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IMPACT OF SPATIAL POSITION IN LASER WELDING ON QUALITY LEVEL OF WELDED JOINTS OF AISI 321 STEEL

A.V. Bernatskii, V.D. Shelyagin, O.V. Siora, V.M. Sydorets and **O.M. Berdnikova**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

The objective of the study was determination of the impact of spatial position in laser welding of corrosion- heat-resistant austenitic steel AISI 321 on the microstructure and quality level of welded joints. Penetration beads were made in plates of 3 mm thickness at different angles of inclination to the horizontal plane. «Uphill» and «downhill» laser welding was performed both in the continuous and pulsed modes of laser generation. Results of visual and radiographic testing and analysis of the data of metallographic examinations were used for evaluation of quality level of the produced specimens for compliance with the requirements of valid standards. In «uphill» and «downhill» welding in the continuous mode of laser generation no inner defects in the form of cracks, pores and inclusions were found at all the angles of inclination. A tendency to increase in both the quantity as well as in the size of pores at reduction of the angle of inclination from 90 to 0° was found in «downhill» and «uphill» welding in the pulsed mode of laser generation. By the data of metallographic examinations, no significant differences were observed in the structure of welded joints made in different spatial positions on steel AISI 321 of 3 mm thickness. At different values of the angle of inclination, the microhardness and dimensions of the crystallites differ by approximately 10 %. Contrarily, the shape of welds in the produced penetration beads differs quite significantly. Dependencies of quality characteristics of welded joints of AISI 321 steel in laser welding were derived for the first time for different spatial positions. The derived dependencies provide determination of tendencies of changing the shape and quality of welded joints at the change of position or technological parameters of laser welding process. 13 Ref., 2 Tables, 6 Figures.

Keywords: laser welding; corrosion-resistant steel; heat-resistant steel: austenitic steel; technological parameters; spatial position; quality; structure; porosity

Analysis of recent investigations and publications and problem statement. The assortment of products for the power engineering, aerospace, chemical, food and other industries includes parts of both small and large sizes of corrosion- heat-resistant steels [1–3]. Their design often has a complex spatial shape with curvilinear surface profiles. Therefore, a need arises to produce different types of welded joints of such structures in different spatial positions [4–6]. In such circumstances, it is necessary not only to take into account the physical effects, accompanying welding, but also to try to use them for the benefit. For example, considering the forces of gravity and surface tension, it is possible to influence the degree of opening of the penetration channel when moving the weld pool in different directions [7]. The global trends demonstrate the ever increasing use of laser welding technologies for the manufacture of such structures [8–10]. By means of scanning, regulation of speed of movement and pulse control of laser radiation power, it is possible to impact the heat input into the treatment zone and the stability of formation of the penetration channel and the degree of absorption of radiation in the near-surface plasma [7, 11–13]. Thus, the problem arises of taking into account the abovementioned features, which should allow obtaining a set of necessary indicators of the process of laser welding in different spatial positions.

The lack of knowledge about the dependence of weld shape and the characteristics of welded joints on spatial position does not allow determining the technological parameters of laser welding, which are the most rational in terms of achieving a high quality and compliance with the requirements of valid standards.

The objective of the study was determination of the impact of spatial position in laser welding of corrosion- heat-resistant austenitic steel AISI 321 on the quality level and structure of welded joints.

Methods, object and subject of investigations. The object of investigations was the process of laser welding of AISI 321 steel in different spatial positions.

The subject of investigations is the impact of spatial position in laser welding of AISI 321 steel on the quality and structure of welded joints.

The quality level of welded joints was determined by DSTU EN ISO 13919-1:2015 «Welding. Elec-

A.V. Bernatskii — http://orcid.org/0000-0002-8050-5580, V.D. Shelyagin — http://orcid.org/0000-0001-8153-6533,
O.V. Siora — http://orcid.org/0000-0003-1927-790X, V.M. Sydorets — http://orcid.org/0000-0002-8498-4726,
O.M. Berdnikova — http://orcid.org/0000-0001-9754-9478

tron and laser beam welded joints — Requirements and recommendations on quality levels for imperfections — Part 1: Steel», according to which three levels of quality were established, which correspond to a certain range of maximum permissible sizes of defects and relate to welded joints.

