https://doi.org/10.37434/tpwj2020.01.08

IMPROVEMENT OF THE EFFECTIVENESS OF LASER WELDING PROCESSES BY RECIPROCATING MOVEMENT OF THE FOCUS*

V.Yu. Khaskin[2], **V.M. Korzhyk**[1,2], **Ch. Dong**[2] and **E.V. Illyashenko**[1]
[1]E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua
[2]Guangdong Institute of Welding (China-Ukraine E.O. Paton Institute of Welding)
363 Chiansin Str., 510650, Guangzhou, Tianhe. E-mail: wuby@gwi.gd.cn

The work is devoted to evaluation of the impact of lens focus scanning along the laser radiation axis in laser and laser-arc welding on welding-technological properties of the processes and physicomechanical characteristics of weld metal in joints of low-alloyed and high-alloyed steels. It is noted that the effectiveness of welding processes here can be increased by optimization of frequency and amplitude of focus scanning. 12 Ref., 2 Tables, 9 Figures.

Keywords: *laser welding, hybrid laser-MIG welding, carbon steel, stainless steel, technological experiments, energy input*

One of the main disadvantages of technological processes using laser radiation is their low efficiency (as a rule, not more than 60 %) [1]. This is associated both with a relatively low absorption coefficient of radiation by metals (about 10–40 %), as well as with a small length of its caustic neck (about 0.2–2.0 mm) [2]. Therefore, in order to increase the efficiency of such processes as welding and cutting using laser radiation, it is reasonable to increase the absorption coefficient by heating the treated surface and elongation of the radiation caustic neck. These effects can be achieved by applying a vertical reciprocating focus scanning with specific amplitudes and frequencies. Such an approach can be the basis for innovative industrial developments that can significantly save laser power.

In the manufacture of modern lightweight structures used in different fields of engineering, steels and alloys are often used, characterized by increased strength. Thus, for example, in the manufacture of fragments of hulls of large passenger liners and cargo ships, high-strength and corrosion-resistant steels are used; in the manufacture of similar hull structures of small-displacement ships, high-strength aluminum alloys can be used. At the same time, a great popularity was gained by lightweight honeycomb structures welded in slot welds using laser radiation [3].

As far as for the formation of high-quality welded joints it is necessary to achieve the formation of upper and lower reinforcements of the weld, the use of appropriate filler material is required, most often in the form of a solid wire. As investigations showed, to reduce the consumption of laser energy, it is advisable that such wire was fed with its simultaneous melting by an electric arc [4]. Moreover, the effect between the arc and consumable electrode is not limited to input of additional heat to the weld pool from the molten electrode wire. When interacting with laser radiation (primarily with ionized vapor arising above the vapor-gas channel under the effect of radiation), the electric arc is constricted, falls into the formed vapor-gas channel and complements the laser energy in a hybrid laser-arc process [5]. The so-called binding of the arc to the focus of laser radiation occurs, which provides the well-known advantages of hybrid welding.

However, while using laser and laser-arc (laser-MIG) welding to produce butt, fillet and tee joints, a number of characteristic defects may occur:

- defects associated with the formation of welds, which mainly consist in the formation of shrinkage cavities and undercuts on the both sides of the reinforcement bead (Figure 1);
- formation of inner pores (Figure 2);

---

[*] Based on the materials of the report presented at the International Conference «Beam Technologies in Welding and Materials Processing», September 9–13, 2019, Odessa.

