УДК 621.791.725
UDC 621.791.725

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INFLUENCE OF LASER WELDING PARAMETERS ON THE GEOMETRY OF WELDED JOINTS OF THIN-SHEET STAINLESS STEEL AISI 304

Laser welding is one of the most promising methods of joining metals, combining high precision, minimal thermal deformation, and the possibility of process automatization. Due to the high energy density of the laser beam, the technology provides deep penetration with a narrow heat-affected zone, making it effective for welding corrosion-resistant austenitic steels, in particular AISI 304. At the same time, the peculiarities of thermal processes in laser welding, such as intense heating and rapid cooling of the metal, significantly affect the formation of the structure and properties of the welded joint, so the choice of optimal modes is crucial for preventing defects and ensuring high quality of the welded joint. The paper presents the results of an experimental and statistical study of the laser welding process of 1.5 mm thick AISI 304 steel using response surface methodology (RSM). The aim of the study was to determine the patterns of influence of the main parameters of laser welding on the formation of the geometry of the welded joint. Based on a factorial experiment, regression models were developed to describe the change in the area and width of the weld depending on changes in process parameters. Analysis of the results has shown that the main factors determining the geometry of the joint are the power of the laser radiation and the welding speed. Increasing the laser power contributes to an increase in the weld area, while increasing the speed reduces it. At high values of laser radiation power, the process becomes more stable, and the weld geometry becomes less sensitive to parameter changes. Laser beam defocusing has a negligible effect, only slightly increasing the width of the weld. The most pronounced interaction was found to be between power and speed, which tends to determine the maximum values of the weld area. The developed regression equations with a deviation of less than 10% confirmed the adequacy of the model and the effectiveness of using RSM to predict the geometry of the welded joint. The optimal welding modes identified in the study ensure the formation of high-quality, defect-free joints that defect-free joints and correspond to quality level "B" according to EN ISO 13919-1:2019.

Keywords: laser welding, thin-walled products, welding process optimization, response surface methodology, stainless steels, AISI 304.

INTRODUCTION

Laser welding is one of the most promising modern methods of joining metals. This technology is actively growing due to its unique advantages over traditional welding methods. Compared with plasma, microplasma, and argon arc (TIG) welding, laser welding is characterized by higher precision in the formation of welded joints, minimal thermal deformation and residual stresses, as well as a significantly higher process speed [1, 2]. This is due to the high energy density of the laser beam at the focal point, which allows deep penetration with a minimal heat-affected zone. Due to the combination of high quality, reproducibility of results, and the possibility of process automatization, laser welding has become an integral technology in the production of products for the aviation, automotive, electronic, energy, medical industries, etc.

One of the most widely used steels in industry that can be welded using laser radiation is austenitic corrosion-resistant steel, such as AISI 304. This material has a range of technological and operational advantages: low thermal conductivity, high resistance to oxidation and aggressive environments, stability of mechanical properties at elevated temperatures, and the ability to effectively absorb laser radiation [3, 4]. At the same time, the peculiarities of thermal processes during laser welding - rapid heating and cooling - significantly affect the structure formation, phase transformations, and mechanical properties of austenitic steels, distinguishing their behavior from the reaction to welding with high heat input [5]. One of the main problems during the welding of corrosion-resistant steels is sensitization, a process in which part of the chromium in the alloy binds with carbon to form $Cr_{23}C_6$ carbides along the grain boundaries. This leads to local depletion of the solid solution of chromium and, as a result, to a decrease in the corrosion resistance of the welded joint [6]. To prevent this phenomenon, it is necessary to take into account the parameters of laser welding and the cooling rate.

The formation of the geometry of a welded joint, in particular its penetration depth and width, significantly depends on the technological parameters of welding, such as laser radiation power, welding speed, laser beam defocusing, and the composition and flow rate of the shielding gas [7]. Even slight changes in these parameters can lead to defects such as undercut, incomplete fusion, porosity, or burn-through [8]. Therefore, selecting the optimal parameters is crucial for achieving the required balance between the depth, width, and shape of the welded joint.