The material of investigations were plates with the size of 300×100×3 mm made of corrosion-heat-resistant austenitic steel AISI 321 (analogue of 12Kh18N10T) with a tensile strength σ_t = 520–560 MPa and the following chemical composition, wt.%: up to 0.12 % C; up to 0.8 % Si; 1–2 % Mn; 10–11 % Ni; up to 0.2 % S; up to 0.035 % P; 17–19 % Cr; up to 0.6 % Ti; Fe is the remnant).

According to the experimental procedure, investigations of laser welding in different spatial positions were performed by using the laboratory bench (Figure 1), which was assembled on the base of ND: YAG-laser DY044 of the ROFIN-SINAR Company (Germany).

According to the scheme, shown in Figure 2, in the plates of AISI 321 steel the penetrations were made at different angles of inclination α to the horizontal plane of the mechanism of moving the laser head and the clamp with a specimen, namely: in the flat position; in the vertical position; at angles of 60; 45 and 30°. In all the variants (except of flat position), welding was carried out in «uphill» (Figure 2, *a*) and «downhill» (Figure 2, *b*) directions. Welding was performed in continuous and pulsed modes of laser generation at preliminary selected welding modes. The angle of incidence of laser radiation *1* on the plate *2* (Figure 2) remained unchanged at different spatial positions and amounted to 90°.

According to the results of visual, radiographic testing and metallographic examinations of the produced specimens, their quality level was evaluated for compliance with the requirements of the standard DSTU EN ISO 13919-1:2015.

Technological experiment and its results. In the continuous mode of laser generation, the technological parameters of welding process were as follows: power of laser radiation was 4.4 kW; welding speed was 100 mm/s, deepening of position of the focal plane of the lens relative to the surface of welded specimens was 1 mm; flow rate of shielding gas (argon) was 500 cm^3/s.

In the pulsed mode of laser generation, the technological parameters of welding process were as follows: maximum power of laser radiation was 4.4 kW, ratio of pulse duration and a pause (duty cycle) was 1.67; pulse repetition rate was 120 Hz; other parameters were similar to welding modes at the continuous laser generation.

Figure 1. Laboratory bench for laser welding in different spatial positions

According to the results of visual inspection of the made penetrations in the specimens of AISI 321 steel, the following was established:

● depending on the direction of movement, significant differences in appearance of the weld surface are observed, namely, in «downhill» welding during weld formation the annealing colours were not recorded, and during «uphill» welding the annealing colours were observed on the joint surface;

● splashes were fixed during the use of continuous and pulsed mode in all spatial positions, their number was minimal during penetration in the flat position, it increased slightly at an angle of inclination of 60° and in the vertical position, and the highest number of splashes was observed in laser welding at the angles of inclination of 30 and 45°;

● during «uphill» welding in a continuous mode of laser generation at all the angles of inclination, the upper bead of welded joint is formed with a slight depression and with the formation of a «comb», the height of the «comb» and the value of depression grows with the increase in the angle of inclination to the horizontal plane;

● during «downhill» welding in a continuous mode of laser generation, the upper bead of welded joint is

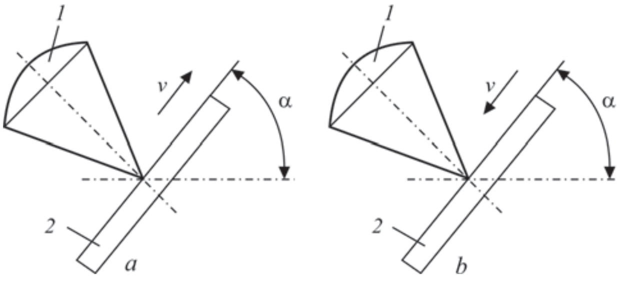


Figure 2. Schemes of making penetrations in plates during laser welding in «uphill» (*a*) and «downhill» (*b*) directions: *1* — laser radiation focused by the lens; *2* — plate; α — angle of inclination of plate to the horizontal plane

