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FEATURES OF SYNERGISTIC EFFECT MANIFESTATION IN LASER-PLASMA WELDING OF SUS304 STEEL, USING DISC LASER RADIATION

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It is shown in the work that laser-plasma welding of 3 mm SUS304 stainless steel, using disc laser radiation, a stable manifestation of the synergistic effect and a ratio of powers of the laser and plasma components of 1:1–1:3 were found that allows penetration depth to be increased by approximately 25 % without any change in the welding speed. The stability of the synergistic effect and increase of penetration depth are influenced by the ratio of powers of the process components, method of feeding and composition of the shielding gas. In order to improve the hybrid welding effectiveness at coaxial feed of shielding and plasma gases, it is rational to use an additive of 2–3 % oxygen to shielding gas argon. Stabilization of the synergistic effect due to selection of mode parameters and shielding gas composition, allows replacing up to 40 % of the laser power by plasma power. The strength of joints of SUS304 stainless steel produced by hybrid laser-plasma welding is equal to approximately 95 % of that of the base metal. 8 Ref., 1 Table, 7 Figures.

Keywords: laser-plasma welding, stainless steel, synergistic effect, process experiments, penetration depth, power ratio, shielding gas

Active development of the processes of hybrid laser-arc (laser-plasma) welding of steels and alloys has been observed over the recent years [1, 2]. The interest to these processes is caused, primarily, by new technological capabilities that open up due to their application. This is related to manifestation of the synergistic effect (it is sometimes called the hybrid effect), which is manifested in violation of the additivity of thermal effect of the arc and radiation on the metal being welded, intensification of the dynamic impact of welding current on the melt pool, as well as in the change of the hydrodynamics of the pool proper. As a result, the effective efficiency of the welding process becomes higher, and the energy used for metal melting, can more than two times exceed the sum of the respective energies, evolving in the metal when using each heat source taken separately [3].

As shown by a number of studies, however, the manifestation of the synergistic effect in hybrid laser-arc processes cannot always yield the anticipated positive result, which is manifested in greater penetration depth. For instance, in work [4] it is shown that the manifestation of the synergistic effect, binding of arc plasma to the zone of laser radiation impact and process stability at high speeds, depend more on the degree of focusing of laser radiation, than on its wave length (Figure 1). In work [5] it is noted that the effectiveness of hybrid laser-TIG welding greatly depends on the kind of shielding gas and used shielding method. In work [6] it is shown that at hybrid process penetration of stainless steels, the penetration depth is influenced by the location (in the welding direction) of the component energy sources and distance between them, as well as welding current of the TIG component. Thus, studying the resultativeness of the synergistic effect and stability of its impact on increase of the penetration depth becomes urgent.

The objective of this work is determination of the possibilities for increasing the penetration depth and partial replacement of laser radiation power by plasma power, based on studying the synergistic effect manifestation in laser-plasma welding of stainless steel.

In order to determine the resultativeness of synergistic effect manifestation during hybrid laser-plasma welding, bead deposition and butt welding was performed on plates of thickness $\delta = 3.0$ mm from SUS304 steel (analog of 08KhN10) in argon atmosphere. Presence of through-thickness penetration was determined by the criterion of formation of a back bead of not less than 0.5 mm width at simulta-

