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FEATURES OF LASER-PLASMA WELDING OF CORROSION-RESISTANT STEEL AISI 304 WITH LASER APPLICATION

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ABSTRACT

The paper confirms the presence of synergistic effect at laser-plasma welding, using fiber laser, by comparing the cross-sectional areas of penetrations, made in AISI 304 plate (δ = 4 mm) by laser, plasma, and hybrid processes at close power values of laser radiation and plasma arc (~2 kW each). It is determined that the manifestation of this effect depends on welding speed. At the speed of 2 m/min the hybrid penetration cross-sectional area can exceed the sum of areas of penetrations produced with the laser and plasma processes by up to 30 %, and for the speed of 4 m/min by ~20 %. Comparison of input energy of the laser and hybrid processes of stainless steel welding showed that the difference between them depends on the welded sheet thickness (or penetration depth). This value first decreases from ~100 % for sheets with δ = 2 mm to 50 % for sheets with δ = 6 mm, and at further increase of penetration depth it rises to 60 %. The nature of dependencies of the factor of area ratio φ, weld geometry K and penetration depth Φ on the speed of hybrid welding of AISI 304 steel allows recommending the range of speeds of 1.5–2.0 m/min, as a more acceptable one by the criteria of synergistic effect and penetration depth. It is found that at hybrid welding with application of fiber laser radiation, the plasma component promotes elimination of such defects of weld upper bead formation, characteristic for laser welding, as undercuts and a ridge, etc.

KEY WORDS: hybrid laser-plasma welding, fiber laser, stainless steel, synergistic effect, penetration depth, energy input

INTRODUCTION

Partial (up to 50 %) replacement of laser power by arc power in the hybrid laser-plasma process at preservation of relatively small width of the welds can make such a welding process quite attractive for a range of industrial tasks [1]. One of such tasks can be, for instance, welding of aluminium panels for railway carriages and boats, as well as stainless pipes for pipelines [2]. Due to a considerable lowering of equipment cost, it can successfully compete with laser welding, which is becoming ever wider applied now. Owing to increase of thermal locality and minimization of residual deformations, compared to the known arc welding processes, laser-plasma welding can be used for fabrication of structures from sheet materials up to 6 mm and greater thickness. Such a task is urgent, in particular, for welding stainless steels in fabrication of structures for chemical and food industries [3].

Hybrid processes of laser-arc welding attract specialists because of a range of such advantages as presence of the synergistic effect, which helps reducing the welding energy input, lowering of the requirements to edge preparation for welding, modification of the thermal cycle, which promotes elimination of hardening structures and improvement of the joint ductility, etc. [4]. At such a type of welding the arc is stabilized by the presence of focused laser radiation. However, different wave lengths of laser radiation initiate different mechanisms of arc stabilization, leading to a difference in the obtained results. This is related to a considerable dependence of total absorption rate κ_ω of laser radiation in arc plasma on its wave length λ.

In work [5] it was revealed that the stabilizing effect of the action of Nd:YAG-laser radiation is attributable to two phenomena: laser energy absorption by the arc plasma and change of arc plasma composition, caused by strong evaporation of the blank material. Both the phenomena lead to lowering of effective potential of plasma ionization and, thus, ensure higher conductivity and stability of the plasma channel. It stabilizes the arc column, promotes overcoming the disturbances caused by external forces, and improves formation of the weld root. In work [6] it is noted that at application of short wave ($\lambda \approx 1$ μm) radiation of solid-state (Nd:YAG) or fiber lasers in the hybrid process the laser beam absorption in arc plasma is negligible ($\kappa_\omega \approx 1$ m^{-1}). In this case, intensive evaporation of metal from the weld pool surface takes place un-

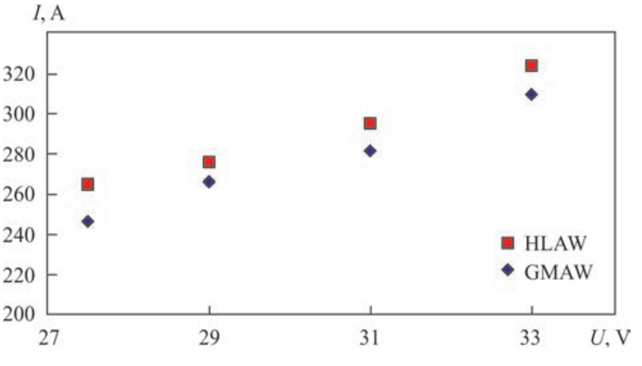

Figure 1. Dependence of welding current on applied voltage for feeding Mn4Ni2CrMo wire (1.2 mm diameter) in the case of hybrid (HLAW) and arc (GMAW) [8]

der the impact of highly-concentrated source of laser heating, which has a significant influence on the composition, heat, gas-dynamic and electromagnetic characteristics of the arc plasma and, consequently, leads to the change of its thermal and dynamic interaction with the metal being welded.