V.M. Korzhyk — http://orcid.org/0000-0001-9106-8593

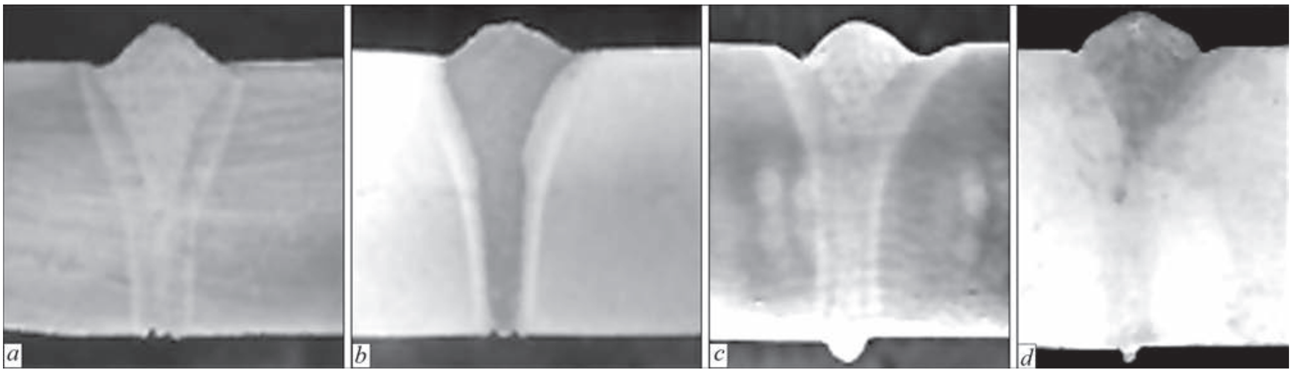

Figure 1. Typical defects in the formation of butt joints of high-strength steel DOMEX 390 XP (δ = 10 mm) during hybrid laser-MIG welding [6]: concavity of the weld root (*a*, *b*), undercuts in the upper part (*a*–*d*)

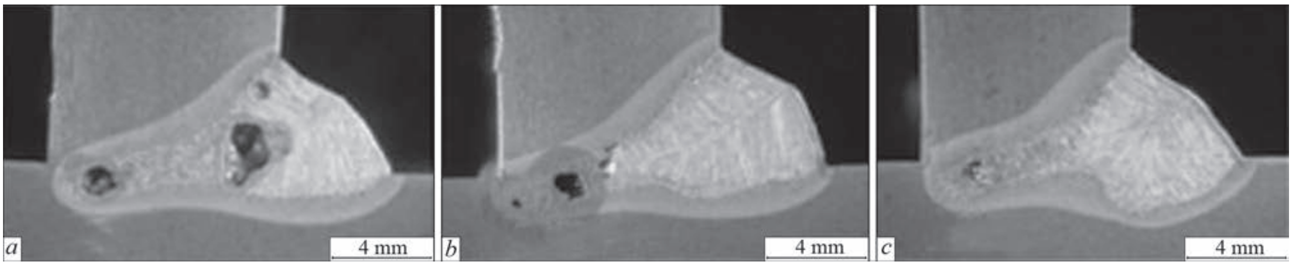

Figure 2. Formation of inner pores in tee joints during hybrid laser-MIG welding of high-strength AN36 steel with OK Aristorod 12.50 electrode wire (1.2 mm in diameter) using fiber laser radiation: *a*, *b* — power 8.0; *c* — 10.0 kW [7]

● heterogeneity of alloying the weld metal with electrode or filler wire over the depth of the weld pool (Figure 3);

● formation of cracks both during laser or laser-arc welding (Figure 4), and during the further operation of welded joints, low values of cyclic fatigue tests (alternating cyclic loads) (Figure 5).

Figure 3. Absence of a uniform distribution of the electrode wire metal along the weld depth during laser-MIG welding of steels of large (over 8 mm) thicknesses on the example of welding SSAB Domex 420MS steel (standard EN 10149-2) [8]

Therefore, the aim of this work is to create a fundamentally new universal approach to eliminating the characteristic defects of laser and laser-arc welding, which at the same time allows increasing the process efficiency, reducing its energy input and achieving saving of laser energy.