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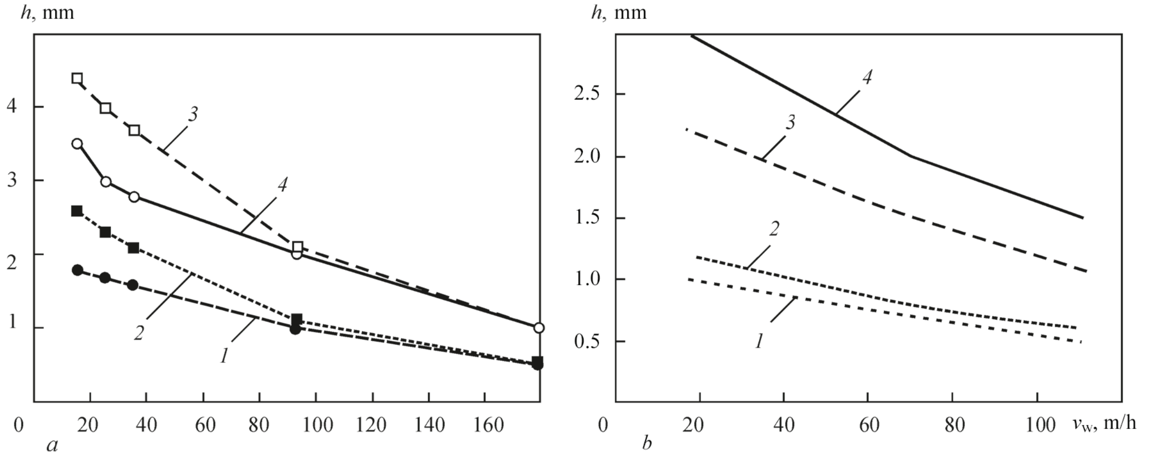

Fig re 1 Dependencies of penetration depth h on speed v_w of laser-plasma welding, using diode laser radiation [4]: *a* — of 2 kW power and argon plasma of 2 kW for SUS321 stainless steel; *b* — of 1.2 kW power and argon plasma of 0.8 kW for aluminium alloy 5083 (*1* — laser welding; *2* — plasma welding; *3* — laser + plasma (arithmetic sum of h values); *4* — hybrid)

neous formation of quality upper bead. Undercuts and sagging of the upper bead, pores and wormholes were regarded as inadmissible defects of weld formation.

Technological studies of the process of hybrid laser-plasma welding were conducted by a scheme given in Figure 2. A disc laser with radiation wavelength $\lambda = 1.03$ μm, the power of which was changed in the range of 0.3–1.4 kW, was used during the experiments. The focal spot diameter was about 0.4 mm. Investigations were performed using an integrated coaxial plasmatron of direct action with four pin cathodes, the design of which is described in detail in [7]. The constricted arc power was up to 2.3 kW at welding current of up to 80 A. The focused laser radiation and constricted arc were taken out jointly through a common nozzle of 2.5 mm diameter onto a welded sample located at approximately 3 mm distance from the nozzle tip. The focal plane of laser radiation was located at approximately 0.5 mm depth relative to the sample surface. Continuous-action straight polarity constricted electric arc was used in the experiments. Sheets of SUS304 steel of 200×100×3 mm size were used as samples for butt welding and bead deposition. The integrated plasmatron was moved relative to the welded sample, using an anthropomorphous robot KUKA KR30HA (Figure 3).

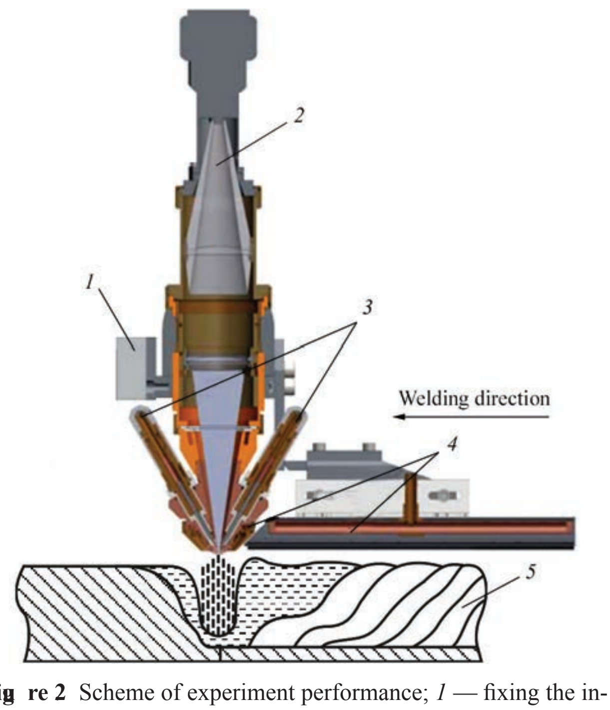

Fig re 2 Scheme of experiment performance; *1* — fixing the integrated plasmatron to the robot arm; *2* — supplying laser radiation; *3* — cathode assemblies; *4* — gas shielding; *5* — sample being welded

