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DEVELOPMENT AND TESTING OF AUXILIARY TECHNOLOGICAL EQUIPMENT FOR LASER WELDING OF THIN-WALLED T-JOINTS IN VARIOUS SPATIAL POSITIONS

This study examines ways to improve the efficiency of laser welding of T-joints by developing specialized welding equipment. It is shown that, despite a significant body of research on the properties of welded joints, the issue of ensuring welding process stability through equipment design remains understudied. The aim of this work is to create and experimentally test technological equipment for laser welding of T-lap joints in various spatial positions. The developed equipment includes a clamp for fixing samples and a laboratory stand with a two-axis laser head movement system. The clamp design ensures precise alignment of the joint elements, adjustable fixing of the edge, and uniform supply of shielding gas from both sides of the edge. The laboratory stand enables controlled movement along the X and Z axes using servo drives and ball-screw drives, which allows for high positioning accuracy and process reproducibility. The ability to change the spatial position of the weld by tilting the work frame is provided. Experimental studies were conducted on the welding of T-joints made of austenitic and austenitic-ferritic stainless steels using an Nd:YAG laser with a power of up to 4.4 kW. Microstructural analysis revealed the formation of a fine-grained austenitic weld structure with a negligible content of δ-ferrite and a narrow heat-affected zone. It was established that the weld geometry is stable, and the structural characteristics are uniform throughout the welded joint. The results of mechanical tests confirmed the high strength of the welded joints. The results obtained demonstrate the effectiveness of the developed process equipment and the possibility of its use for forming high-quality T-joint welds in various spatial positions that meet the requirements of DSTU EN ISO 13919-1:2019 and are characterized by the highest quality level «B».

Keywords: laser welding, thin-walled components, T-joints, stainless steels, spatial positions, welding challenges, equipment development.

INTRODUCTION

The current stage of industrial production is characterized by the widespread adoption of high-tech material processing methods, among which laser technologies play a particularly significant role. One of the most promising areas is laser welding, which is actively used in mechanical engineering, as well as in the aviation, automotive, shipbuilding, energy, and electronics industries. This is due to a number of significant advantages, including high energy concentration, a minimal heat-affected zone, high process speed, the possibility of automation, and the assurance of consistent weld quality [1–3]. In addition, laser welding allows for effective processing of thin-walled materials and complex product geometries, which is crucial for modern manufacturing [4].

The use of laser welding contributes to increased labor productivity, reduced consumption of materials and energy resources, and improved performance characteristics of products. Due to the contactless nature of the process and the ability to precisely control laser radiation parameters, high repeatability of results is ensured, and the influence of the human factor is minimized [5]. Studies [6, 7] have shown that laser welding produces welded joints with high mechanical properties and minimal defects in materials such as corrosion-resistant steels and titanium alloys.

Of special interest is the laser welding of thin-walled T-joints, which are widely used in structures such as stiffening panels, heat exchange equipment, vehicle components, and power plant components. Such joints are characterized by increased requirements for assembly accuracy, joint geometry, and welding process stability. As shown in the study [8], even minor deviations in the relative position of the elements or the presence of a gap can significantly affect the formation of the weld, its geometry, and strength characteristics.

This necessitates the development and use of special auxiliary technological equipment that allows parts to be fixed in a specified position, ensures uniform clamping, and minimizes deformation during welding.

LITERATURE REVIEW AND PROBLEM STATEMENT

An analysis of current scientific literature in the field of laser welding indicates that a significant portion of research focuses on the study of the formation processes of welded joints, including T-joints, primarily in the lower spatial position, which is the most technologically stable and convenient for implementation. In such studies, the primary focus is on the influence of laser radiation energy parameters (power, welding speed, focal position), as well as heat removal conditions, on the formation of weld geometry, microstructure, and mechanical properties of the joints. It has been established that the vast majority of studies concern laser welding of thick-walled materials, primarily structures made of carbon and low-alloy steels, including various types of joints, in particular T-joints, which are widely used in heavy machinery and building structures. For such materials, the patterns of deep penetration formation, the stability of the "keyhole" mode, and the mechanical properties of joints have been studied in detail [9–11]. At the same time, the issue of laser welding of thin-walled elements, especially those made of stainless steels, particularly T-joints, has been addressed in a significantly smaller number of studies and lacks a sufficient level of generalization [12, 13].