In this regard, it is particularly important to develop mathematical models that describe the relationship between the technological parameters of the process and the characteristics of the resulting joint. Such models make it possible not only to interpret the results of experiments, but also to predict the behavior of the system under various combinations of parameters, which significantly reduces the number of experimental studies and saves time and resources [9].

To improve the efficiency of research and the accuracy of forecasting, numerical and statistical methods for optimizing technological parameters have been actively implemented in recent years. In particular, Response Surface Methodology (RSM) allows for determination of the relationships between process parameters and system response [9]. This method also allows optimization of the expected characteristics of a welded joint by adjusting technological parameters such as laser power, welding speed, and beam defocusing. It is effectively used to build mathematical models that predict output parameters, such as penetration depth, aspect ratio, and joint area, while determining the optimal combination of input parameters [10]. The Taguchi method aims to reduce the influence of random factors and ensure process stability using orthogonal matrices and statistical analysis of variance [11]. In addition, genetic algorithms (GA) and artificial neural networks (ANN) are used to model complex nonlinear dependencies, which allow effectively finding the optimal process conditions even with a large number of interacting factors [12, 13].

LITERATURE ANALYSIS AND PROBLEM STATEMENT

Response Surface Methodology (RSM) is an effective statistical approach to modeling and optimizing processes where the result depends on several variables. When planning laser welding experiments, this method allows for investigation of the relationship between power, speed, focus position, gas protection parameters, and joint characteristics. The use of RSM makes it possible to reduce the number of experiments, identify key influencing factors, and obtain optimal welding modes with minimal heat input and defects. For this reason, this method has been widely used to analyze and improve laser welding processes in recent years, as confirmed by the results of a number of studies.

In a study by Vijayan et al. [9], the effectiveness of RSM and genetic algorithm (GA) methods was compared in optimizing the parameters of laser welding of low-carbon steel. The experiments were conducted on 7 mm thick plates using a CO_2 laser with power of up to 3.5 kW. Power, speed, and focal length were selected as variables. The models developed using RSM proved to be quite accurate (R^2 of up to 0.87). It was found that with an increase in power, the penetration depth increases, while with an increase in speed, it decreased. RSM showed better accuracy and reliability in determining the optimal modes compared to the GA method.

Chellu et al. [14] applied RSM to optimize the welding of 2.5 mm thick AISI 304 steel using a CO_2 laser. This paper focused on studies of the effect of welding power and speed on weld width, penetration depth, and heat input. The study confirmed that increasing the power deepens the weld, but excess heat widens it and increases the heat affected zone (HAZ), while increasing the speed reduces the depth but improves the depth-to-width ratio. The optimal modes ensured minimal thermal impact and a stable weld shape.

In the work of Touileb et al. [10], RSM was used to study the influence of laser welding parameters and sulfur content on the shape of a 2 mm thick AISI 316 steel weld. It was found that the focal length and amount of sulfur significantly affect the convection currents in the molten pool and the penetration depth. For steel with a high sulfur content, deeper, narrower welds were formed, while for steel with a low sulfur content, wider and shallower welds were formed. The best results in this study were obtained at a laser power of 5 kW, a welding speed of 2.4 m/min, a focal length of 2 mm, and the use of 100% helium as a shielding gas.

Thus, all the considered studies confirm the effectiveness of RSM as a method for determining the influence of laser welding process parameters on weld geometry. However, the complex influence of material composition, welding parameters, and gas protection require further study to ensure process stability and improve joint quality.

AIM AND OBJECTIVES OF THE RESEARCH

The aims of this study are:

1. Optimization of the laser welding process of thin-walled stainless steel AISI 304 with a thickness of 1.5 mm using response surface methodology (RSM);
2. Selection of optimal welding parameters that ensure creation of defect-free welded joints.