In connection with the impact of the kind and method of supplying the shielding gas on the obtained results, mentioned in work [5], experiment performance was started from studying the features of shielding gas supply into the weld pool formation zone. Gas was supplied through the protection nozzle made coaxial to the plasma-forming nozzle. Here, two methods were used: producing a laminar argon flow and turbulent argon flow. It was found that in hybrid laser-plasma welding the coaxial laminar supply of argon leads to a considerable (up to two times) decrease of the penetration depth and a certain increase of weld width, compared to hybrid welding using the

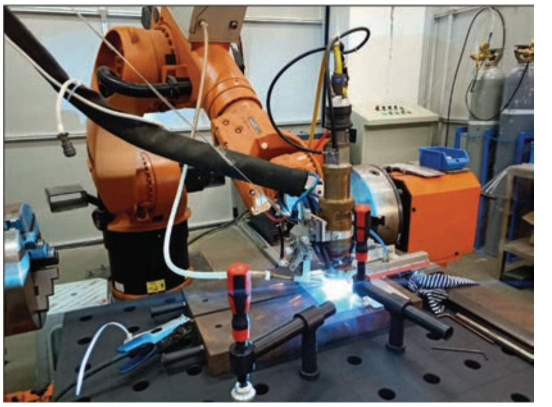

Fig re 3 Appearance of the stand for laser-plasma welding with application of KUKA KR30NA robot during operation

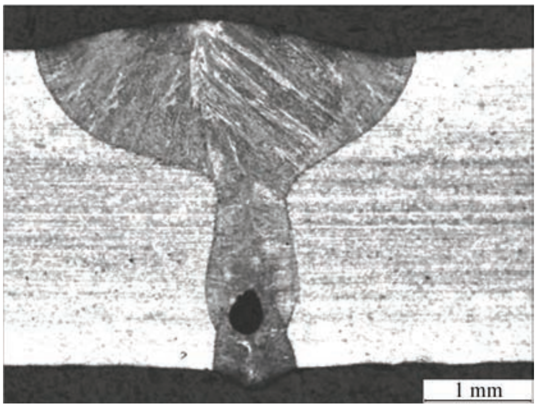

Fig re 4 Structure of the welded joint of SUS304 steel produced by laser-plasma method, with pore formation in the weld lower part

turbulent argon supply. This is explained by penetration of a certain quantity of atmospheric air into the weld pool due to its mixing with argon, which is supplied turbulently. Let us note that an air ingress into the weld pool leads to porosity in welds (Figure 4).

It is known from study [8] that the argon-based gas composition, which includes oxygen in the amount of approximately 0.6 up to 1.9 %, allows greatly increasing the welding speed, joint tolerance and minimizing burns-through with preservation of high mechanical characteristics. No internal pores form here. Also known are the works, in which the share of oxygen in the shielding gas in welding was 3 % and higher. Therefore, in order to eliminate the negative phenomenon of pore formation at preservation of the positive

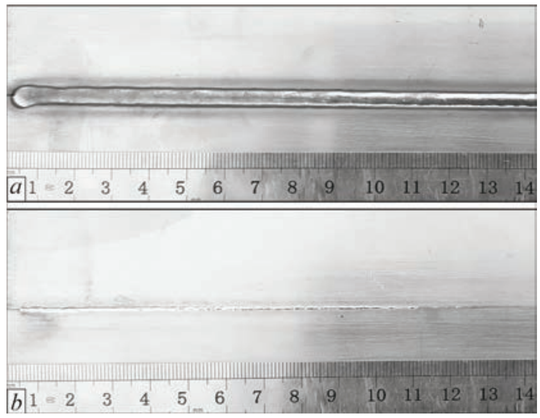

Fig re 6 Appearance of butt joint of SUS304 steel (δ = 3.0 mm): *a* — upper bead; *b* — weld root

effect of increase of penetration depth, a decision was taken to use a mixture of argon with a small amount (2–3 %) of oxygen additive as the shielding gas.