In the framework of the existing approach to laser and laser-arc welding, the abovementioned defects can be eliminated by different methods, the simplest of which is the selection of mode parameters. However, in most cases, when using the currently existing commercially available equipment for laser and laser-arc welding (for example, laser-MIG heads manufactured by Fronius and Cloos Companies [10]), solving the problem of producing high-quality welded joints of steels and alloys is difficult. The disadvantages of the technological scheme of the process realized by such equipment include the inability to control the

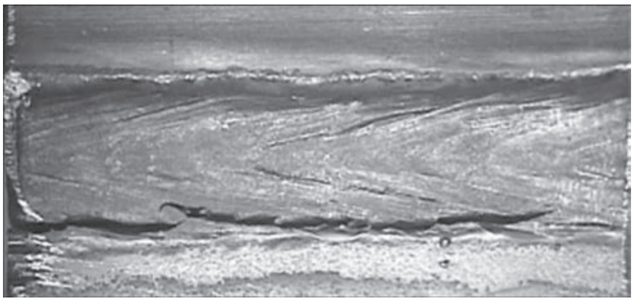

Figure 4. Typical geometry of a longitudinal crack on the surface of a butt joint of SS2333 stainless steel (δ = 10 mm), produced by laser-arc welding with Avesta 253MA electrode wire (1.2 mm in diameter) [9]

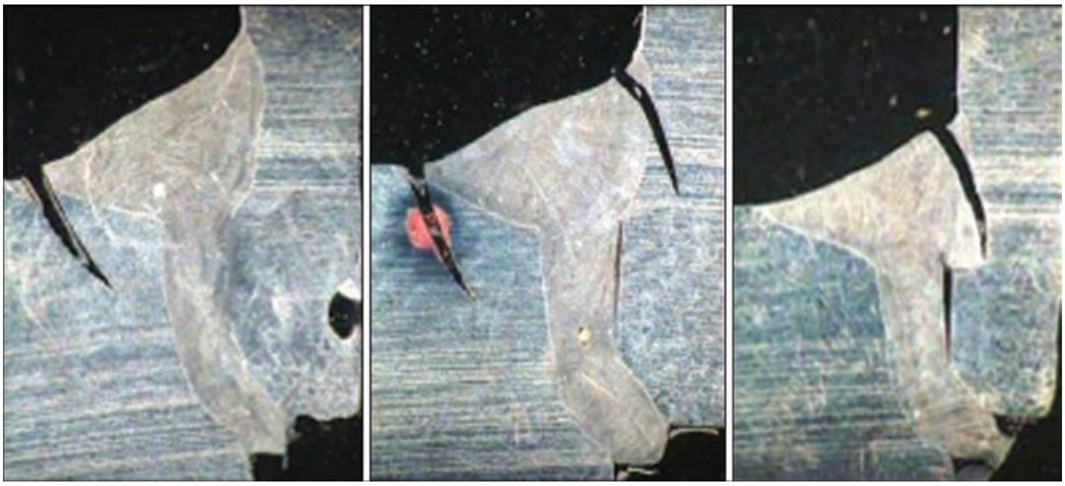

Figure 5. Propagation of longitudinal cracks and fracture of the joint during cyclic fatigue tests. Cross-section of fillet joints of steel SS2333, welded using laser-arc method [9]

hydrodynamics of weld pool, which would contribute to increasing the uniformity of chemical composition in the weld throughout its height even at significant (over 8 mm) thicknesses of welded edges, eliminating pore formation, and increasing quality of the fusion zone, improvement of resistance to cyclic alternating stresses. Such a control of hydrodynamics of the melt pool would become possible in case when an additional factor is introduced into the technological scheme of the process, which increases the intensity of the melt flows in a vertical direction [11]. In addition, this would provide additional possibilities for controlling the thermal cycle of the hybrid laser-arc welding process.

Our proposed approach to obtaining an effective method for controlling the hydrodynamics of a weld pool and, therefore, to improving the quality of laser-arc welding, consists in modernization of the existing technological scheme of laser-MIG welding and creating a new welding tool based on the principle of reciprocating movements (oscillations) of the laser radiation focus along the axis of the beam in the certain intervals of frequency and amplitude. The focus oscillations of, realized by reciprocating movements of the focusing lens, can be also additionally coordinated with a set pulsed mode of modulation of laser radiation and/or burning of the MIG arc during hybrid laser-MIG welding process.

To realize the proposed approach to changing the technological scheme of the laser-MIG welding process, an appropriate laboratory bench with welding head was created, which allows realizing a reciprocating movement (scanning) of the focus along the radiation axis with a frequency of up to 100 Hz and an amplitude of 0–10 mm. The principle of operation of such welding head is shown in Figure 6.

