LASER WELDING OF AUSTENITIC STAINLESS STEEL THIN SHEETS

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Abstract. This paper presents investigations regarding the laser welding of austenitic stainless steel. Several laser welding tests were made using AISI 304 stainless steel in a butt joint configurations. An 3.3 kW Rofin laser and a Rofin welding head manipulated by an ABB six axes robot were used for the achievement of the welding tests. Different laser power, welding speed and spot diameter were used to define the influence of the process parameters to the weld bead geometry. Full penetration was obtained on all welded samples. It was determined that penetration depth is directly influenced by the laser power and the weld bead width depends mainly by the welding speed. Macro and microstructure of the welds are discussed in the article. The optimal parameters interval for welding stainless steel thin sheets was defined to be between 230 and 280 kW/cm^2.

Keywords: laser welding, stainless steel, AISI 304, power density

1. Introduction

Nowadays, the AISI 304 is the most frequently used stainless steel grade in various industries like chemical, food industry, and gas and oil extraction [1]. This steel grade usually contains 18% Cr and 8% Ni (18-8 steel) and has a unique combination of high toughness and very good corrosion resistance [2, 3]. The AISI 304 is characterised by a good weldability using conventional or modern welding techniques. When material thickness is higher than 1 mm the Gas Tungsten Arc Welding (GTAW) procedure is used. The conventional TIG welding with Argon or Helium as shielding gas is investigated in different scientific investigations [4, 5, 6]. If case of material with higher thickness the friction stir welding technique may be employed. By using this technique is attempted to obtain proper weld joints without pore or cracks [7].

In a recent research Lakshminarayanan [8] developed new stirring coated tool to avoid the overheating of the tool during the stainless steel FSW welding.

The austenitic stainless steel has a high susceptibility to hot cracking. In this moment the laser welding is best method to join stainless steel parts. If in case of components with high thickness several conventional method can be used, in case of stainless steel thin sheets (< 0.5 mm) welding the laser is the only suitable technology.

Advantages of the laser welding process compared to the conventional welding technologies are: high concentrated thermal energy, very high welding speed, narrow heat affected zone, non contact welding process and possibility to made remote welding seams [9, 10].

The laser welding process can be conducted in two ways: autogenous and keyhole method. In both cases the laser welding is without filler material.

The laser welding process is characterised by a specific features, respectively the high cooling rate of the melted bath. Due to the rapid solidification of the metal, residual stresses are induced into the weld bead. In order to reduce this downback, a right balance between the laser welding parameters must be used. Laser power, spot diameter and welding speed are the main process parameters of the laser welding. Shielding gas type and flow rate, stand-off distance, and focal point are the secondary parameters of the laser welding process.

In this study is investigated the influence of the process parameters on the geometry of the weld bead in case of laser welding of austenitic stainless steel thin sheets.

2. Experimental frame

Commercial austenitic stainless steel AISI 304 of 30×100×0.5 mm was used for the experimental tests. The chemical composition of the material is presented in Table 1. The steel is characterized by good weldability, the welding thermal cycle having a major influence on the structural characteristics of the material or to the mechanical properties. The high content of chromium and nickel is necessary to prevent the transformation of austenite to ferrite or cementite during cooling process. Nickel stabilizes the austenitic structure. The chromium has also the role to decrease the transformation rate of the austenite with the decreasing of temperature.

Table 1. Chemical composition of AISI 304 steel

C %	Si %	Mn %	P %	S %	Cr %	Ni %	Mo %
0.023	0.345	1.15	0.019	0.004	18.5	8.43	0.107

The experimental tests were conducted using an unusual joint geometry for this thickness, respectively butt joint. Figure 1 show the schematic representation of the square butt welding geometry.

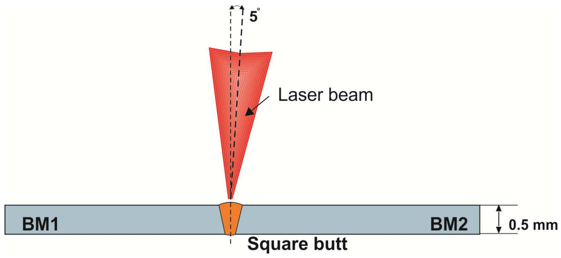

Figure 1. Schematic representation of the joint geometry

The experimental set-up is composed from an ROFIN DY033 Nd:YAG laser and an welding processing head made also by ROFIN. The movement of the welding head was realised using a 6 axe ABB IRB 4400 robot.

The positioning and fastening of the stainless steel plates was realised by a clamping device using four clamps, two for each plate. The laser beam was positioned at the interface between the thin plates. In order to protect the optic system the processing head was tilted at 5º.