At application of CO_2-laser radiation ($\lambda = 10.6$ μm) in the hybrid processes both the interaction mechanisms are significant, namely: laser radiation absorption in arc column plasma ($\kappa_\omega \sim 100$ m^{-1} [6]) and metal evaporation from the melt surface under the impact of a focused laser beam. In work [7] it is shown that the interaction of a focused beam of CO_2-laser radiation with argon arc plasma with a refractory cathode leads to a certain reduction of radiation power, which reaches the surface of the anode (part being welded), as a result of partial absorption of laser radiation in the arc column plasma. Here, beam refraction in non-uniform arc plasma is negligible. Power applied to the metal being welded by the laser beam in hybrid (CO_2-laser + TIG) welding, can be both greater and smaller than the power introduced into the metal at laser welding, depending on the conditions of absorption of laser radiation, reaching the metal surface. For instance, formation of a vapour-gas channel in the weld pool promotes a more effective absorption of laser radiation, than the comparatively flat surface of the melt.

Increase of the fraction of effective (i.e. acting on the part) laser power in hybrid welding using CO_2-laser ($\lambda = 10.6$ μm) can be achieved due to a high content of helium in the welding (shielding) gas. It promotes avoiding plasma formation in the weld pool zone, absorbing the laser radiation. High-speed CCTV showed that radiation with wave length $\lambda \approx 1$ μm (Nd:YAG-, disc, fiber lasers) does not affect the electric arc similar to the case of CO_2-laser ($\lambda = 10.6$ μm) [8]. It allows application of standard gas mixtures (Ar/CO_2) and simplifies selection of parameters of the hybrid process arc component. So, in work [8] it is stated that standard GMAW parameters can be used in the hybrid process without essential correction. Figure 1 shows the effect of addition of 3 kW laser power to the standard consumable-electrode arc. In the experiment a bead was deposited on low-alloyed carbon steel plate at 1 m/min speed by Mn4Ni2CrMo wire (1.2 mm diameter), which was fed with the speed of 9 m/min at arc voltage of 27.5–33.0 V with shielding by 98%Ar+2%CO_2 gas mixture. High-speed video showed that in case of adding 3 KW fiber laser radiation, the arc looks somewhat shorter and a certain disturbance of gas shielding takes place. This disturbance is caused by release of vapor, coming out of the weld pool vapour-gas channel, and which consists both of addition of the metal vapour, and in mixing with oxygen in ambient air. Although the impact of this violation on the shielding gas properties is small, it lowers the welding current by 4–7 % during hybrid welding, compared to pure GMAW.

In work [9] it was determined that the change of arc voltage is associated with the type of laser radiation, used in hybrid welding. Application of CO_2-laser is accompanied by greater impact on the change of arc voltage, characterized by its drop (Figure 2). It was also established that increase of laser power greatly facilitates the change of voltage. At application of radiation of CO_2- and ND:YAG-lasers a practically same increase of the cross-sectional area of

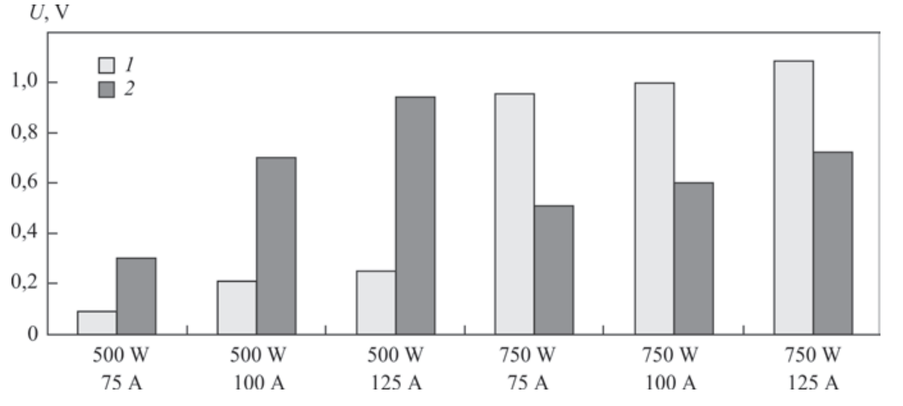

Figure 2. Difference in voltage at constant laser power [9]: *1* — CO_2-laser-TIG hybrid; *2* — Yb:YAG-laser-TIG hybrid