After correction of shielding gas composition, and number of laser, plasma and laser-plasma bead deposits were made in different modes on a plate from SUS304 steel (Figure 5). Then butt joints were welded (Figure 6). Samples for determination of mechanical properties of the produced joints were cut out of butt joints. The nature of manifestation of the synergistic effect and its stability were established by depth and shape of the beads deposited on a plate from SUS304 steel. For this purpose transverse sections of the beads were made and their macrostructures were studied (Figure 7). Modes of bead deposition and obtained re-

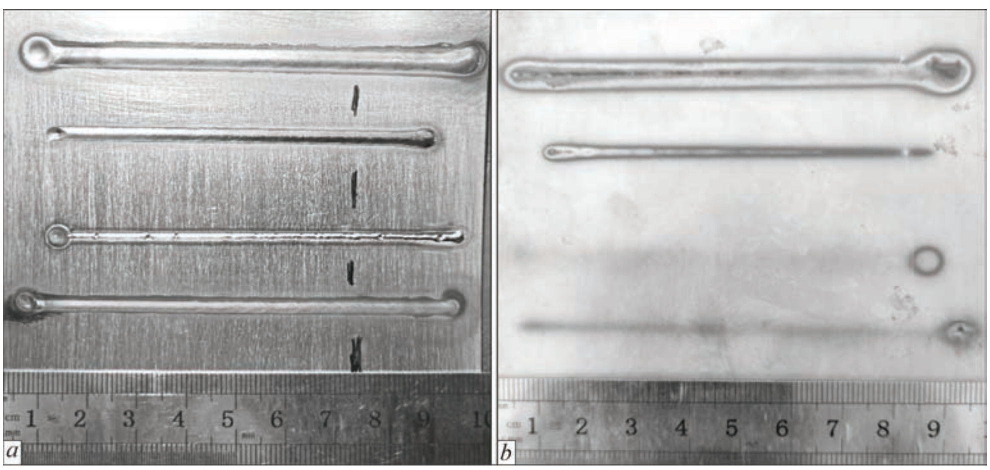

Fig re 5 Appearance of beads on a plate of SUS304 steel of thickness δ = 3.0 mm: *a* — upper side; *b* — reverse side

Welding parameters and geometrical characteristics of beads on SUS304 steel (δ = 3.0 mm) made in argon shielding at the speed of 60 m/h (1.0 m/min)

Sample number	Welding type	Radiation power, kW	Welding current, A	Width *B* of upper weld bead, mm	Penetration depth *H*, mm	Weld form factor *K* = *B*/*H*
D-1	Hybrid	1.4	80	3.94	3.46	1.2
D-2	Laser	1.4	–	2.55	2.55	1.0
D-3	Plasma	–	80	1.83	0.25	7.3
D-4	Hybrid	0.7	40	2.31	1.84	1.3