In the Figure 2 is presented the experimental frame used for the AISI 304 welding in a square butt configuration. Due to the small thickness of the samples the welding was performed without joint gap.

The welding process was shielded using argon 99.98% at a constant flow of 15 l/min. Before welding the samples were degreased, their sub In order to reduce the number of experimental investigations, but also to cover all parameters range experimental tests on laser butt welding were made by using a parameters matrix sequent manipulation was made with gloves.

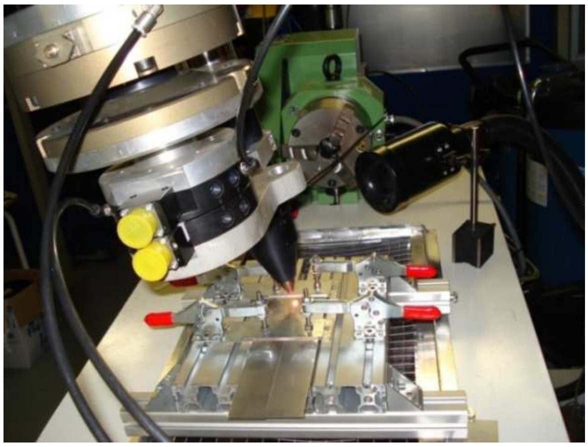

Figure 2. Experimental frame used to perform the experimental welding tests

The process parameters used for square butt laser welding of thin sheets and the geometrical measurements of the welded bead are presented in the Table 2.

Table 2. Parameters and response factors used in the lap joint welding of austenitic stainless steel plates

Parameters / Sample	Sample 1.1	Sample 1.2	Sample 1.3	Sample 2.1	Sample 2.2	Sample 2.3	Sample 3.1	Sample 3.2	Sample 3.3
Laser power [W]	450	550	650	450	550	650	450	550	650
Power density [kW/cm^2]	229.29	280.25	331.21	189.50	231.61	273.72	159.23	194.62	230.00
Energy density [J/mm^2]	60	55	65	54.545	66.667	59.091	75	61.11	54.167
Linear energy [J/mm]	30	27.5	32.5	30	36.66	32.5	45	36.66	32.5
Welding speed [mm/s]	15	20	20	15	15	20	10	15	20
Spot diameter [mm]	0.5	0.5	0.5	0.55	0.55	0.55	0.6	0.6	0.6
Penetration depth [µm]	454	429	442	462	494	499	519	469	478
Bead width [µm]	865 684 709	889 782 815	15283 1552	1148 911 847	1203 1197 1361	1269 968 996	1717 1713	1624 1284	1361 1076
Bead area [mm^2]	0.34	0.36	0.64	0.45	0.52	0.6	0.78	0.65	0.55

3. Results and discussion

The welded bead measurements were made by using specialized software (AnalySIS). For a good characterization, the welded bead width was measured in three regions namely at the top, middle and near the root of the bead. The medium values of the bead width were used to analyse the influence of the process parameters on the weld melted area.

In the Figure 3 is presented the geometrical appearance of the cross-section of the welded samples. The samples were prepared by means of cutting, polishing and electrochemical etching in solution of 10% Oxalic acid.

Samples 1.1, 1.2 and 1.3 were made with a minimum laser spot size (0.5 mm) which produces a high concentration of energy. Visual observations during the experimental tests characterize the welding process of samples 1.1 and 1.2 as been stable, but with plasma formation. In case of the sample 1.3 it was observed an unstable process with plasma and splashes formation.