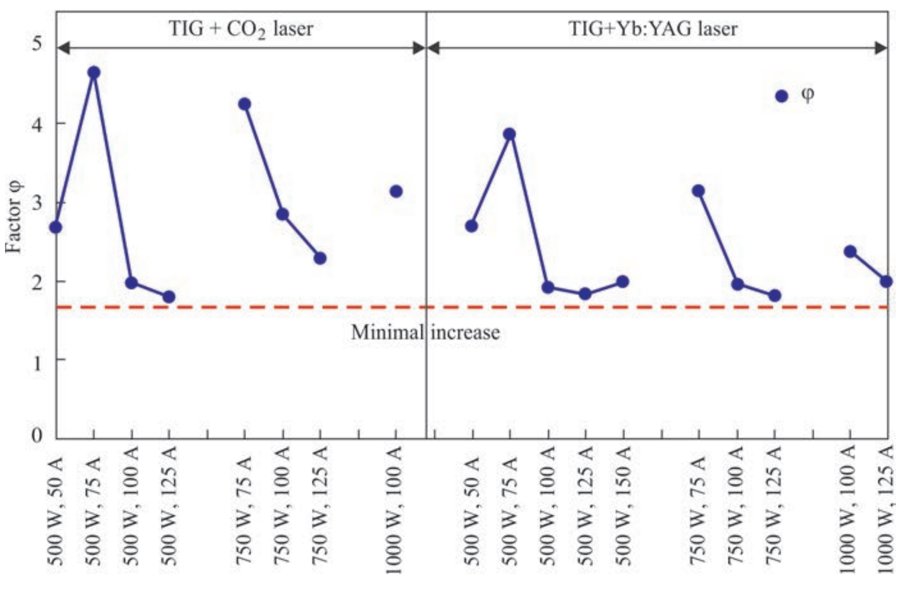

Figure 3. Factor $\varphi = \frac{A_H}{A_T + A_L}$ as the ratio of cross-sectional area of hybrid penetration A_H to the sum of individual cross-sectional areas of TIG (A_T) and laser (A_L) penetrations [9]

penetration at hybrid welding is observed — at least by 1.8 times, compared to the sum of separate areas of the laser and arc (TIG) penetrations (Figure 3). Moreover, it is stated that laser radiation promotes better weld formation (Figure 4).

In recent years, fiber and disc lasers became accepted by industry. Application of CO_2-lasers is rather limited, predominantly for cutting (so-called slit lasers) [10]. Fiber and disc lasers also prevail in hybrid welding processes. Mostly MIG/GMAW, more seldom TIG torches are used as an arc source in such processes. In the opinion of the authors, however, application of a plasma source will allow improving the total efficiency of hybrid welding, due to constriction of the nonconsumable electrode arc. Moreover, the laser-plasma process will allow avoiding the need for edge preparation, which is applied in hybrid welding of more than 5 mm thick steel sheets [11]. Therefore, a process combining welding by fiber laser radiation with plasma welding is of interest for research.

The objective of this work is investigation of the features of laser-plasma welding of up to 10 mm stainless steel, using fiber laser radiation in the mode of deep penetration of square edges.

In order to achieve this objective, the following problems were solved:

1) selection of the modes of laser, plasma and hybrid welding of stainless steel by the criteria of the quality of weld formation without edge preparation;

2) comparison of the cross-sectional areas of penetrations, made by the three studied processes, to determine the presence of the synergistic effect;

3) comparison of energy inputs of the laser and hybrid processes of stainless steel welding;

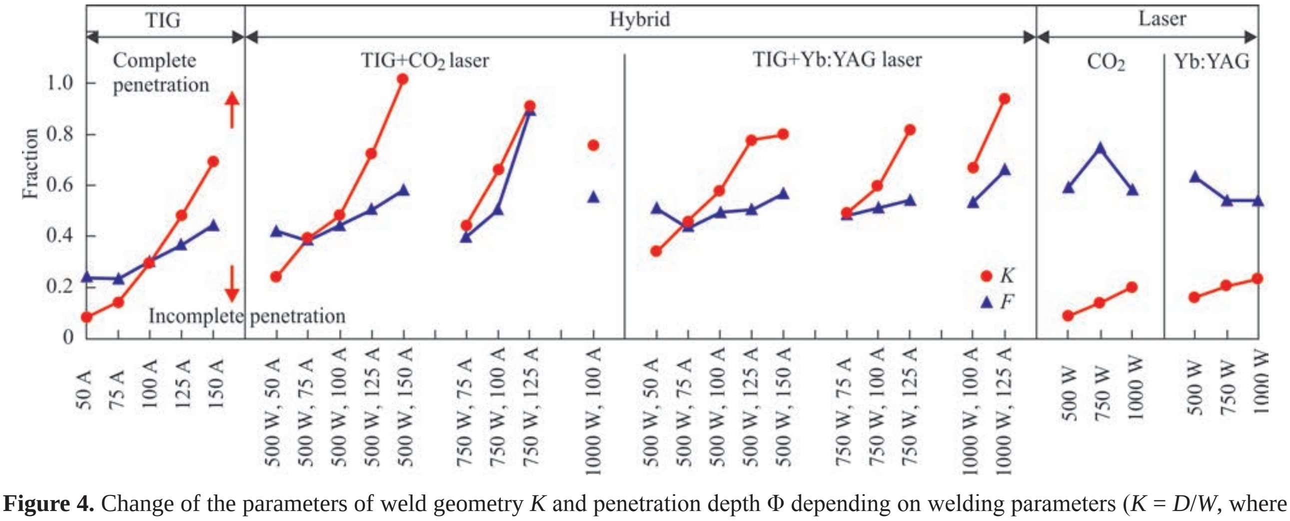

Figure 4. Change of the parameters of weld geometry K and penetration depth Φ depending on welding parameters ($K = D/W$, where D is the penetration depth; W is the weld width; $\Phi = D/T$, where D is the penetration depth; T is the blank thickness) [9]