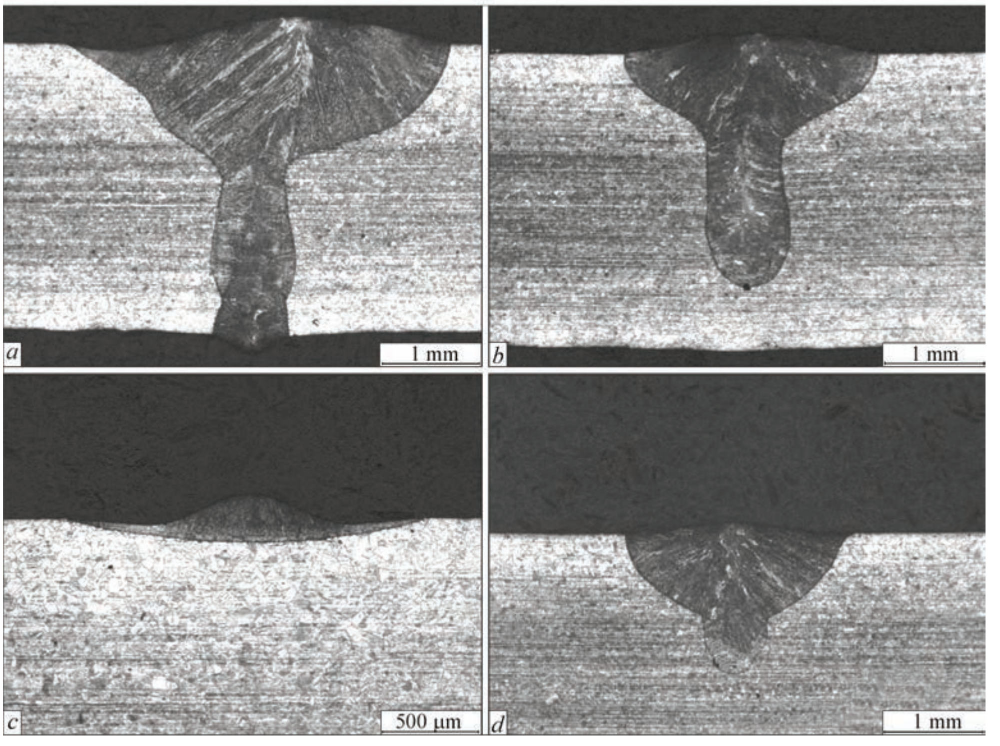

Figure 7 Macrostructure of transverse sections made in a plate of SUS304 steel of thickness δ = 3.0 mm by different methods: *a* — hybrid (sample D-1); *b* — laser (sample D-2); *c* — plasma (sample D-3); *d* — hybrid with half of the power (sample D-4)

sult (values of width *B* of the upper bead and depth *H* of penetration) are given in the Table.

During experiment performance, the high stability of manifestation of the synergistic effect in laser-plasma welding of SUS304 steel in the selected range of powers of the laser and plasma components was established, provided the ratio of these powers is kept close to 1:1.0–1:1.5. When lowering the laser radiation power from 1.4 to 0.3–0.4 kW, while simultaneously keeping the welding current on the level of 80 A (plasma component power is close to 2.3 kW), i.e. at approximately 1.6 power ratio, a reduction of penetration depth with simultaneous increase of its width was observed. The cross-sectional shape of the weld here was close to that achieved in plasma welding that leads to the conclusion of lowering of the stability of the synergistic effect manifestation.

As follows from the Table, the sum of the depth of penetrations in laser (D-2 sample) and plasma (D-3 sample) processes is equal to 2.8 mm, i.e. it is equal to approximately 20–25 % of penetration depth in hybrid laser-plasma process (D-1 sample). In the case of replacement of half (0.7 kW) of the laser power by plasma power (sample D-4) the penetration depth is equal to approximately 75 % of the depth, achieved in laser welding with total power of 1.4 kW (sample D-2). Further experiments showed that in laser-plasma welding of stainless steel, using disc laser radiation, 40 % of laser power can be replaced by plasma. Here, the ratio of laser and plasma powers in the hybrid process should be 1:3. Analysis of weld form factors showed that weld formation in hybrid welding is much closer to laser welding than to plasma welding (see Table).

Samples of XIII (XIIIa) type (GOST 6996–66) were cut out of joints of SUS304 steel (δ = 3.0 mm) to conduct mechanical testing. Static tensile tests were performed using a rupture testing machine of MTS Criterion 45 type on three samples with further averaging of the results. It was found that the strength of joints produced by laser-plasma method is equal to $\sigma_t \approx 750$ MPa, i.e. approximately 95 % percent of that of SUS304 base metal. Relative elongation was $\delta \approx$ ≈ 60 %, i.e. 100 % relative to base metal.

The conducted studies lead to the following conclusions:

1. In laser-plasma welding of SUS304 stainless steel of thickness δ = 3.0 mm, using disc laser radiation a stable manifestation of the synergistic effect was recorded in the range of 1:1–1:3 ratios of laser and plasma components that allows increasing the penetration depth by approximately 25 % without changing the welding speed, as well as replacing up to 40 % of the laser power by plasma power.