In this regard, a pressing scientific and technical challenge is the development of effective auxiliary technological equipment for laser welding of thin-walled T-joints made of stainless steel in various spatial orientations. Such equipment must ensure precise mutual positioning of the welded elements, the absence or minimization of gaps, the limitation of deformations, and the reproducibility of the geometric parameters of the welded joint. Solving this problem will improve the quality of welded joints, reduce the number of defects, and expand the scope of laser welding applications.

PURPOSE AND OBJECTIVES OF THE STUDY

The aim of this work is to develop and test auxiliary welding equipment for welding thin-walled T-joints in various spatial positions, as well as to optimize welding parameters to produce defect-free welded joints.

RESEARCH RESULTS

One of the most technically challenging T-joint welds is a T-lap joint where there is no access to the joint edge (Fig. 1).

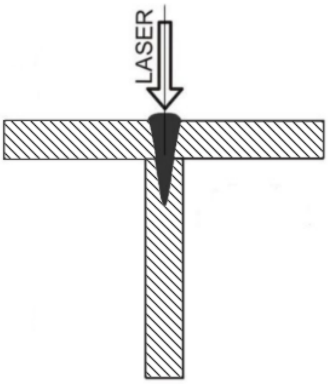


Fig. 1. Scheme of a T-lap joint

During welding such joints in the lower spatial position, a number of specific problems arise:

1. ensuring precise alignment of the laser beam along the joint edge;
2. melted metal flowing out of the weld pool;
3. forming the weld geometry (upper bead and fillets);
4. effective heat dissipation in the welding zone;
5. ensuring stable gas shielding of the welding zone.

Accordingly, to address these issues, the authors of the article developed and created additional technological equipment for laser welding of T-lap joints in various spatial positions. The equipment consists of a clamp for T-joints, as well as a laboratory stand that allows for laser welding in various spatial positions.

The clamp, designed for welding T-joints (Fig. 2), consists of two housings made of 10-mm-thick 20 grade steel. The first housing is rigidly mounted on the plate, while the second is movable and can be displaced relative to the first in the same plane to secure the web of the T-joint. The range of this movement is 0…11 mm. The movable housing is moved using bolts mounted on a bracket on its side along the longer side. The dimensions of the housings allow for the installation of shelves and edges with dimensions up to 500×200 mm.

The clamp design allows for laser welding T-lap joints that reaches the edge from the side of the shelve. Shielding gas is supplied to the back side of the shelve on both sides of the edge along the entire length of the welded joint.

The housings of the technological equipment used to manufacture test specimens of T-joint welds are hollow inside to ensure a uniform flow of shielding gas (Fig. 2). Gas is supplied to each of the two housings, providing protection for the weld on both sides of the web beneath the flange. The groove for the supply of shielding gas is formed by 5×5 mm bevels on the edges of the housings at a 45° angle. There are

39 outlet holes with a diameter of 2 mm on these bevels. The surfaces of the clamp's fixed and movable housings, against which the specimen shelve rests, are located in the same plane, with a maximum deviation from flatness not exceeding ±0.1 mm. The T-joint edge is installed between the bodies in the central part of the shelve at a 90° angle to it. The shelve with welded specimens is secured to the bodies using clamping plates. Secure contact between the edge and the shelve is ensured by the movable body using a clamping plate and bolts.

The 40-mm-thick clamping plates are bevelled at a 60° angle toward the weld, ensuring unobstructed movement of the gas shielding device over the weld pool. The internal volume of each chamber (90×16×480 mm) is 619 cm^3. The overall dimensions of the clamp for welding T-joint specimens are 625×255×167 mm, and its weight is approximately 30 kg.