RESULTS OF RESEARCH

The optimization of laser welding parameters for 1.5 mm thick AISI 304 stainless steel was performed using response surface methodology (RSM). For this purpose, the laser welding parameters were coded (Table 1) and an experimental matrix was planned (Table 2) based on a simple polynomial model, equation (1):

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \dots + b_xx_k \quad (1)$$

Table 1. Coding of laser welding parameters

Coding	-1	0	+1
Laser radiation power (P), kW	1,5	2,5	3,5
Welding speed (V), m/min	1,5	2,5	3,5
Laser beam defocusing value (ΔF), mm	0	+2	+3

The following independent variables were selected: laser power (P), welding speed (V), and laser beam defocusing (ΔF). The response function Y was selected as the weld area Y_s and weld width Y_b.

Таблиця 2. Матриця експерименту

№	1	2	3	P, kW	V, m/min	F, mm	№	1	2	3	P, kW	V, m/min	F, mm
1	1	1	1	1,5	1,5		5			1	2,5	2,5	3
2	1	1		1,5	1,5	2	6		1	1	2,5	3,5	
3	1	1	1	1,5	1,5	3	7		1		2,5	3,5	2
4	1		1	1,5	2,5		8		1	1	2,5	3,5	3
5	1			1,5	2,5	2	9	1	1	1	3,5	1,5	
6	1		1	1,5	2,5	3	20	1	1		3,5	1,5	2
7	1	1	1	1,5	3,5		21	1	1	1	3,5	1,5	3
8	1	1		1,5	3,5	2	22	1		1	3,5	2,5	
9	1	1	1	1,5	3,5	3	23	1			3,5	2,5	2
10		1	1	2,5	1,5		24	1		1	3,5	2,5	3
11		1		2,5	1,5	2	25	1	1	1	3,5	3,5	
12		1	1	2,5	1,5	3	26	1	1		3,5	3,5	2
13			1	2,5	2,5		27	1	1	1	3,5	3,5	3
14				2,5	2,5	2							

Based on the compiled experiment matrix, bead-on-plate welding was performed. A Rofin-Sinar DY044 solid-state laser with a maximum laser power of P = 4.4 kW and a wavelength of λ = 1.06 µm was used for the experiments. The chemical composition of AISI 304 steel is shown in Table 3.

Table 3. Chemical composition of AISI 304 steel, % by wt.

C	Si	Mn	Ni	S	P	Cr	Cu	Ti	Fe
≤0,08	≤0,8	≤2,00	9,00 – 11,00	≤0,02	≤0,035	17,00 – 19,00	≤0,3	≤0,5	Bal.

The bead-on-plate welds obtained were certified in accordance with EN ISO 13919-1:2019 for the presence of such weld defects as pores, undercuts, lack of fusion, and other defects specified by this standard. In addition to identifying visual defects, the quality of gas protection of the welding zone was also taken into account. Welded joints with obvious heat tints and non-penetrations (experiments 4, 7-9) were not taken into account when determining the optimal welding modes.

Cross-sections, made from the obtained welds, were examined using optical microscopy, and the area and width of the welds were measured. The results of the measurements are shown in Table 4.

Table 4. Results of measurements of the area and width of the obtained welds

Sample No.	Area, mm^2	Width, mm	Sample No.	Area, mm^2	Width, mm
1	1,81	1,97	15	1,57	1,61
2	2	1,83	16	1,29	1,55
3	2,26	1,94	17	1,41	1,36

Continued from Table 4.