Laser radiation *1* is focused using lens *2* on the butt line of parts to be welded. Lens *2* is installed in casing *3* of focusing lens, which, in turn, is located in mandrel *4*, having a possibility of reciprocating movement using the system *5*. The system *5* provides a controlled scanning along the axis of radiation with a frequency f = 0–100 Hz and an amplitude A = = ±(0–5) mm. This allows changing the location of focal plane of lens *2* relative to the surface of parts to be welded by the value $\pm\Delta F$, regulated by a change in the amplitude A. The composition of the system *5* for scanning laser radiation includes solenoids *6* and *7*, with whose anchors *8* and *9* mandrel *4* is rigidly connected. The system *5* also includes rubber pads *10*–*13* for braking anchors of solenoids and control device *14*, which includes a master pulse generator and an electric signal amplifier. For realization of the arc component of the laser-MIG welding process, the electrode wire feed is provided using the nozzle *15*, which has the ability to adjust the position relative to the radiation focus and feed angle within the range of 30–80° relative to the radiation axis (10–60° relative to welded butt surface).

We should note that the design of scanning lens (focus of radiation) shown in Figure 6 is considered as an example as one of the possible variants. Other variants of the design for such scanner are also possible. For example, the reciprocating movement of the lens along the axis of radiation can be carried out using piezoelectric motors or eccentric cams, driven into rotation by DC motors.

The action of the proposed device is as follows (see Figure 6). Laser radiation *1* by means of lens *2* is focused on the butt line of the parts to be welded with the desired deepening ΔF of focal plane of the lens relative to the surface of parts to be welded. After applying an electric signal to solenoids *6* and *7* using control device *14*, anchors *8* and *9* provide vertical reciprocating movements of mandrel *4* with casing *3* of focusing lens *2* with a frequency f = 0–100 Hz and

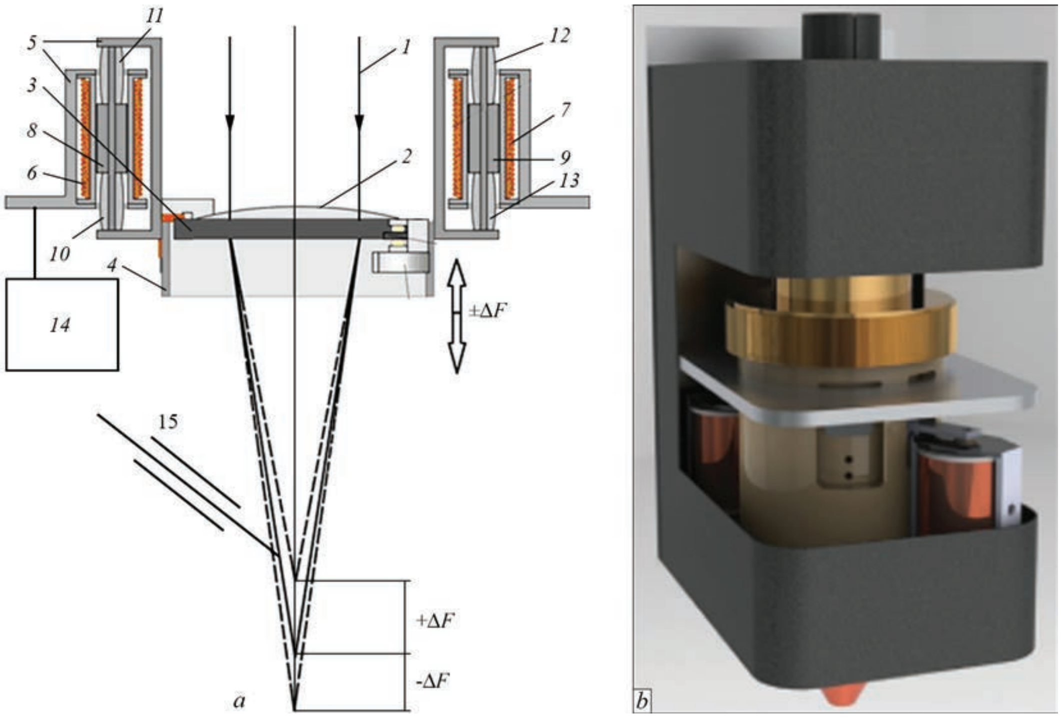

Figure 6. Scheme of design (*a*) and general appearance (*b*) of the head for laser and hybrid laser-MIG welding with the system of reciprocating movement (scanning) of the focus (±Δ*F*) along the axis of the radiation (designations see in the text)