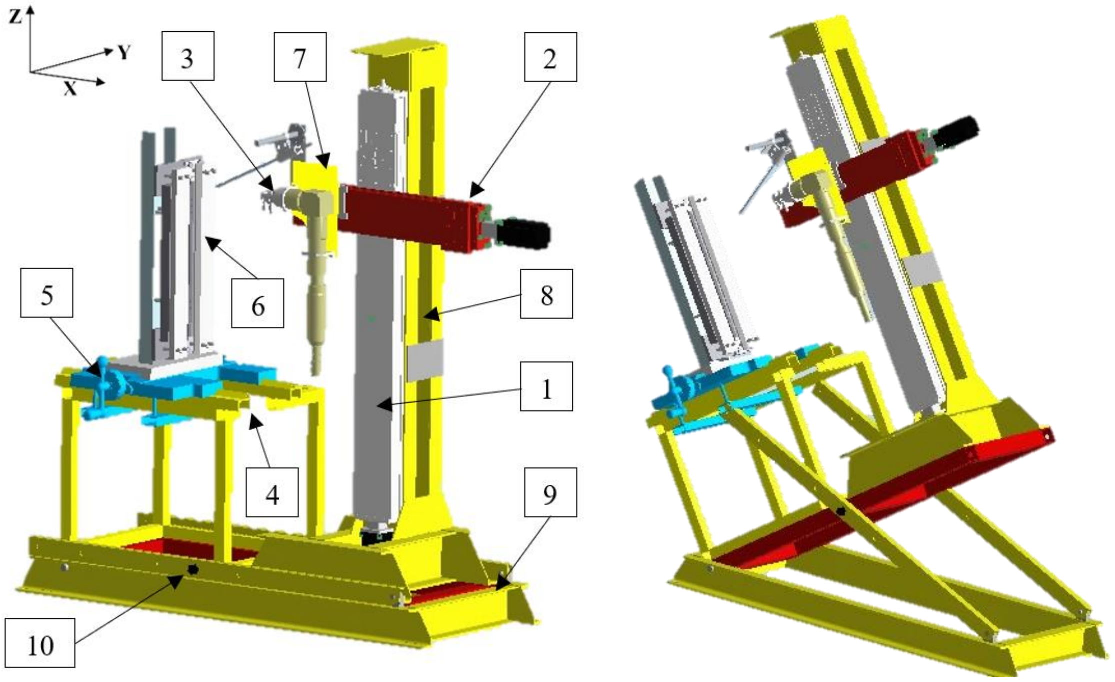

a b c

Fig. 2. Clamp for welding T-joints: (a) 3-D model, (b) front view, (c) side view

The laboratory test stand is designed for the development and testing of laser welding technologies for T-joint welds in steels and alloys with thicknesses ranging from 0.3 to 20.0 mm. It consists of an integrated system of interconnected electromechanical and electronic components, assemblies, and a process laser. The welding head moves along the X and Z axes. The stand consists of the following main components: a two-axis manipulator, a movable platform, a platform for mounting a clamp, as well as control and automation units (Fig. 3).

The test stand design incorporates two linear servo drives based on synchronous AC motors. The voltage applied to the motor windings is controlled by servo amplifiers (frequency converters), in which position feedback is provided by incremental encoders. The encoder shafts are rigidly connected to the motor shafts. The rated rotational speed of the motors is 50 rev/s.

In both servo drives, rotational motion is converted to linear motion using ball-screw drives with a lead of 10 mm/rev. The position and speed of both servo drives are controlled via external pulse control using the «Step/Dir» discrete interface. The «Dir» input is used to set the direction of the carriage's movement. The servo drives are configured such that when a single pulse is received at the «Step» input, the carriage moves 10 µm in the corresponding direction depending on the signal at the «Dir» input.



a b

Fig. 3. Model of the laboratory test bench (a): 1 – linear motion module along the Z-axis, 2 – linear motion module along the X-axis, 3 – welding head, 4 – clamp for fixing welding specimens, 5 – platform for moving the clamp in the XY plane, 6 – clamp with a specimen, 7 – bracket for mounting the welding head, 8 – column, 9 – fixed frame, 10 – rotary hinge mechanism; (b) Model of the laboratory stand in an inclined position

Structurally, the linear modules are mechanically connected to one another and form a three-link kinematic chain. The first link is a fixed frame that serves as the base of the entire system (item 9 in Fig. 3a) and measures 1620×650 mm; it is fabricated by welding No. 12 steel channels. The second and third links are represented by linear modules (items 1 and 2 in Fig. 3a).