Sample No.	Area, mm^2	Width, mm	Sample No.	Area, mm^2	Width, mm
4	0,94	1,44	18	1,38	1,41
5	1,38	1,5	19	2,53	1,81
6	1,23	1,46	20	2,62	1,71
7	0,7	1,28	21	2,54	1,9
8	0,83	1,25	22	2,04	1,87
9	0,67	1,23	23	2,07	1,59
10	2,43	1,45	24	2,15	1,8
11	2,6	1,52	25	1,59	1,64
12	2,43	1,92	26	1,7	1,61
13	1,68	1,61	27	1,87	1,4
14	1,6	1,5			

To develop a linear regression equation for the area and width of welds (2), it is necessary to determine the regression coefficients of the main factors b_0, b_1, b_2, b_3 using formulas (3) and (4), as well as the interaction coefficients between factors b_{12}, b_{13}, b_{23}, using formula (5):

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{12}x_1x_3 + b_{23}x_2x_3 \quad (2)$$

$$b_0 = \frac{1}{N}\sum_{i=1}^{N} Y_i \quad (3)$$

$$b_j = \frac{\sum_{i=1}^{N} x_{ji}Y_i}{\sum_{i=1}^{N} x_{ji}^2} \quad (4)$$

$$b_{ji} = \frac{\sum_{i=1}^{N}(x_{ji}x_{ji})Y_i}{\sum_{i=1}^{N}(x_{ji}x_{ji})^2} \quad (5)$$

As a result of the calculations, regression coefficients for the weld area were obtained: b_0 = 1,752, b_1 = 0,405, b_2 =– 0,543, b_3 = 0,06, b_{12} = 0,11, b_{13} = –0,02, b_{23} = –0,01.

After substituting the obtained regression coefficient values and independent variable designations into the formula (2), the regression equation for the weld area (6) was obtained:

$$Y_s = 1{,}752 + 0{,}405P - 0{,}543V + 0{,}06\Delta F + 0{,}11PV - 0{,}02P\Delta F - 0{,}01V\Delta F \quad (6)$$

Similarly, the regression equation for the width of weld was calculated (7):

$$Y_b = 1{,}598 - 0{,}184P + 0{,}079V + 0{,}002\Delta F + 0{,}1PV - 0{,}08P\Delta F - 0{,}01V\Delta F \quad (7)$$

Based on the regression coefficients of equations for the area (6) and width (7) of welds, vector diagrams were created to show the influence of factors and their interaction on the area and width of welds (Fig. 1 a, b).

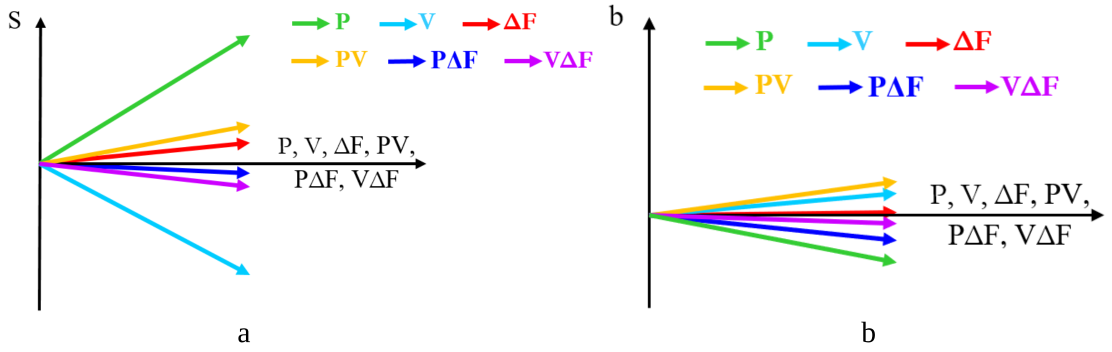

Fig. 1. Vector diagrams of the influence of factors on: (a) weld area, (b) weld width

The vector diagram of the influence of factors on the weld area (Fig. 1a) shows that the speed of laser welding has the most significant impact on the weld area. As the welding speed increases, the area decreases, and this effect is more pronounced than the effect of other individual factors. The second most important factor is the power of the laser radiation. Its increase contributes to an increase in the area, and this effect is slightly weaker than the effect of power, but they act in opposite directions. Beam defocusing has the least effect and causes only a slight increase in area. Between the interactions, the most significant is the combination of power and welding speed, which leads to an increase in the weld joint area. The interactions between power and defocusing, as well as between speed and defocusing, have a negligible negative effect.