amplitude *A* = ± (0–5) mm, which provides the corresponding vertical focus oscillations. At the same time, rubber pads *10–13* soften and inhibit the movement of anchors.

After the start of vertical oscillations of the focus of laser radiation 1, the electrode wire is driven by the wire feed mechanism, the electric contact of which with the positive potential of the arc power source is performed using nozzle *15*. After touching the electrode wire with a part to be welded under the negative potential of the source, an electric arc appears that is «attached» to an oscillating focus and also gets the opportunity to realize an oscillation movements. In the case of welding in the flat position, these are vertical oscillations. After this, the process of hybrid laser-MIG welding begins, in which due to the vertical scanning of the focus with certain frequency and amplitude, the effect of increasing the penetration depth without increasing the laser radiation power, as well as the effects of a more uniform weld alloying along the entire height of the metal electrode wire and eliminating the formation of inner pores are achieved by improving the conditions for the floating of gas bubbles on the weld pool surface.

Thus, the described technical solution for manufacturing head for laser-MIG welding with focus scanning along the axis of laser radiation provides new technological possibilities. These possibilities can be more fully revealed when the focus scanning frequency is increased, for example, during welding of steels to the optimum values of a pulsed effect on the weld pool (as is shown in [12]), or to the values of the order of 500 Hz. Such a frequency of effect on the molten pool is threshold, after which the metal of the pool stops reacting to pulsed oscillations. In our opinion, in the long term, the proposed equipment and the technologies of hybrid welding implemented with the help of it, as compared to conventional laser-MIG welding, can have the following advantages:

- more than twice increase in the penetration depth without growing the power of laser radiation;
- possibility of welding loose adjacent edges due to oscillations of the arc of the consumable electrode during the welding process;
- possibility of increasing the welding speed by 2 or more times without increasing the radiation power;
- possibility of modifying the thermal cycle of welding, which helps to eliminate the formation of undesired quenching structures in welds;
- possibility of a more uniform weld alloying along its entire height by the metal of the electrode wire;
- reducing the risk of inner pores formation in the welds.

Verification of the effectiveness of the proposed method was performed at the E.O. Paton Electric Welding Institute by conducting the necessary experiments in the robotic laboratory bench created for this purpose (Figure 7). The bench consisted of anthropomorphic robot-manipulator for moving integrated head for laser-MIG welding, as well as the head itself, mechanism for electrode wire feed, electrical pow-

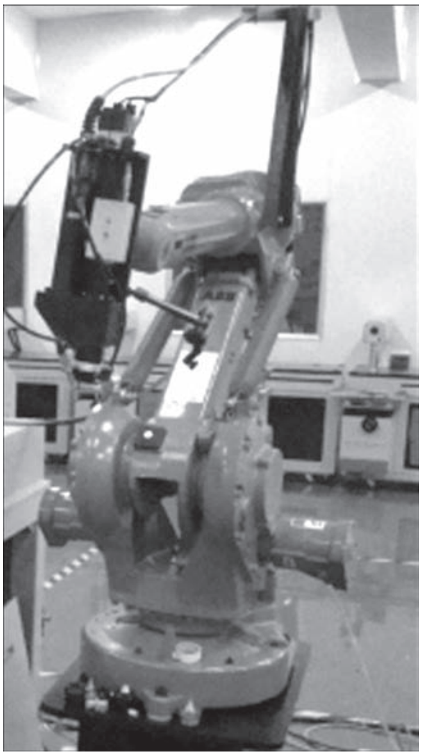

Figure 7. Appearance of robotic laboratory bench for laser arc welding with laser focus oscillations