The second section is connected to the first via a rotary hinge mechanism (item 10 in Fig. 3a), which allows it to be tilted from the vertical position within a range of 0° to 90° (Fig. 3b).

The inclination of the movable frame is adjusted in discrete steps at angles of 30°, 45°, 60°, and 90°, and the position is secured by side plates and M20 bolts. The side plates are mounted on the axes of the fixed frame housings. Currently, the inclination mechanism is not equipped with a servo drive, so the angle is adjusted manually. The linear module of this link is mounted on a 1650 mm high column (position 8 in Fig. 3, a), made of No. 16 steel channels.

The third link (item 2 in Fig. 3a) is rigidly mounted on the carriage of the second link. The laser head (item 3 in Fig. 3a) is mounted on the carriage of the third link using brackets (item 7 in Fig. 3a).

In the initial position, the second link is oriented vertically (Fig. 3a). In this configuration, each linear module moves the laser head along the corresponding coordinate of the Cartesian coordinate system: the second link is responsible for movement along the Z-axis, and the third link is responsible for movement along the X-axis. The travel range is 540 mm along the X-axis and 1170 mm along the Z-axis.

A personal computer running the Linux operating system is used to implement contour control. To enhance reliability, a modified real-time operating system kernel is employed, ensuring guaranteed execution times for input/output operations. The software for contour motion control allows configuring the CNC system to calculate motion trajectories and control electrical automation. The built-in interpolator enables programming of motions along linear, circular, and cubic spline segments of trajectories in two- and three-dimensional coordinate systems. Support for various interfaces, including a serial port and USB, is provided for interaction with external equipment.

The functional capabilities of the developed manufacturing equipment were evaluated during experimental studies of the laser welding process for T-joints made of stainless steels. The T-joint was fabricated from two grades of steel: the edge was made of 10Kh18N10T austenitic steel, and the shelve was made of 12Kh21N5T austenitic-ferritic steel. The work was performed using a solid-state Nd:YAG laser «DY044» manufactured by ROFIN-SINAR (Germany) with a radiation wavelength $\lambda = 1.06$ μm and a maximum laser power P = 4.4 kW. Fig. 4 shows a laboratory setup for laser welding in various spatial positions.


a b

Fig. 4. Laboratory setup for laser welding in various spatial orientations (a); (b) the process of welding T- joints

Research has shown that the best results in terms of process stability and the formation of dense welds can be achieved using the following parameters: 4.4 kW, 250 Hz, 75/25 duty cycle; -1 mm defocusing; and a welding speed of 4000 mm/min for the vertical position. In all cases, welding is recommended to be performed with argon supplied as a shielding gas at different flow rates to specific areas: 30 L/min to the weld pool; 5 L/min from below the shelve (total for both sides of the edge) to the end of the weld pool, to protect the cooling metal – 20 L/min.

Microstructural studies of the T-joint weld have shown that the weld structure is cast and dispersed (Fig. 5), consisting of fine crystallites oriented in the heat-dissipation direction.

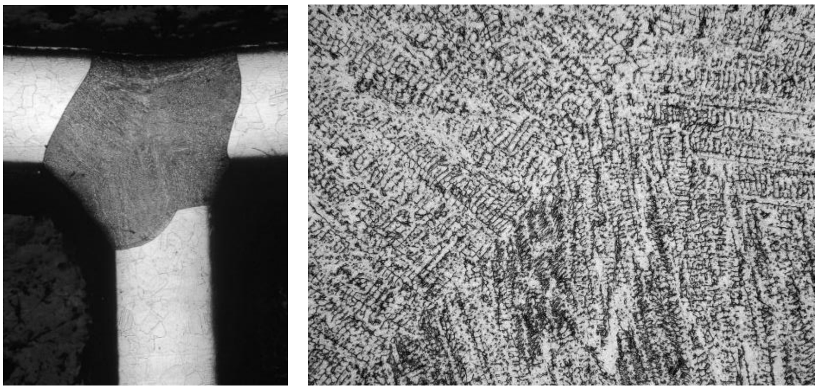

a b

Fig. 5. T-joint weld: (a) general view, ×30; (b) microstructure in the central zone of the weld, ×400