The vector diagram of the influence of factors on the weld width (Fig. 1b) shows that the laser radiation power has the most negative effect – as the power increases, the width decreases. The welding speed also reduces the width, but to a much lesser extent. Defocusing has the opposite effect, contributing to a slight increase in the weld width. The most noticeable interaction is the combination of power and speed, which amplifies the influence of the main factors.

The calculated values of the area and width of the welds were also determined. The deviation from the experimental values was less than 10%, which confirms the adequacy of the obtained regression equations.

In addition to vector diagrams, graphs of the dependence of the influence of laser welding parameters on the weld area were created. These graphs correlate well with the vector diagrams of the influence of factors.

As can be seen from the graphs in Figure 2, with an increase in welding speed, the weld area decreases regularly for all power levels considered. At a power of 1.5 kW (Fig. 2a), there is a noticeable decrease in area from approximately 2.0 mm^2 to 0.7 mm^2 when the speed increases from 1.5 to 3.5 m/min. The largest values of the area are observed when the beam is defocused by +3 mm, especially at low speeds, while at a laser beam defocus of 0 mm, the weld penetration is shallower. For a power of 2.5 kW (Fig. 2b), a similar trend is observed. With increasing speed, the welded joint area decreases from 2.6 mm^2 to about 1.3 mm^2. However, the effect of beam defocusing is not as pronounced here, and the curves are more gradual. At a power of 3.5 kW (Fig. 2c), the decrease in area with increasing welding speed is less intense, and the absolute values of the areas are larger – from 2.6 mm^2 to 1.6 mm^2. Thus, increasing the power of the laser radiation reduces the effect of the welding speed on the weld area, which contributes to a more stable weld formation.