Table 1. Inner defects in the form of single pores or chain pores found during «uphill» and «downhill» welding in the pulsed mode of laser radiation

Welding direction	Angle of inclination α, °	Quantity of single pores	Chain pores/their total length, mm	Maximum size of pores, mm
Downhill	30	–	*	0.4
	45	1	–	0.3
	60	7	–	0.5
	90	–	2/25	0.5
Uphill	30	–	*	0.3
	45	–	–	–
	60	–	2/8	0.3
	90	3	–	0.3
Flat position	0	–	*	0.5

*Along the whole length of the weld.

formed with a slight depression and with a «comb» formation only at an angle of inclination of 30°.

According to the results of radiographic testing of the made penetrations, it was found that during «uphill» and «downhill» welding in a continuous mode of laser generation, at all the angles of inclination, no inner defects in the form of cracks, pores and nonmetallic inclusions were found.

Radiographic testing of penetrations, made during «uphill» and «downhill» welding in the mode of a pulsed laser generation showed the presence of inner defects in the form of single pores or chain pores at all the angles of inclination (Table 1).

In Figure 3 the macrostructure of welded joint produced in the flat spatial position during continuous laser generation is given, the microstructure of metal in the centre and on the fusion line.

The structure of weld metal in the welded joint, produced in the flat position, is dispersed and cast. In Figure 3 two zones are clearly seen: in the central part of the weld, throughout the entire height the structure is cellular-dendritic, in the middle part of the weld closer to the fusion line, a region of thin columnar crystallites is observed growing in the direction of heat removal. The zones are separated by a strip of more refined crystallites. The microstructure in the central part of the weld represents an austenitic matrix with a small amount of δ-ferrite (1.5–1.7 %). The size of cells is generally 12–13 μm. The hardness of weld metal of the welded joint in the central part is *HV*1–2950–3090 MPa, there are areas where the hardness increases to *HV*1–3200–3380 MPa. In the lower part of the weld, the hardness increases to *HV*1–3320–3650 MPa. On the fusion line of the welded joint, the microstructure also contains austenite and δ-ferrite, it is more refined than in the center of the weld. The width of crystallites is 2–9 μm. The hardness of the metal on the fusion line of the welded joint is *HV*1–2990–3030 MPa. There are separate areas where the hardness increases to *HV*1–3160 MPa. In the weld metal nitrides (in a small quantity) and single slag inclusions are observed. The heat-affected-zone (HAZ) is not distinct, its structure contains austenite, the grain size number in the HAZ of welded joint is No.6. The hardness of the HAZ of welded joint is *HV*1–2650–2840 MPa.

As metallographic examinations showed, there are no significant differences in the structure of welded joints produced at different spatial positions in AISI 321 steel of 3 mm thickness. At different angle of inclination, the values of microhardness in the respective zones, sizes of crystallites, grain size number in the HAZ of welded joint differ by about 10 %. Contrarily, the shape of the resulting penetrations changes quite substantially, as is seen from Table 2.

Discussion of the obtained results. The analysis of X-ray patterns (Figure 4) shows a tendency to increase both the quantity as well as the size of pores in the specimens of AISI 321 steel at the reduction of angle of inclination from 90 to 0° during «downhill» and «uphill» welding in the pulsed mode of laser generation. The small values of a total pores projection during welding with the use of a continuous laser radiation and at the angles of 0 and 90° in the pulsed mode of welding should be noted. At the same time, it is worth noting the tendency of reducing the quantity and size of single pores (or the length of pore chains) during «uphill» welding as compared to «downhill» welding mode at the same angle during the pulsed mode of laser generation.