Table 1. Chemical composition of AISI 304 steel sheets used in studies

Fe	C	Si	Mn	Cr	Ni	Ti	Cu	S	P
Base	≤0.8	≤0.8	≤0.2	17.0–19.0	9.0–11.0	≤0.5	≤0.3	≤0.02	≤0.035

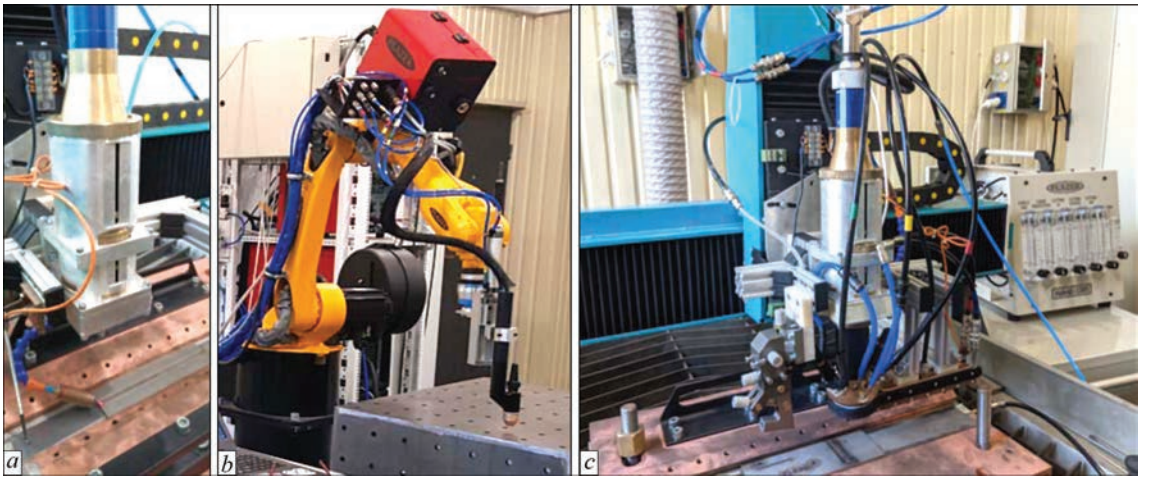

Figure 5. Appearance of laboratory stands for conducting technological studies on welding: *a* — laser; *b* — plasma; *c* — hybrid

4) optimization of hybrid welding mode by the parameters of the ratio of penetration areas and weld geometry;

5) determination of the difference in application of fiber laser radiation from application of the diode, Nd:YAG- and CO_2-lasers.

Sheets of 100×50×δ mm to 300×100×δ mm size from stainless steel AISI 304 of thickness δ = 2, 4, 6 and 10 mm (Table 1) were used as the sample material. Welding was performed in argon shielding (flow rate of ~30 l/min). Argon was also used as plasma gas.

A laboratory stand was built to perform the experiments, which was fitted with the heads for laser, plasma and hybrid welding (Figure 5). At the first stage of studies, investigations were performed to compare the influence of lateral and coaxial methods of shielding gas feeding on the produced penetration depth in welding by fiber laser radiation. These investigations showed comparatively close results, which is indicative of a low level of radiation losses in the plasma flame, forming above the weld pool.

More over, at the same stage of the study the main technological parameters of butt welding of AISI 304 steel samples by laser and plasma processes were established. The welding speeds and heat source powers, at which sound formation of butt welded joints is observed, were determined experimentally (Table 2). It was also established that in laser welding of up to 6 mm thick sheets application of filler wire to improve formation of the upper bead and weld root is not mandatory. However, with increase of welded sheet thickness the upper bead formation can become worse, because of undercut appearance.

Table 2. Comparison of the effectiveness of different processes of AISI 304 steel welding by energy input criterion (*E*, J/mm)

No	Welding process/ number of passes	Sheet thickness δ, mm	Power *P* ($P_{las} + P_{pl}$), kW	Current I, A	Arc voltage *U*, V	Welding speed, *V*, m/min	$E_{las} + E_{pl}$, J/mm	E_{Σ}, J/mm
1	Laser/1	2	0.8	–	–	1.0	36	36
2	Plasma/1	2	2.2	80	28	0.3	336	336
3	Hybrid/1	2	0.8 + 2.2	80	28	1.5	24 + 68	92
4	Laser/1	4	1.6	–	–	1.0	72	72
5	Hybrid/1	4	1.6 + 2.2	80	28	1.5	48 + 66	114
6	Hybrid/1	4	1.5 + 2.9	95	30	1.5	45 + 87	132
7	Hybrid/1	4	1.8 + 2.0	83	25	1.5	54 + 60	114
8	Laser/1	6	1.8	–	–	0.8	104	104
9	Hybrid/1	6	1.8 + 2.0	80	25	1.2	71 + 82	153
10	Laser/2	10	1.8	–	–	0.75	108·2	108·2
11	Hybrid/2	10	1.8 + 2.0	80	25	1.0	(81+90)·2	171·2

