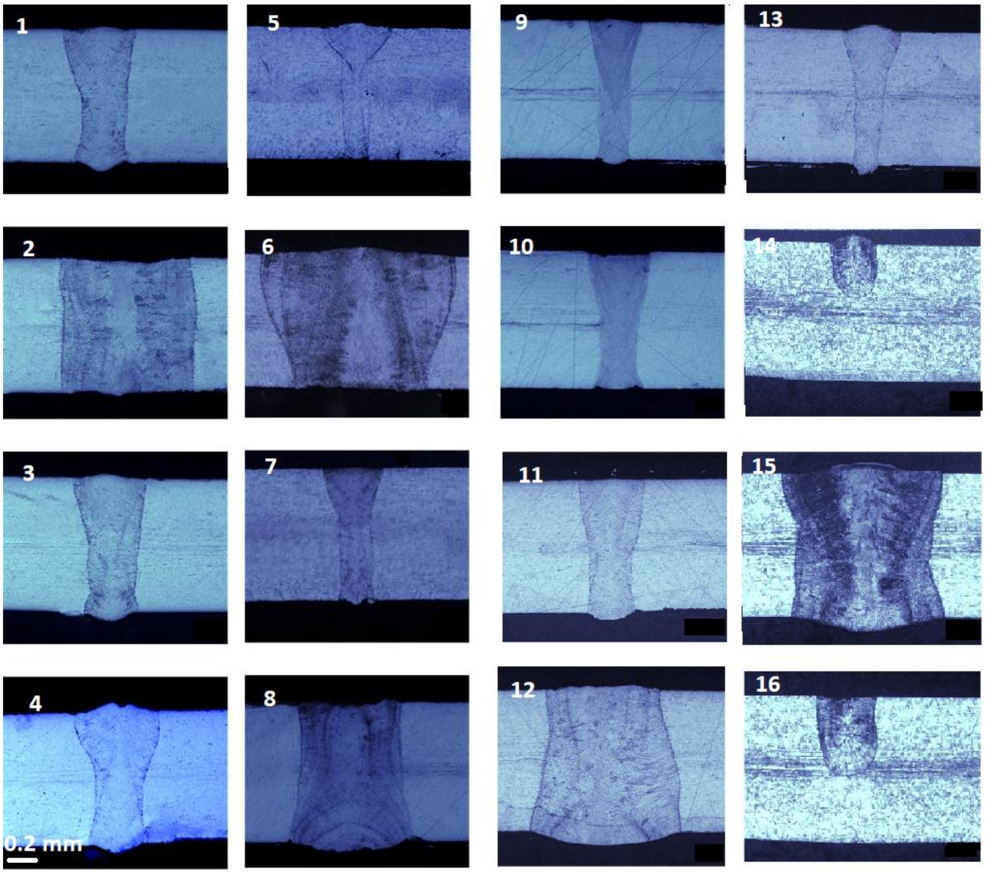

Fig. 4. Cross-section of laser welds obtained using parameters presented in Table 1; numbers on weld cross-sections corresponds to position in Table 1.

Welding speed presents the largest influence on front weld width. By increasing the welding speed, the width becomes smaller. This is due to the line energy input decreasing as the welding speed increases.

The results show that the laser beam diameter defines the general weld width, for the utilized laser power. The vertical focal position has a minor effect on the weld width. If the positioning of laser focus is above the weld sample, the laser spot size on the surface of the workpiece produces a larger weld width. By positioning the focusing point into the workpiece, the weld width is slightly smaller, since the laser spot size is bigger and out of the focus.

3.1 Optimization of the process parameters

The optimization of process responses includes the construction of a proper regression model for every single response and then searching for the best conditions in order to optimize all the responses. This step can be done numerically using desirability function analysis by selecting the desired goals for each factor and response. Numerical optimization searches the design space for the factor settings that optimize any combination of goals, using the developed regression model.

In the numerical optimization two criteria were introduced. The goal is to reach maximum welding speed and tensile strength with no limitation on focus position, and front, middle opposite and back weld width.

The optimal welding condition derived from the criterion that would lead to maximum joint tensile strength of about 567.121 MPa. The program delivers a set of ten best Pareto-optimal solutions. The first solution is better than others, so according to the first criterion, the optimal parameters for welding speed have to be 0.5 m/min, for a 0.5 mm focus. Based on these results the optimal welding conditions that give the highest tensile strength of 567 MPa, front weld width of 1.324 mm, middle weld width of 1.227 mm, back weld width of 1.189 mm and weld area of 1.11 mm^2 at the position 0.5 mm above the surface of the workpiece.

The software combines a set of six best solutions. According to the second criterion, the optimal parametric range for welding speed has to be between 1.835 – 1.912 m/min, in order to obtain strength between 491 – 495 MPa. A speed of 1.858 m/min and for a 0.5 mm vertical focal position above the specimen top surface seems to be the optimal solution in order to obtain maximal values for strength and speed. Using these parameters, we have been obtained a tensile strength of 494 MPa, front weld width of 0.56 mm, middle weld width of 0.321 mm, back weld width of 0.334 mm and weld area of 1.033 mm^2.

Less deformation, cracks, blow holes and spatter were obtained by decreasing the welding speed. This leads to a better quality of the weld. The focus position was kept at 0 mm, therefore the laser spot was 54 µm. The welding speed was changed three times: 0.5 m/min, 1.5 m/min and 2.9 m/min. Results clearly indicate that the dimension of the weld width is decreasing as the speed increases.

4. Conclusions

Numerical models that were developed to predict the weld strength obtained through butt-welding suggest that both welding speed and vertical focus position greatly influences the tensile strength. Results indicate that the influence of welding speed is larger than vertical focus position. Increasing the welding speed reduces the joint tensile strength, since less material is melted.

The width of the back weld increases as the welding speed decreases. Varying the vertical focal point position results in minor changes of results. Front weld width increases slightly with the focus position. Weld thickness increases as well, when the focus position is decreased. Optimal welding conditions, that give the highest tensile strength of 494 Mpa, a front weld width of 0.56 mm and a back weld width of 0.33 mm, are as follows: welding speed of 1.8 mm/min and focus position vertical 0.5 mm above the top surface of the workpiece.

Optimal welding conditions for maximal welding speed at higher weld tensile strength are determined to be: welding speed of 0.5 mm/min and vertical focus position of 0.5 mm above the top surface of the workpiece.

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