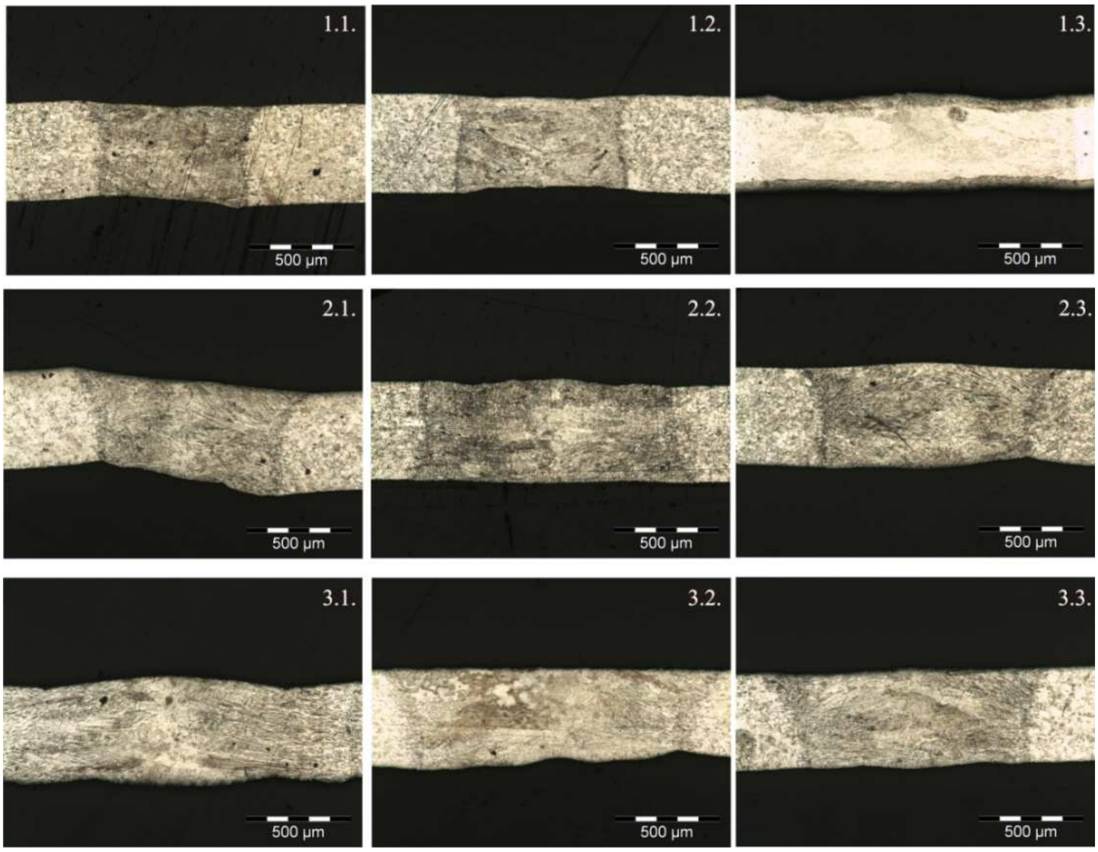

Figure 3. Cross section of the welded samples

Visual and microscopic examination of samples 1.2 and 1.3 reveals the major influence of the power density on the welded joint. It was observed that an increase with 20% of the input energy has led to breakthrough metal sheets and also a massive extension of the heat affected zone was produced (sample 1.3, Figure 3). It was determined that higher values of power density (< 270 kW/cm^2) are not recommended for this type of welding, even if high welding speed of 20 mm/s is used.

Microscopic analysis of the test samples 1.1 and 1.2 showed a minimum heat affected zone, with a directly transition from base material to the weld zone.

The experimentally obtained data were correlated with the exponential function that expresses a tendency for $Y = a \cdot e^{b \cdot x}$, where a and b are the function coefficients.

The algorithm of smallest squares (Gauss method) was used for determination. The exact domain of energy density influence on the penetration depth was achieved by calculating the exponential regression function:

$$Y = a \cdot e^{b \cdot x} \qquad (1)$$

where a is origin moving on 0Y axis and b is the slope of the regression line.

In Figure 4 is presented the graphical representations of the laser energy density influence on the penetration depth, as exponential function regarding the equations (1). The transparent red highlights the prediction area of the mathematical regression error.

Based on analytical correlation it was obtained the equation that defines the dependence between the laser energy density and penetration depth in case of stainless steel AISI 304 butt welding

$$D_e = 12.58998746 \cdot e^{0.00341021 \cdot p} \qquad (2)$$

were: D_e – energy density [J/mm^2], p – penetration depth [μm].

In Figure 5 is presented the geometrical and microstructural appearance of the sample made with a spot diameter of 0.55 mm. Visual observations during the experimental test characterize the welding process as been stable without splash or plasma. It was noted that for samples 2.1 and 2.2 by increasing the energy density with 20% it was obtained an increase in both penetration and bead width. Macroscopic images from Figure 3 (samples .2.1, P.2.2 and P.2.3) reveal a uniform distribution of the thermal field with no noticeable difference between the three samples.