At the second stage of the study, experiments on hybrid welding were performed in the range of speeds of 0.25–4.0 m/min at up to 2 kW laser power and up to 100 A welding current. A directly proportional influence of laser radiation power on the penetration depth and of plasma power on its width was established. In addition, plasma component of the hybrid process promoted better formation of upper bead of the welds and eliminated the danger of undercut appearance in welding sheets of 4–10 mm thickness (Figure 6). It allows achieving sound weld formation in the entire range of the studied thicknesses without filler wire application.

At the third stage of the study, presence of a synergistic effect was found, which is usually characteristic for hybrid laser-plasma welding. For this purpose, the cross-sectional planes of penetrations, made in AISI 304 sheet ($\delta = 4$ mm) by the three studied processes at the speeds of 2 and 4 m/min were measured and compared (Figure 7). Here, the energy parameters of each of these processes were unchanged and equal to: radiation power $P = 1.6$ kW, welding current $I = 80$ A at arc voltage of 24 V. Cross-sectional area $S1$ of hybrid penetration was compared with the sum of planes $S2$ and $S3$ of the laser and plasma penetrations. In the case of welding at the speed of 4 m/min, the plasma process practically did not produce any penetration. It was established that at the speed of 2 m/min area $S1 = 3.121$ mm^2 of hybrid penetration exceeds the sum of planes $S2 + S3 = 2.383 + 0.046$ mm^2 by almost 30 %, and at the speed of 4 m/min (hybrid — 1.653 mm^2, laser — 1.32 mm^2, no penetration in plasma process) by ~20 %. This is indicative of the indubitable presence of the synergistic effect at hybrid welding.

For comparison of the effectiveness of the studied laser, plasma and hybrid welding processes the values

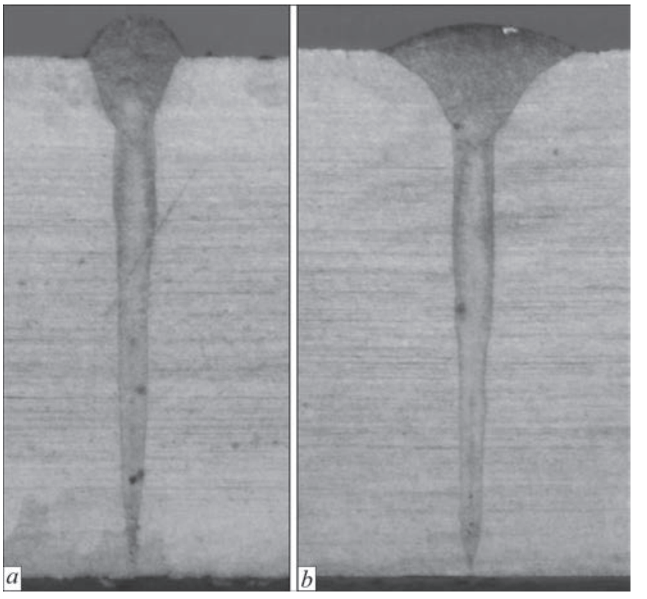

Figure 6. Transverse sections of penetrations in AISI 304 sheet ($\delta = 4$ mm) made by laser (*a*) and hybrid (*b*) processes at the speed of 4 m/min

of their energy inputs E_{las}, E_{pl}, and E_{Σ}, J/mm were used. These values were defined as the ratio of welding source power to welding speed, multiplied by the respective process efficiency. The efficiency values were taken from the recommendations in published sources. So, the efficiency of welding stainless steel by fiber laser radiation is equal to 75 % [12, 13]. The efficiency of plasma welding can be selected in a similar fashion [14]. It is anticipated that the efficiency of laser-plasma welding should equal to approximately 75 %. This is confirmed by investigations of the authors of [15]. The data, entered into Table 2, were derived, proceeding from the performed studies and given values of total efficiency of the above-mentioned processes.