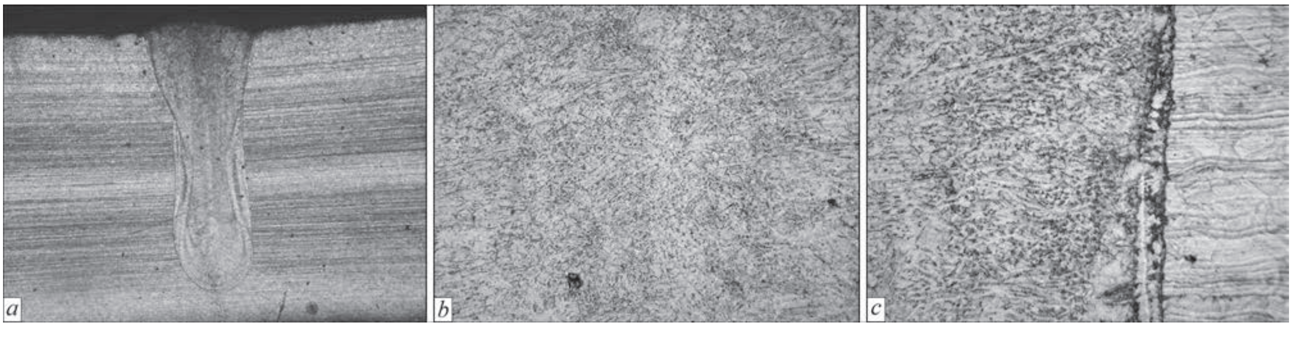


Figure 3. Structure of welded joint metal, made in the flat position: *a* — cross-section of the weld, ×30; *b* — center of the weld, ×400; *c* — fusion line, ×400

Table 2. Shapes of penetrations in the plates of AISI 321 steel with angles of inclination to the horizontal plane from 90° to 0° in laser «downhill» and «uphill» welding with different modes of laser radiation

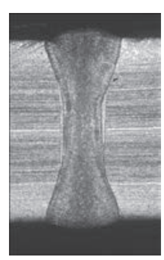
Welding direction	Angle of inclination, °	Pulsed mode	Continuous mode
		Shape of penetration, magnification	
Downhill	30	 ×40	 ×50
	45	 ×40	 ×25
	60	 ×30	 ×25
	90	 ×50	 ×40
Uphill	30	 ×50	 ×30
	45	 ×40	 ×30

Table 2. Cont.

Welding direction	Angle of inclination, °	Pulsed mode	Continuous mode
		Shape of penetration, magnification	
Uphill	60	 ×25	 ×25
	90	 ×50	 ×30
Flat position	0	 ×50	 ×30

According to the requirements of DSTU EN ISO 13919-1:2015, in order to obtain the highest level of quality «B», the value of the total projection of pores for welded joints of AISI 321 steel of 3 mm thickness, produced by laser welding in different spatial positions, should not exceed the value of 0.7 %. The analysis of the obtained data allows confirming, that according to this index all the produced welds meet the specified requirements.