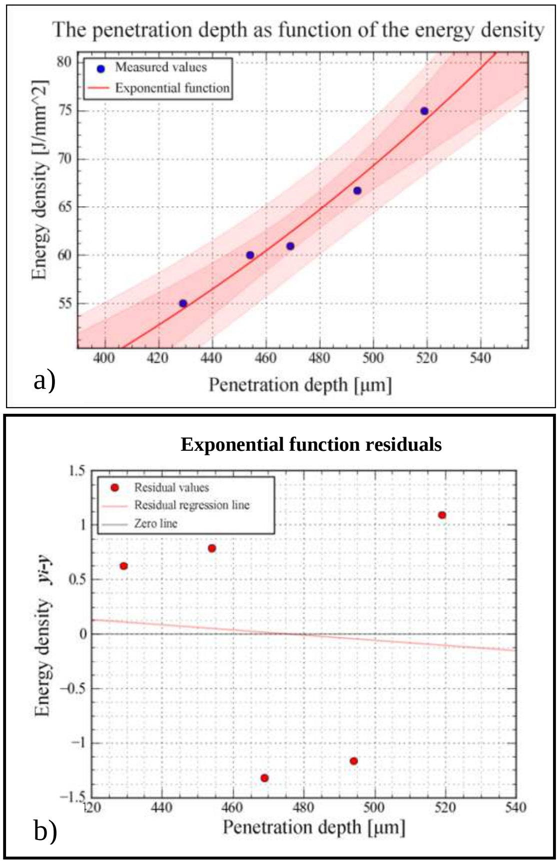

Figure 4. a) Graphical representation of the energy density influence on penetration depth, b) residual values of the exponential function

Comparing the sample 2.3 (Figure 5) with the sample 1.3 it can be seen that by increasing the laser spot with only 0.05 mm a better distribution in the welded bead without break-through will be obtained.

Figure 7 shows the geometrical and micro structural appearance of test samples made with a high laser spot diameter, respectively 0.6 mm. Characteristic for this samples is the stability of the process. It was determined that an increasing of the spot diameter will produce a more stable process both at low and high speeds.

In this experimental set (set 3), particularly important is the sample 3.1 which was achieved with a low welding speed (10 mm/s). It was noted that the reduced speed had a negative effect on the welded joints.

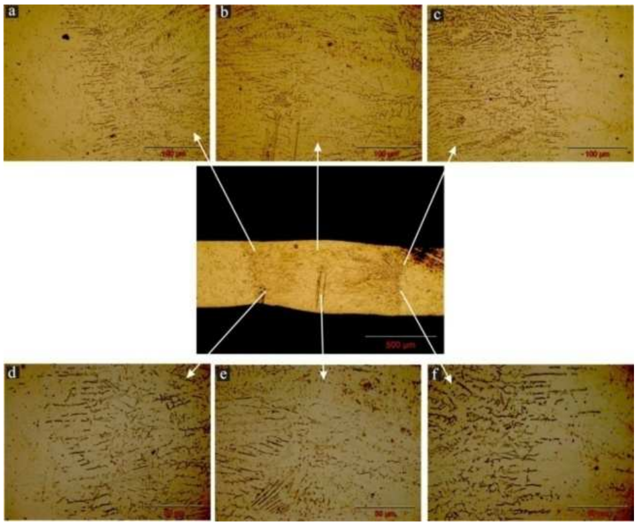

Figure 5. Optical microscopy of different areas of the weld cross section, sample 2.3

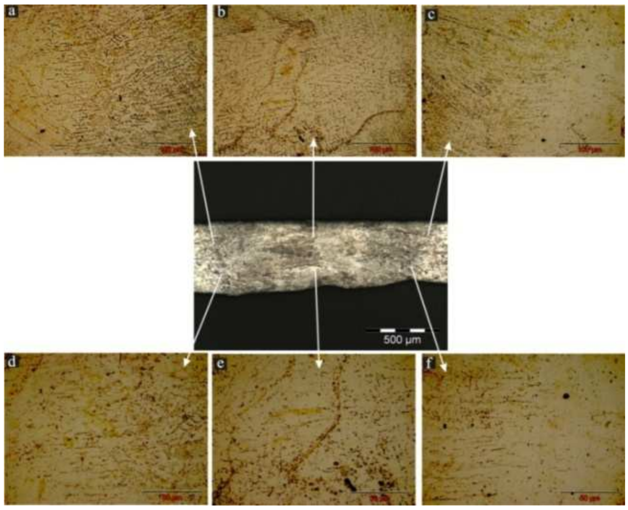

Figure 6. Optical microstructure of different areas of the weld cross section, sample 3.1

The microscopic analysis of sample 3.1 (Figure 6) indicates an extended heat affected zone, although it was used a low power density and a low welding speed with a spot diameter of 0.5 mm.

4. Conclusions

All the welded beads had a complete penetration in case of butt joint geometry, the difference between them consisting in the weld bead width and the deformation effects produced in the joint area.

Using the experimental investigations on the butt-welding thin plates it was determined that the best geometrical results may be obtained by using the parameters presented in Table 3.

In order to obtain an optimal weld appearance (minimum width and uniform height and penetration depth) the power density must be within the range 230-280 kW/cm^2 (for AISI 304 steel components with thickness of 0.5mm).

Tabel 3. Optimal values for welding parameters and seam geometrical parameters

Sample	Power density [kW/cm^2]	Laser spot diameter [mm]	Width [μm]	Average weld height [μm]
1.2	280	0.5	889	429
2.3	273	0.55	1269	499
3.3	230	0.6	1361	478

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