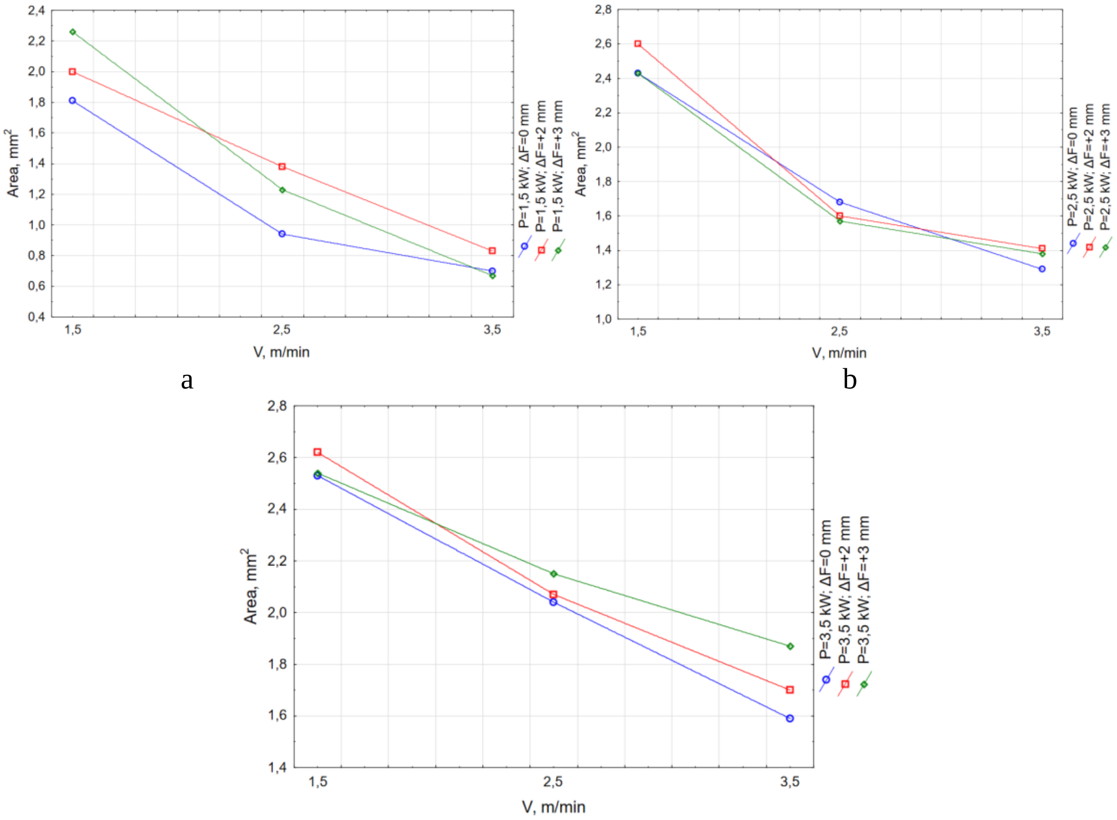

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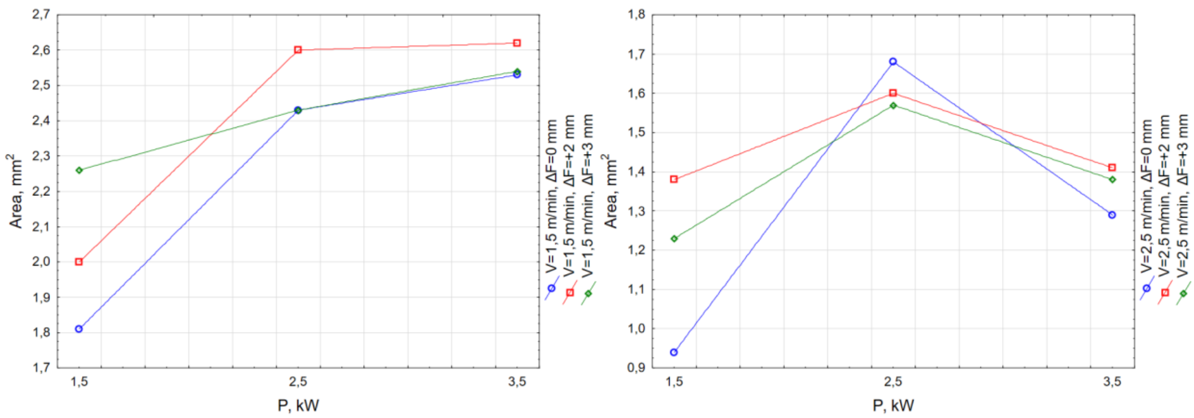
Fig. 2. Graphs of dependence of weld area on welding speed at laser radiation power: (a) 1.5 kW; (b) 2.5 kW; (c) 3.5 kW

The graphs in Figure 3 show the dependence of the weld area on the laser power when the welding speed is changed. An increase in the laser power leads to a regular increase in the weld area, and this dependence is more noticeable at low welding speeds. At a speed of 1.5 m/min (Fig. 3a), the area increases from 1.8–2.0 mm^2 at a power of 1.5 kW to 2.5–2.6 mm^2 at 3.5 kW. The largest area is formed at a beam defocus of +2 mm, which indicates a more uniform distribution of energy at the beam focus point. At a speed of 2.5 m/min (Fig. 3b), the area also increases with increasing power, but the effect of defocusing is less significant in this case. At a speed of 3.5 m/min (Fig. 3c), the increase in area with increasing power is maintained, but the amplitude of changes decreases from 0.7 mm^2 to 1.8 mm^2. This indicates that with an increase in the power of laser radiation, the process becomes more stable even at high welding speeds.