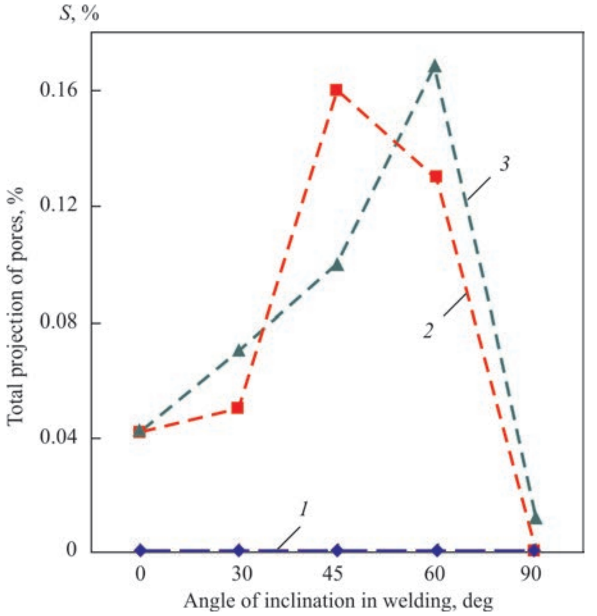


Figure 4. Dependence of total area of projections of pores on parameters of modes of laser welding of AISI 321 steel 3 mm thick, produced in different spatial positions: *1* — continuous mode; *2* — pulsed «uphill» mode; *3* — pulsed «downhill» mode

It was established that dependence of the penetration area on the angle of inclination at its increase from 0 to 90° has a nonmonotonic nature both during «downhill» as well as in «uphill» welding regardless of the mode of laser radiation (Figure 5). It was established that the maximum values of penetration area in all the modes are observed at an angle of inclination of 45°. This phenomenon can be explained by a change in the character of flows in the melt pool, as well as by a change in the degree of impact of gas protection in the welding zone. However, to formulate the final conclusions, this phenomenon requires an additional comprehensive study.

It should be noted that for the dependences of cross-sectional area in the welds of welded joints of AISI 321 steel of 3 mm thickness, produced by laser welding in different spatial positions (Figure 5), it was characteristic that in a continuous «uphill» mode, the value of cross-sectional area of welded joints at different angles of welding differs by not more than 1.31 times. Whereas during «downhill» welding in a continuous mode of laser radiation, the maximum and minimum values of dependences differ by almost 2.1 times (Figure 6). In this case, the maximum cross-sectional areas of the welds produced during «downhill» and «uphill» welding at an angle of inclination of 45° in the continuous mode of laser generation differ by almost 1.5 times. Obviously, this occurs due to a longer stay of welded joint metal at the temperatures higher than the melting point. This leads to an increase in the volume of molten metal pool and, as a result, the welded joint area. It was established that when the mode of laser generation is changed from a continuous to a pulsed one at an angle of inclination of welding of 45°, the tendency of significant increase in the penetration area is absent.

During welding in different spatial positions using the pulsed laser generation mode, the indicated data on the cross-sectional area of welds differ significantly (see Figure 5). Thus, in both pulsed «uphill» and «downhill» welding, the maximum and minimum values of cross-sectional area of welds differ by about 2.5 times for the angles of 0 and 45° (Figure 5). In this case, the cross-sectional areas of welded joints produced during «downhill» and «uphill» welding at the same welding angles in the pulsed mode of laser generation differ by less than 5 %.

Figure 6 shows the dependence of the weld height in different spatial positions on the angle of inclination. The same as for the penetration area, the nature of dependencies is nonmonotonic. However, the difference in the values obtained for «uphill» and «downhill» welding for the vast majority of reference points does not exceed 15 % at one and the same laser generation mode. An interesting fact is that the highest values are observed during welding at an angle of inclination of 45° in the pulsed «downhill» and continuous «uphill» modes (Figure 6). Whereas during welding in a continuous «downhill» and «uphill» pulsed modes, the maximum values are obtained at an angle of inclination of 60°. The values, exceeding the thickness of 3.0 mm in the plates to be welded, are explained by the formation of upper and lower beads of a welded joint at a full penetration of specimens. It is worth noting, that the change in the weld height in the joints of AISI 321 steel with a thickness of 3 mm when changing the angle of inclination during laser welding at a continuous «uphill» mode does not exceed 22 %. Whereas during «downhill» welding in the continuous mode of laser generation, this value amounts to 27 %, and when changing the generation mode into a pulsed one, it approaches to 100 %.