er systems (including MIG power source, providing welding current of up to 500 A), control and supply of shielding gases. The integrated head for hybrid laser-MIG welding consisted of focusing system with a focus scanning along the axis of laser radiation and MIG torch. The vertical scanning system provided focusing of radiation by the lens with a focal length *f* = 300 mm and vertical reciprocating oscillations of the lens with a frequency of 0–100 Hz and an amplitude of ±(0–5) mm. The tests of this bench were carried out using radiation from a disc laser of the model TruDisc 10002 (TRUMPF Company) with a radiation power of up to 10.0 kW. In this case, penetrations and butt welds were produced in the flat position using specimens of $300\times100\times\delta$ mm in size of steels SM41B (09Mn2Si or 09G2S) of $\delta = 4–18$ mm thickness, AN36 (A36) of $\delta = 4–18$ mm thickness, and also SUS304 (08Kh18N10) with a thickness of $\delta = 8–10$ mm using welding wires of the solid cross-section 08Mn2Si (Sv-08G2S) and 01Cr18Ni10 (Sv-01Kh18N10) with a diameter of 1.2 mm (Table 1).

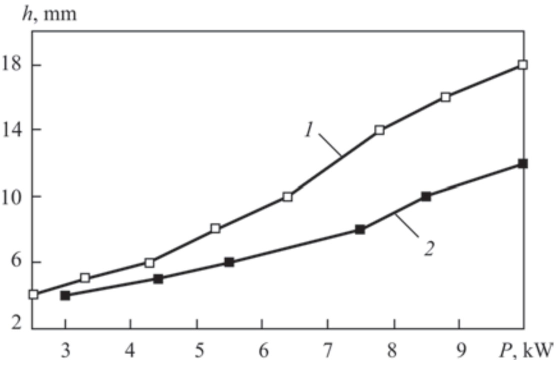

Figure 8. Dependence of the penetration depth h on the radiation power *P* during laser-MIG welding with focus scanning (*f* = = 100 Hz, *A* = 3 mm) along the radiation axis (curve *1*) and without scanning (curve *2*)

During the experiments the results of welds formation during butt laser-arc welding of plates of the mentioned steels, produced in the flat position with and without vertical focus oscillation, were compared. In this case, the focus oscillation frequency was 100 Hz, and the amplitude was selected close to half of the thickness of welded edges. The focus was scanned so that its deepening relative to the top of the plates being welded in the upper position was 1–2 mm. Based on the results of the experiments, a diagram was plotted showing the dependence of the thickness of the edges of the welded sheets (penetration depth *h*) of carbon steel on the laser radiation power during welding at a speed of about 80–90 m/h, welding current of about 220–250 A and arc voltage of 22–24 V (Figure 8).

Tests on static strength were carried out using the MTS Criterion 45.305 tensile testing machine (with a load of up to 300 kN) on the specimens of type XIII (XIIIa) (GOST 6996–66), which were cut out from butt welded steel plates of SUS304 steel with a thickness of $\delta = 10$ mm. 3 groups of specimens were subjected to rupture tests — produced using laser-MIG welding with and without focus scanning, as well as cut out from the plates of base metal. Each group included 3 specimens; the obtained test results were averaged. The welded specimens were mostly ruptured identically — the upper ones to about 3 mm along the fusion line, then through the weld to the opposite fusion zone. The tensile strength of the specimens welded without a focus scanning was 620–640 MPa and with scanning — 630–650 MPa. For the base metal, the tensile strength was 640–660 MPa. Thus,

Table 1. Chemical composition (wt.%) of materials of welded specimens and welding wires

Material	C	Si	Mn	Cr	Ni	Ti	Cu	S	P	Other
09Mn2Si	≤0.12	0.5–0.8	1.3–1.7	≤0.3	≤0.3	–	≤0.3	≤0.04	0.035	N ≤ 0.008
AH36	≤0.18	≤0.5	0.9–1.6	–	–	–	–	0.035	0.035	–
SUS304	≤0.8	≤0.8	≤0.2	17–19	9–11	≤0.5	≤0.3	0.02	0.035	–
Wire 08Mn2Si	0.05–0.11	0.70–0.95	1.8–2.1	0.20	0.25	–	–	0.025	0.030	–
Wire 01Cr18Ni10	0.02	0.4	1.0–2.0	17.0–19.0	9.5–11.0	–	–	0.02	0.02	–