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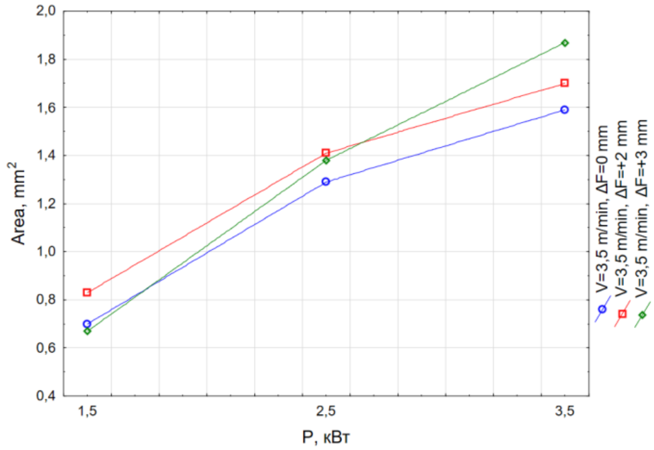

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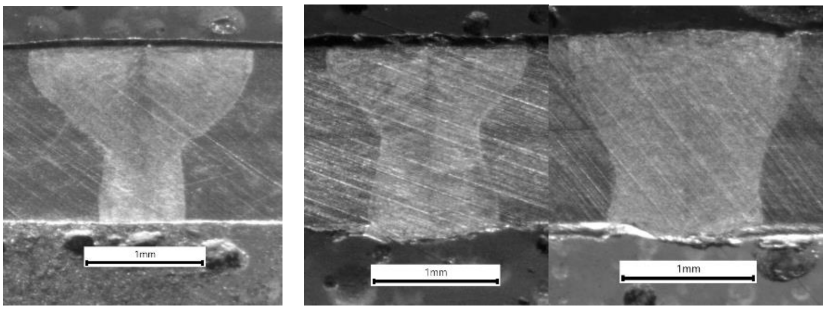
Fig. 3. Graphs of dependence of weld area on laser power at welding speeds: (a) 1.5 m/min; (b) 2.5 m/min; (c) 3.5 m/min

Based on the results of weld geometry research, three welding modes with the same energy input of 60 J/mm and laser beam defocusing of 0 mm were selected, which ensure high-quality welds in terms of geometry, gas protection quality, and defect-free welds, and correspond to the highest level "B" according to EN ISO 13919-1:2019 (Fig. 4).



a b c

Fig. 4. Cross sections of welds made at optimal welding parameters: (a) P=1.5 kW; V=1.5 m/min; ΔF=0 mm; (b) P=2.5 kW; V=2.5 m/min; ΔF=0 mm; (c) P=3.5 kW; V=3.5 m/min; ΔF=0 mm

DISCUSSION OF THE RESEARCH RESULTS

The results of laser welding of 1.5 mm thick AISI 304 steel using response surface methodology (RSM) demonstrate the effectiveness of the proposed approach for quantitative assessment of the influence of technological parameters on the shape and geometry of the weld. The use of RSM made it possible to systematically investigate the interaction of laser power, welding speed, and laser beam defocusing and to determine their contribution to the stability of weld formation.

Comparing the results of studies on welding AISI 304 steel with the results of Touileb et al. [10] on welding AISI 316 steel, the following conclusion can be drawn. Under conditions of similar geometric scales and steel types, the influence of the main technological factors is similar. Laser beam defocusing and radiation power determine the depth of penetration, while speed affects the area and width. At the same time, for AISI 316 steel with a higher sulfur content, there is significantly greater variability in the geometry of the penetration due to changes in convection currents, while welding of AISI 304 steel without modifying additives demonstrates a more predictable and stable geometry of the joint. As the power of the laser radiation increases, the process becomes more thermodynamically stable and the effect of defocusing weakens, which is consistent with the conclusions of Touileb et al. In general, the results indicate the feasibility of optimizing laser welding parameters based on a balance between power and welding speed with a correctly selected defocusing value of the laser radiation, which ensures efficient energy absorption and optimal weld geometry.