The size of the crystallites in the center of the weld and near the fusion line differs only slightly (Fig. 6). In the center of the weld, the width of the crystallites ranges from 2.5 to 7.5 μm; near the fusion line, it ranges from 2.5 to 3.5 μm, occasionally reaching 5.0 μm (shelve). The microstructure of the weld is austenitic, with a small (up to 1.5%) amount of δ-ferrite.

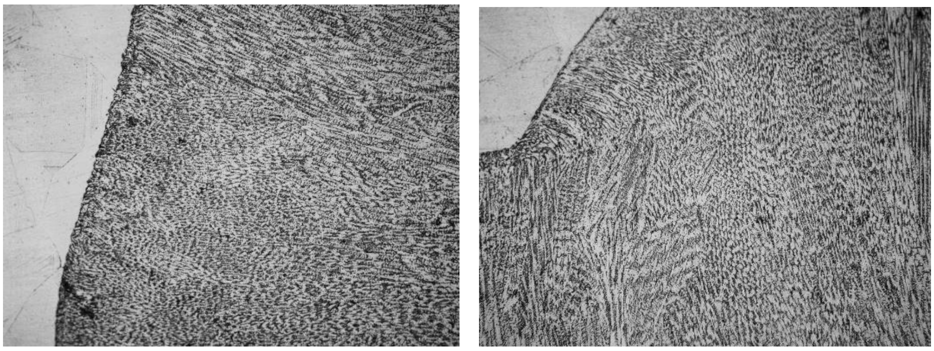

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Fig. 6. Microstructure of a welded joint near the fusion line, ×200: (a) from the shelve side; (b) from the edge side

The heat-affected zone is practically non-existent on both the rib and flange sides (Fig. 7). The microstructure consists of large austenite grains. The difference between the microstructure of the heat-affected zone and that of the base metal lies in the reduced etchability of the grain boundaries on both the rib and flange sides. The grain size of the shelve HAZ corresponds mainly to No. 3, rarely to No. 4 according to GOST 5639-82, while in the edge HAZ, the grain size is mainly No. 4. The width of the shelve HAZ is approximately 700–800 μm, and the width of the edge HAZ is 750 μm. The hardness of the metal in the shelf HAZ is HV 0.1–2640, 2740, 2740, 2800 MPa, and in the rib HAZ, HV 0.1–2450, 2740, 2330, 2280 MPa.

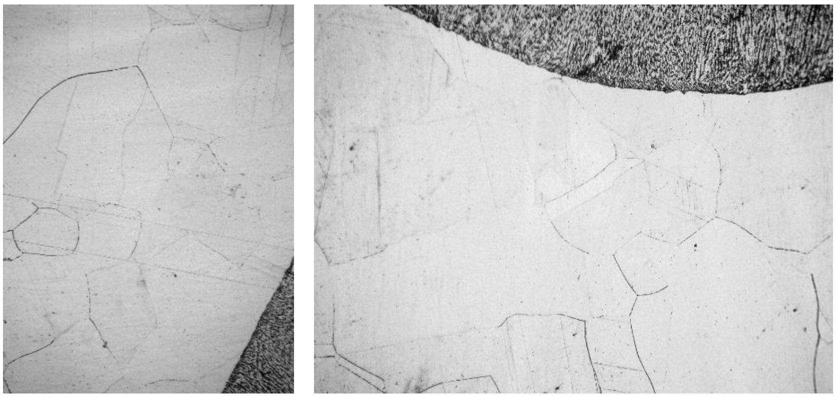
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Fig. 7. Microstructure of the heat-affected zone, ×200: (a) shelve; (b) edge

The microstructure of the base metal of the shelve at a distance of more than 5 mm from the fusion line consists of austenitic grains with twins, indicating metal deformation and the precipitation of a small amount of an excess phase along the grain boundaries (Fig. 7, a, b); this is likely δ-ferrite, since the base metal contains up to 0.3% of the α-phase. The amount of precipitates along the grain boundaries increases with distance from the fusion line (Fig. 7, c).