Performed investigations showed that in welding 2 mm samples the process is predominantly heat con-

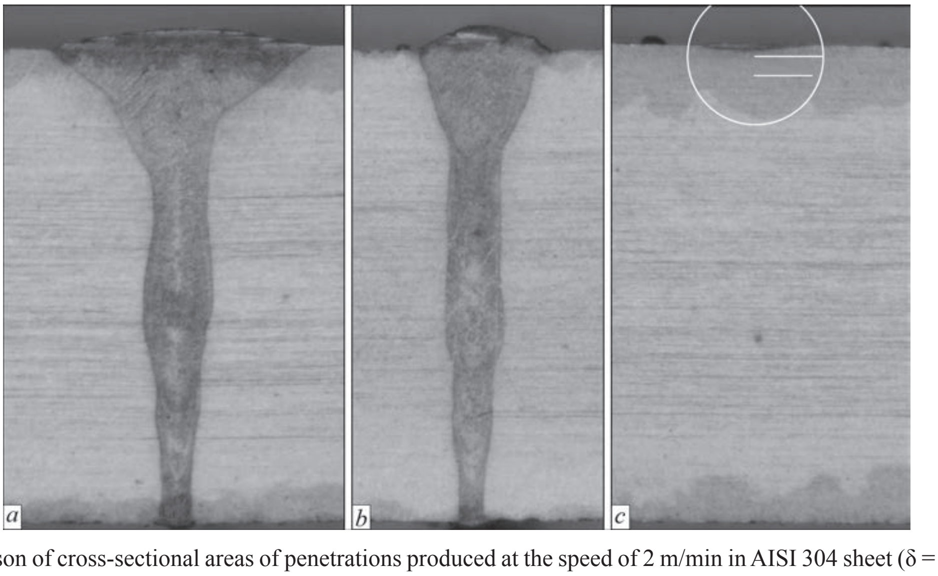

Figure 7. Comparison of cross-sectional areas of penetrations produced at the speed of 2 m/min in AISI 304 sheet ($\delta = 4$ mm) by hybrid (*a*), laser (*b*) and plasma (*c*) processes

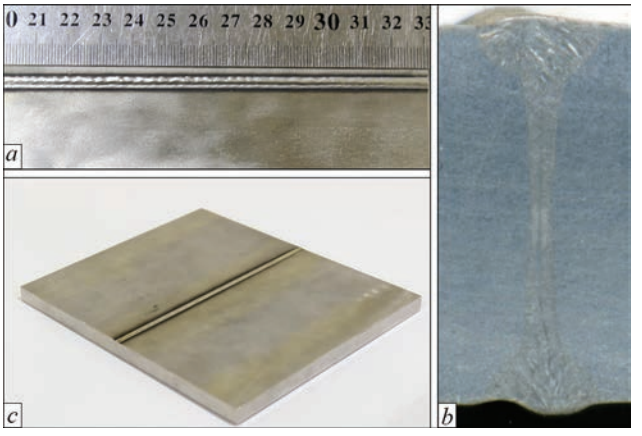

Figure 8. Two-pass hybrid welding of AISI 304 sheets (δ = = 10 mm): *a* — weld appearance; *b* — transverse section; *c* — welded joint appearance

ducting, and does not require the presence of filler materials. At increase of the sample thickness up to 4 mm and higher, weld formation goes into the keyhole mode. In order to increase the penetration depth, attempts were made to lower the welding speed. Penetration of AISI 304 sheet of thickness δ = 10 mm with radiation power of 2.0 kW allowed reaching a depth of the order of 7–8 mm at laser and 8 mm at the hybrid process in the case of 0.45 m/min speed. In both the cases, further lowering of welding speed from 0.45 to 0.25 m/min did not lead to deeper penetration. Therefore, in order to produce a butt joint of sheets of thickness δ = 10 mm, two-pass welding was used, which was made from two sides with weld root overlapping (Figure 8). Further static rupture tests of the welded samples showed that strength of the joints produced by hybrid welding is on the level of 95 % of base metal strength.

At the last fourth stage of studies comparison of input energies of the laser and hybrid processes of stainless steel welding was performed. It showed that the difference between them somewhat decreases with increase of the welded sample thickness. So, in welding AISI 304 of thickness δ = 2 mm the difference in energy input of the hybrid process is approximately two times higher than that of the laser process (Table 2, modes No.1 and No.3), for δ = 4 mm this difference is equal to approximately 60 % (Table 2, modes No.6 and No.7), and for δ = 6 mm it is on the level of 50 % (Table 2, modes No.10 and No.11). Further increase of penetration depth (for instance, to 8 mm) leads to increase of this difference to 60 % (Figure 9). This can be partially related to transition from the heat conductivity process of welding samples of thickness δ = 2 mm to the keyhole process, characteristic for greater thicknesses.

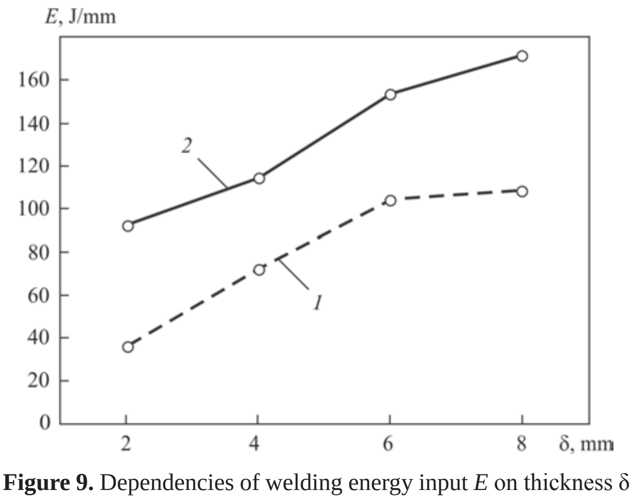

Figure 9. Dependencies of welding energy input *E* on thickness δ of AISI 304 steel sample: *1* — laser welding; *2* — hybrid welding