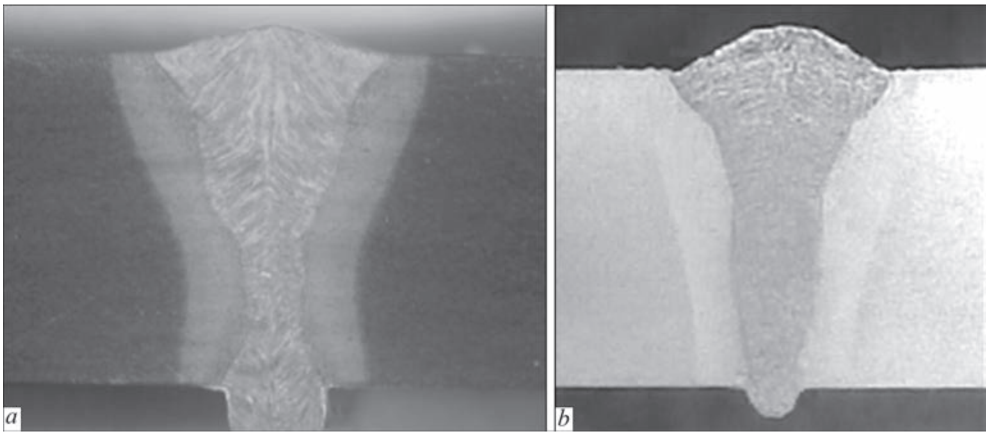

Figure 9. High-quality joints of high-strength steel 10 mm thick (*a*) and corrosion-resistant steel SUS304 8 mm thick (*b*), produced using focus scanning along the axis of radiation in hybrid laser-MIG welding

Table 2. Change in energy input of laser-MIG welding depending on thickness of welded edges

Energy input E, kJ/m	Thickness of welded edges δ, mm								
	4	5	6	8	10	12	14	16	18
Without scanning	320–330	390–400	440–450	520–540	570–590	640–650	–	–	–
With scanning	300–320	340–360	390–410	430–450	480–500	510–530	550–560	590–610	650–670

the strength of welds produced by welding without scanning amounted to about 98–99 % relative to the base metal, and with scanning to 99–100 %.

To carry out metallographic examinations according to standard procedures, the specimens of cross-sections of the produced welds were prepared, which were studied with the use of the Neophot-32 optical microscope at magnifications of up to 1500 times. As a result, it was found that introduction of focus scanning along the axis of radiation improves the formation of welds and increases the uniformity of their alloying with the metal of the electrode wire over their height (Figure 9). In addition, the size of dendrite grains of the cast zone of the welds is reduced as compared to conventional hybrid laser-MIG welding.

It can be assumed that overheating and increase in the volume of remelted metal, as well as increase in the penetration depth in case of introducing focus oscillations along the radiation axis at a fixed radiation power, lead to improvement in the absorption of laser radiation and increase in the efficiency of welding. The input energy of laser-arc welding is reduced by about 15–20 % (Table 2). The carried out experiments showed that the use of vertical focus oscillations allows increasing penetration depth by 20–50 % without increasing the radiation power. The effect of increasing penetration depth due to scanning of the radiation focus becomes noticeable at thicknesses larger than 4–5 mm and affects the more, the thicker the welded edges. This allows performing laser and hybrid welding of the edges of metal parts of significant (up to 10 and up to 18 mm, respectively) thicknesses with a minimal consumption of laser radiation power (for example, up to 6.0 kW).

Conclusions

1. A new approach to laser and laser-arc welding, which consists in supplementing the existing technological schemes of processes by scanning the focus along the axis of laser radiation with a certain frequency and amplitude, allows increasing the intensity of melt flows in the weld pool (including vertical direction) and further modifying the thermal cycle of welding, which increases the uniformity of distribution the alloying additives along the height of the weld, minimizes the risk of formation of inner pores and at the same time by 20–50 % increases the efficiency of the process and reduces its energy input by at least 15–20 %.