2. The stability of the synergistic effect and increase of penetration depth are influenced by the ratio of powers of the process components and method of supplying and composition of the shielding gas. In order to improve the effectiveness of hybrid welding at coaxial supplying of shielding and plasma gases, it is

rational to use an additive of 2–3 % oxygen to shielding gas argon.

3. The strength of the produced by hybrid laser-plasma welding joints from SUS304 stainless steel is equal to approximately 95 % of base metal strength, and relative elongation is similar to this parameter of the base metal. For the majority of the welding tasks the given values are satisfactory.

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1. Utsumi, A., Matsuda, J., Yoneda, M., Katsumura, M. (2002) Effect of base metal travelling direction on TIG arc behaviour. Study of high-speed surface treatment by combined use of laser and arc welding (Report 4). *Welding Int.,* 16(**7**), 530–536.
2. *Cho* Won-Ik, Na Suck-Joo (2007) A study on the process of hybrid welding using pulsed Nd:YAG laser and dip-transfer DC GMA heat sources. *J. of Welding and Joining*, 25(**6**), 71–77.
3. Seyffarth, P., Krivtsun, I.V. (2002) Laser-arc processes and their applications in welding and material treatment. London, Taylor and Francis Books. (Welding and Allied Processes).
4. Shelyagin, V.D., Krivtsun, I.V., Borisov, Yu.S. et al. (2005) Laser-arc and laser-plasma welding and coating technologies. *The Paton Welding J.*, **8**, 44–49.
5. Kah, P., Salminen, A., Martikainen, J. (2010) Laser-arc hybrid welding processes (Review). *Ibid.*, **6**, 32–40.
6. Naito, Y., Mizutani, M., Katayama, S. (2003) Observation of keyhole behavior and melt flows during laser-arc hybrid welding. In: *Proc. of Int. Cong. of Applications of Laser and Electro-Optics, ICALEO, 2003,* Jacksonville (USA). Jacksonville, LIA, Section A, 159–167.
7. Krivtsun, I.V., Korzhik, V.N., Khaskin, V.Yu. et al. (2017) *New generation unit for laser-microplasma welding.* In: *Proc. of 8th Int. Conf. on Beam Technologies in Welding and Materials Processing. Ed. by I.V. Krivtsun*. Kiev, IAW, 95–100.
8. *William* de Abreu Macedo, Vinicius de Oliveira Correia (2006) *Gas composition for arc welding. Praxair Technology, Inc., Danbury, CT (US)*. Pat. US 7071438 B2: B23K9/73.

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HYBRID LASER-MICROPLASMA WELDING OF STAINLESS STEEL

Welded products from thin-sheet stainless steels are made by the modern industry for the purpose of application in the fields of engineering connected with need of operation of strong enough designs, subject to corrosion and certain mechanical influences.

At the same time the task of thick welding of stainless steels up to 3.0 mm butt is often set. One of the modern innovative methods of welding, which allows to minimize residual deformations, to obtain high-quality and sound joints, is a hybrid laser-microplasma welding. In the PWI the basic technological methods of hybrid laser-microplasma welding of thin-sheet stainless steels have been developed and the choice of mode parameters has been made, as well as the mechanical and corrosion properties of the obtained joints have been studied. Hybrid laser-microplasma welding of thin-sheet stainless steels without filler wire and with its application was performed. It was determined that the use of filler wire is advisable starting with a thickness of at least 1.0 mm.

In this case, for complete melting of wire with a diameter of 0.8 mm in the case of welding with tightly joined edges, the energy inputof the process must be increased by 20–40 %, and in the case of welding with a gap between the edges by 15–30 %. The size of the gap should be about 15–20 % of the thickness of the edges. Determination of mechanical and anticorrosive properties obtained by hybrid laser-microplasma welding of stainless steel joints confirmed the prospects for industrial application of this method.