On the whole, investigation of laser-plasma welding leads to the conclusion that the impact of plasma is predominantly reduced to the following: heating of the surface of the metal being welded, remelting of the weld upper part, improvement of upper bead formation. In its turn, plasma heating of the surface of the metal being welded, promotes improvement of the absorption coefficient of laser radiation that improves the effective efficiency of welding [16]. The impact of fiber laser radiation in the hybrid laser-plasma process is reduced to ensuring a certain penetration depth and root bead formation. Investigations show that both at laser, and at laser-plasma welding fixed laser power allows reaching a fixed penetration depth. Here, speed lowering below a certain threshold, does not allow increasing this depth. To increase it, it is necessary to raise the laser power. Formation of the welded joint root bead in the hybrid process is somewhat improved, compared to the laser process, primarily due to increase of the energy input.

In the case of the hybrid process with mode parameters P = 1.8 kW, I = 80 A; U = 25 V at application of fiber laser, graphs of the dependencies of weld geometry parameters on welding speed V, recommended in work [9], were plotted (Figure 10). The shape of these dependencies allows stating that increase of welding speed from 1.5 to 2.0 m/min is rational. Further increase of speed somewhat impairs the synergistic effect from the hybrid process. However, at continuous raising of the speed to 4.0 m/min an increase of the weld geometry parameter K is observed**,** even though it is not as intensive, as before, and decrease of factor φ is not too rapid. It allows stating that in the considered case of laser-plasma welding, the range of speeds of 1.5–2.0 m/min is the most favourable.

Comparison of the above-given data with the earlier obtained results of laser-plasma welding using diode and CO_2-laser radiation (for instance, [17]) shows the following. Diode laser radiation was focused into a spot of rather large diameter (~1.0 mm) so that its power density was up to $2.5\cdot10^5$ W/cm^2. A smaller diameter of the radiation focal spot of a fiber laser (of the order of 0.05 mm) allows reaching a higher power density (up to 10^8 W/cm^2) and much greater penetration depth, compared to the diode laser. In all the other aspects, the effect of both the types of laser radiation on the hybrid process is similar. A similar situation was observed in the case of application of Nd:YAG-laser radiation, which was focused into a 0.4 mm spot (power density up to $3.5\cdot10^6$ W/cm^2). Reduction of penetration depth, both at laser, and at hybrid welding by Nd:YAG-laser radiation is also promoted by a smaller radiation absorption coefficient (close to 50 %, in keeping with [18]).

In the case of application of CO_2-laser radiation, a fundamentally different mechanism of its impact on the hybrid process is in place. A significant part of such radiation is absorbed by the plasma component of the laser-plasma process, overheats it, directs it to the point of impact on the part being welded and provides the simultaneous action of the two heat sources. Due to that, the synergistic effect of the laser-plasma process at application of CO_2-laser radiation is more pronounced and increases the cross-sectional area of the welds up to 50 %, compared to the sum of the planes of welds produced by the laser and plasma components separately. However, due to smaller values of radiation power density (up to 10^7 W/cm^2) and its absorption coefficient (on the level of 20–40 % according to [19]), the penetration depth is smaller, compared to application of the fiber laser, both in laser, and in hybrid welding.

Investigations showed that in the case of close values of energy, applied to the samples being welded (radiation and plasma powers of ~2 kW each at process speed of the order of 1.5 m/min), application of diode laser radiation in the hybrid process allows welding stainless steel sheets of ~2 mm thickness, application of Nd:YAG laser — up to 3.5 mm, for CO_2-lasers it is ~3 mm, while application of a fiber laser allows joining more than 4 mm (tentatively 5 mm). In the case of laser welding at the same speed at 2 kW power the penetration depths will be equal to: for diode laser radiation – up to 1 mm, for Nd:YAG-laser — up to 3 mm, for CO_2-laser — up to 2 mm, and for fiber laser — more than 4 mm (tentatively 4.8 mm). It can be stated that application of the radiation of diode, Nd:YAG-, CO_2- and fiber lasers, allowing for the difference in power density and absorption coefficients in laser-plasma welding, increases the penetration depths by 100, 15, 33 and 4 %, respectively, compared to their laser welding. Here, the effectiveness of application of a fiber laser in the hybrid process exceeds the effectiveness of diode laser application by 60 %, Nd:YAG-laser — by 30 %,