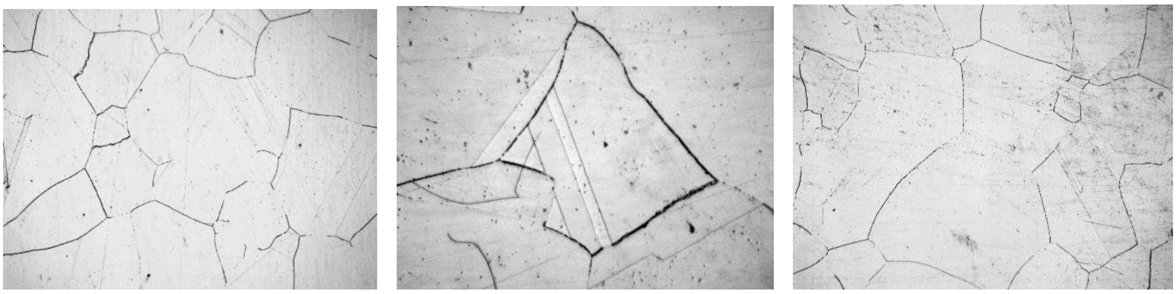
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Fig. 7. Microstructure: (a) shelve metal, ×200; (b) precipitation along the grain boundaries of the austenite in the base metal of the shelve, ×500; (c) edge metal, ×200

The strength characteristics of the T-joint weld were also determined. Five 20-mm-wide specimens were cut from the tested single T-joint weld specimen. Static tensile tests of the welded specimens were conducted on an MTS 318.25 servo-hydraulic testing machine in accordance with GOST 6996-66 on three specimens cut from the welded specimen under study. The purpose of the test was to determine the load required to fracture the specimen under static tensile loading and to identify the location of the fracture in the T-joint weld. Conditions for the static tensile tests: gauge length 40 mm, loading rate 10 mm/min, ambient temperature 20 °C.

Table 1 below presents the results of static tensile and low-cycle fatigue tests on single T-joint specimens.

Table 1. Results of static tensile and low-cycle fatigue tests on a single T-joint weld.

№	**Width, mm**	**Thickness, mm**	**Breaking force P_{max}, N**	**UTS, MPa**	**Notes Location of the damage**
1	20,0	1,1/1,2	15737	656	Along the edge
2	20,0	1,1/1,2	15586	649	Along the edge
3	20,0	1,1/1,2	14574	662	Along the seam (shelve)
4*	20,0	1,1/1,2	-		Low-cycle fatigue test with a load of 7,500 N – 50 load cycles at a frequency of 1 Hz
4	20,0	1,1/1,2	15993	667	Along the edge
5*	20,0	1,1/1,2	-		Low-cycle fatigue test with a load of 7,500 N – 50 load cycles at a frequency of 1 Hz
5	20,0	1,1/1,2	14221	592	The specimen deformed and slipped (stretched) out of the equipment