2. An increase in the efficiency of laser and laser-arc welding can consist in either an increase in the speed of the process, or in the possibility of welding edges of larger thickness without increasing the energy input. In this case, the effect of increasing the penetration depth due to scanning the radiation focus becomes noticeable at the thicknesses over 4–5 mm and affects the more, the thicker the welded edges.

3. Mechanical tests showed that tensile strength of corrosion-resistant steel joints produced by laser-arc welding with a focus scanning along the radiation axis approximately corresponds to the strength of the base metal. Metallographic examinations showed an improvement in the formation of welds, an increase in

the uniformity of their alloying with the metal of the electrode wire in height, a decrease in the grain size of the dendrites of the cast zone of the welds as compared to the conventional hybrid laser-MIG welding.

4. To increase the efficiency of the proposed approach to laser and laser-arc welding, it is advisable to optimize the frequency and amplitude of focus scanning along the axis of the laser radiation.

Note. The work was carried out in the framework of the Project No.2018GDASCX-0803 «Research and development of laser and plasma technologies for hybrid welding and cutting», Guangzhou, China.

1. Grigoryants, A.G., Shiganov, I.N. (1988) *Laser technique and technology*. In: 7 books. Book 5: Laser welding of metals. Ed. by A.G. Grigoryants. Moscow, Vysshaya Shkola [in Russian].
2. Vvedenov, A.A., Gladush, G.G., Yavokhin, A.N. (1983) On mechanism of maintain of deep key hole in liquid using laser beam. *PMTF*, **1** 48–41 [in Russian].
3. Oikawa, M., Minamida, K., Yoshida, Y., Suzuki, N. (2004) Development of all laser welded honeycomb structure for civil transports. *Nippon Steel Technical Report*, **89**, January, 96–101.
4. Shelyagin, V.D., Khaskin, V.Yu. (2002) Tendencies in development of laser-arc welding (Review). *The Paton Welding J*., **6**, 25–28.
5. Shelyagin, V.D., Khaskin, V.Yu., Garashchuk, V.P. et al. (2002) Hybrid CO_2-laser and CO_2 consumable-arc welding. *Ibid*., **10**, 35–37.
6. Engström, H., Nilsson, K., Flinkfeldt, J. et al. (2001) Laser hybrid welding of high strength steels. In: *Proc. of ICALEO 2001, 20th Int. Congress on Applications of Lasers & Electro-Optics (October 15–18, 2001, Jacksonville*, Florida, USA). Ed. Xiangli Chen, Laser Institute of America, 2001, 125–134.
7. Unt, A., Poutiainen, I., Salminen, A. (2015) Influence of filler wire feed rate in laser-arc hybrid welding of T-butt joint in shipbuilding steel with different optical setups. *Physics Procedia*, **78**, 45–52.
8. Frostevarga, J., Kaplan, A. F.H. (2014) Undercuts in laser arc hybrid welding. *Ibid*., **56**, 663–672.
9. Alam, Md. M. (2009) *A study of the fatigue behaviour of laser and hybrid laser welds* (Licentiate thesis). Luleå, Luleå Tekniska Universitet, **133**.
10. Krivtsun, I.V., Khaskin, V.Yu., Korzhik, V.N., Ziyi Luo (2015) Industrial application of hybrid laser-arc welding (Review). *The Paton Welding J*., **7**, 41–46.
11. Golubev, V.S. (2009) Hydrodynamic phenomena in laser welding with channeling penetration of radiation. In: *Deep channeling and filamentation of power laser radiation in substance*. Ed. by V.Ya. Panchenko. Moscow, Intercontact Nauka, 35–63 [in Russian].
12. Khaskin, V.Yu., Pavlovsky, S.Yu., Garashchuk, V.P. et al. (2001) Peculiarities of welding thin-sheet low-carbon steels using a pulsed-periodic radiation of CO_2-laser. *The Paton Welding J*., **2**, 42–46.

Received 21.10.2019