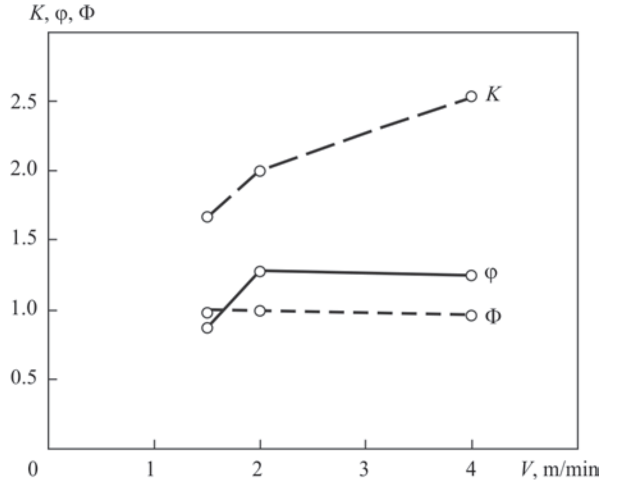

Figure 10. Dependence of factor of plane ratio φ, weld geometry *K* and penetration depth Φ on speed *V* of hybrid welding of AISI 04 steel

CO_2-laser — by 40 %. Therefore, the general result of application of fiber laser radiation in laser-plasma welding can be regarded as the most effective in terms of penetration depth and improvement of the process effective efficiency.

CONCLUSIONS

1. Presence of the synergistic effect on laser-plasma welding with fiber laser application was confirmed by comparing the cross-sectional areas of penetrations made in a sheet of stainless steel of AISI 304 grade (δ = 4 mm) by laser, plasma and hybrid (laser-plasma) processes. It was found that the manifestation of this effect depends on welding speed. At the welding speed of 2 m/min at the power of laser radiation and plasma arc of ~2kW each the cross-sectional area of hybrid penetration (3.121 mm^2) is greater than the sum of cross-sectional areas, obtained by laser (2.383 mm^2) and plasma (0.046 mm^2) processes, by 30 %, and for the speed of 4 m/min the specified excess reaches ~20 %.

2. It was determined that the laser-plasma welding of stainless steel using a fiber laser differs from similar processes with application of diode, Nd:YAG-, CO_2-lasers, namely, it allows increasing the penetration depth at simultaneous reduction of its width. So, at application of laser and plasma power of ~2 kW each at the speed of ~1.5 m/min, the penetration depth with application of the fiber laser in the hybrid process increases, compared to the use of the diode laser by 60 %, Nd:YAG-laser — by 30 %, CO_2-laser — by 40 %.

3. Increase of penetration depth at hybrid laser-plasma welding, compared to the laser process, depends on radiation wave length, power density and absorption capacity of the welded surface. So, in stainless steel welding with application of laser and plasma power of ~2 kW each at the

speed of ~1.5 m/min the contribution of the plasma energy source increases the penetration depth at diode laser application by ~100 %, for Nd:YAG-laser — by 15 %, for CO_2-laser — by 33 %, and for fiber laser — by 4 % (compared to laser welding by the same radiation of ~2 kW at the speed of ~1.5 m/min).

4. Comparison of input energies of laser (E_{las}, J/mm) and hybrid (E_{Σ}, J/mm) processes of stainless steel welding showed that the difference between them depends on the welded sheet thickness (or penetration depth). E_{Σ}/E_{las} parameter first decreases from ~100 % for sheets with δ = 2 mm to 50 % for sheets with δ = 6 mm, and at further increase of penetration depth from 6 to 8 mm this value rises from 50 to 60 %.

5. Analysis of the behaviour of factor φ (ratio of the cross-sectional area of hybrid penetration to the sum of cross-sectional areas of plasma and laser penetrations), which characterizes the synergistic effect, shows its increase in 1.5–2.0 m/min speed range of AISI 304 steel welding with further slight decrease in the range of 2.0–4.0 m/min. Weld geometry parameter *K* (ratio of penetration depth to weld width) increases in the entire analyzed speed range (1.5–4.0 m/min). The penetration depth parameter Φ (ratio of penetration depth to blank thickness) somewhat decreases in this range. Comprehensive analysis of the behaviour of these three parameters allows recommending the speed range of 1.5–2.0 m/min for laser-plasma welding of stainless steel with application of fiber laser radiation, as more acceptable one by the criteria of the synergistic effect and penetration depth.

6. At hybrid welding with application of fiber laser radiation the plasma component promotes elimination of such defects of weld upper bead formation, characteristic for laser welding, as undercuts and ridge, and increases the radiation absorption coefficient due to heating of the welded part surface. In the range of speeds of 0.25–4.0 m/min at fiber laser power from 0.8 to 2.0 kW and welding current from 0 to 100 A a directly proportional increase of penetration depth from 2 to 8 mm (depending on laser power), and increase of upper bead reinforcement width from 1.5 to 5.5 mm (depending on plasma power) are in place.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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DECEMBER 14, 1922 Opening of the underground metro line in Glasgow, Scotland took place. The line is the third oldest underground system in the world after the London and Budapest metro. This is the only metro in the British Isles outside London, which is located completely underground. During the construction of the metro, arc welding was used.