DISCUSSION OF RESEARCH RESULTS

An analysis of recent scientific publications shows that most studies in the field of laser welding focus primarily on investigating the properties of T-joint welds – their strength, microstructure, durability, and failure mechanisms – but much less frequently address the development of specialized process equipment for their fabrication [12, 13]. In contrast to this approach, the present work focuses primarily on the creation of process equipment followed by experimental verification of its functional capabilities. The developed clamp ensures reliable fixation of the T-joint elements and allows for the formation of a T-lap joints from the shelve side with simultaneous supply of shielding gas from both sides of the edge. Design features, in particular hollow housings and a system of holes for uniform gas distribution, contribute to effective protection of the weld pool and minimization of oxidation. The laboratory test bench, in turn, enables laser welding in various spatial positions thanks to the presence of a two-axis manipulator and the ability to adjust the working frame's tilt angle from 0 to 90 degrees. The use of servo drives with ball-screw drives and discrete «Step/Dir» control ensures high positioning accuracy. The experimental results obtained confirm the effectiveness of the developed equipment. Microstructural analysis revealed the formation of a fine-grained austenitic weld structure with a negligible amount of δ-ferrite, which is characteristic of the laser welding process. The HAZ width is approximately 700–800 μm, indicating a localized thermal effect. The results of mechanical tests demonstrate a sufficiently high level of strength in the welded joints, with fracture occurring both along the edge and along the weld, indicating the comparability of their strength characteristics. Thus, compared to most studies, where the main focus is on the properties of welded joints, this work demonstrates the feasibility and effectiveness of developing specialized process equipment.

CONCLUSIONS

This work has developed and manufactured auxiliary technological equipment consisting of a clamp and a laboratory test bench with a two-axis motion system. The proposed equipment enables laser welding of T-lap joints in various spatial positions, which expands the technological capabilities of the process and increases the flexibility of its application. The design solutions implemented in the clamp, in particular the system for uniform shielding gas supply and ensuring high precision of specimen alignment, contribute to the stability of the welded joint formation. The results of microstructural and mechanical studies indicate the formation of high-quality T-joint welds with a fine-grained weld structure, a limited heat-affected zone, and sufficient strength. It has been established that the resulting welded joints comply with the requirements of DSTU EN ISO 13919-1:2019 and are characterized by the highest quality level «B».

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Сіора О.В., Юрченко Ю.В., Курило В.А., Бондарєва В.І., Бернацький А.В. **Розроблення та апробація допоміжного технологічного оснащення для лазерного зварювання тонкостінних таврових з’єднань у різних просторових положеннях.**

У роботі розглянуто питання підвищення ефективності лазерного зварювання таврових з’єднань шляхом розроблення спеціалізованого технологічного оснащення. Показано, що, незважаючи на значну кількість досліджень, присвячених властивостям зварних з’єднань, питання забезпечення стабільності процесу зварювання за рахунок конструктивних рішень оснащення залишаються недостатньо вивченими. Метою роботи є створення та експериментальна перевірка технологічного оснащення для лазерного зварювання таврових з’єднань прорізним швом у різних просторових положеннях. Розроблене оснащення включає струбцину для фіксації зразків і лабораторний стенд із двокоординатною системою переміщення лазерної головки. Конструкція струбцини забезпечує точне базування елементів з’єднання, регульовану фіксацію ребра та рівномірну подачу захисного газу з обох сторін ребра. Лабораторний стенд реалізує кероване переміщення за координатами X і Z із використанням сервоприводів та кулько-гвинтових передач, що дозволяє досягти високої точності позиціювання і відтворюваності процесу. Передбачена можливість зміни просторового положення зварювання за рахунок нахилу робочої рами. Експериментальні дослідження виконано при зварюванні таврових з’єднань із корозійностійких сталей аустенітного та аустенітно-феритного класів із використанням Nd:YAG-лазера потужністю до 4,4 кВт. Проведений мікроструктурний аналіз показав формування дрібнодисперсної аустенітної структури шва з незначним вмістом δ-фериту та вузькою зоною термічного впливу. Встановлено, що геометрія шва є стабільною, а структурні характеристики рівномірні у всьому зварному з’єднанні. Результати механічних випробувань підтвердили високий рівень міцності зварних з’єднань. Отримані результати свідчать про ефективність розробленого технологічного оснащення та можливість його використання для формування якісних таврових зварних з’єднань у різних просторових положеннях, які відповідають вимогам ДСТУ EN ISO 13919-1:2019 та характеризуються найвищим рівнем якості «B».

Ключові слова: лазерне зварювання, тонкостінні вироби, таврові з’єднання, корозійностійкі сталі, просторові положення, проблеми зварювання, розробка оснащення.

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