The analysis of the results of investigations performed on the plates and described above made it possible to make a scientifically grounded choice of spatial positions and to select the technological parameters on which it is planned to produce reference butt joints of AISI 321 steel of 3.0 mm thickness. During the choice of spatial positions, the following indices were taken into account: achievement of the maximum penetration depth; quality welded joint formation; absence (or minimum number of splashes); absence (or minimum value) of weld depression; absence (or minimum height) of the «comb» of the upper bead. Based on the mentioned provisions, the flat and vertical spatial positions were selected as the most promising for producing butt welded joints that meet the requirements to the highest quality level «B» according to DSTU EN ISO 13919-1:2015.

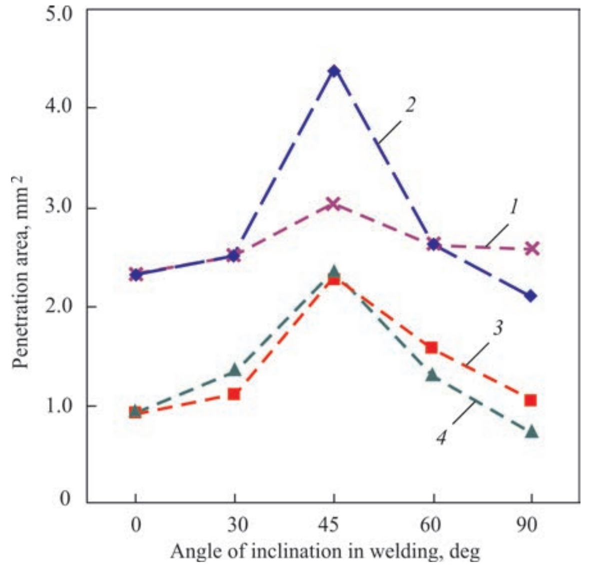


Figure 5. Dependence of cross-sectional area of welds in joints of AISI 321 steel 3 mm thick, produced by laser welding in different spatial positions, from the angle of inclination: *1* — continuous «uphill» mode; *2* — continuous «downhill» mode; *3* — pulsed «uphill» mode; *4* — pulsed «downhill» mode

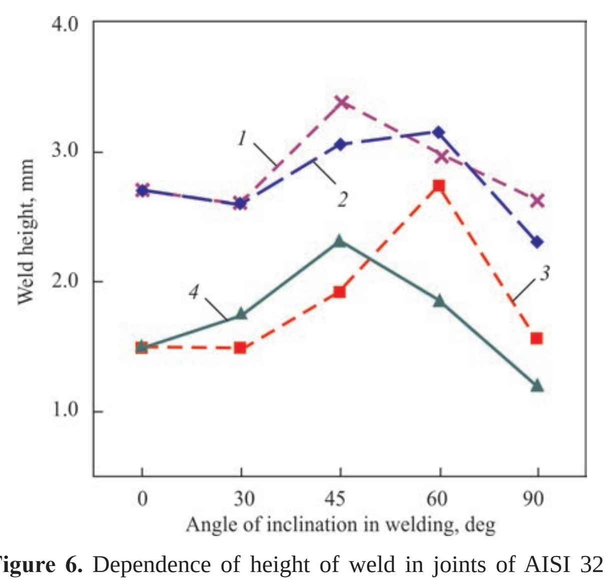


Figure 6. Dependence of height of weld in joints of AISI 321 steel 3 mm thick, produced by laser welding in different spatial positions, from the angle of inclination: *1* — continuous «uphill» mode; *2* — continuous «downhill» mode; *3* — pulsed «uphill» mode; *4* — pulsed «downhill» mode

Conclusions

The spatial position of corrosion- heat-resistant austenitic steel AISI 321in laser welding has a radical impact on the quality level and structure of welded joints.

Reducing the angle of inclination from 90 to 0° during «downhill» and «uphill» welding in the pulsed mode of laser generation leads to increase in both the quantity of pores as well as in their size, whereas in the continuous mode of laser generation, defects in the form of pores are not observed.

In laser welding of butt joints of AISI 321 steel, the most promising are flat and vertical spatial positions, such as those that provide the highest level of quality.

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