CONCLUSIONS

During the research, an analysis was conducted of the influence of laser welding parameters on the geometry of welds in stainless steel AISI 304 with a thickness of 1.5 mm. It was established that the main factors determining the area and width of the weld are the power of the laser radiation and the welding speed.

With an increase in laser radiation power, the weld area increases regularly, especially at low welding speeds, and at high radiation power, the weld is formed more stably and its geometry is less dependent on changes in welding speed. Defocusing the beam has a less noticeable effect, contributing to a slight increase in the area and width of the weld. The interaction between power and welding speed is the most significant among the combinations of parameters and determines the maximum weld area. The obtained regression equations reproduce the experimental data well with a deviation of less than 10%, which confirms their adequacy for predicting the geometry of welds. As a result, it was determined that the optimal welding modes with a linear energy of 60 J/mm and a laser beam defocusing of 0 mm provide high-quality defect-free welds and correspond to the highest quality level "B" according to EN ISO 13919-1:2019.

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Юрченко Ю.В., Сіора О.В., Соколовський М.В., Гринь А.П., Фролов М.О., Бернацький А.В.
Вплив параметрів лазерного зварювання на геометрію зварних з'єднань тонколистової корозійностійкої сталі AISI 304

Лазерне зварювання є одним із найперспективніших методів з'єднання металів, що поєднує високу точність, мінімальні термічні деформації та можливість автоматизації процесу. Завдяки високій щільності енергії лазерного променя технологія забезпечує глибоке проплавлення при вузькій зоні термічного впливу, що робить її ефективною для зварювання корозійностійких сталей аустенітного класу, зокрема AISI 304. Водночас особливості теплових процесів при лазерному зварюванні, такі як інтенсивний нагрів і швидке охолодження металу – істотно впливають на формування структури та властивостей зварного з'єднання, тому вибір оптимальних режимів має вирішальне значення для запобігання дефектам і забезпечення високої якості зварного з'єднання. У роботі представлено результати експериментального та статистичного дослідження процесу лазерного зварювання сталі AISI 304 товщиною 1,5 мм із застосуванням методології поверхні відгуку (RSM). Метою дослідження було визначення закономірностей впливу основних параметрів лазерного зварювання на формування геометрії зварного з'єднання. На основі повнофакторного експерименту побудовано регресійні моделі, що описують зміну площі та ширини провару залежно від зміни параметрів процесу. Аналіз результатів показав, що основними факторами, які визначають геометрію з'єднання, є потужність лазерного випромінювання та швидкість зварювання. Збільшення потужності сприяє зростанню площі провару, тоді як підвищення швидкості зменшує її. При високих потужностях лазерного випромінювання процес стає стабільнішим, а геометрія провару менш чутливою до коливань параметрів. Розфокусування чинить незначний вплив, лише трохи збільшуючи ширину провару. Найбільш вираженою виявилася взаємодія потужності та швидкості, яка визначає максимальні значення площі проплавлення. Розроблені регресійні рівняння з відхиленням менше 10 % підтвердили адекватність моделі й ефективність використання RSM для прогнозування геометрії зварного з'єднання. Оптимальні режими зварювання, що були визначені в ході дослідження, забезпечують формування якісних, бездефектних з'єднань та відповідають рівню якості «B» згідно з EN ISO 13919-1:2019.

Ключові слова: лазерне зварювання, тонкостінні вироби, оптимізація процесу зварювання, методологія поверхні відгуку (RSM), корозійностійкі високолеговані сталі, AISI 304.

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Дата надходження статті до видання: 28.10.2025
Дата прийняття статті до друку після рецензування: 05.11.2025
DOI 10.36910/automash.v2i25.1914