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HYBRID LASER-PLASMA WELDING: EFFICIENCY AND NEW POSSIBILITIES (REVIEW)

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ABSTRACT

Research papers devoted to development of laser-plasma processes during the last two decades are reviewed. It was found that the current directions of scientific research of the processes of laser-plasma welding are focused mainly on studying the peculiarities of simultaneous impact of constricted arc plasma and laser radiation with wave length of 1.03–1.07 μm (first of all, fiber laser) on steels and alloys, as well as investigations of the physical fundamentals of manifestation of the synergic (hybrid) effect at such an impact and determination of the possibilities of its practical application. It was determined, in particular, that increase of the effectiveness of synergic effect manifestation is related to improvement of the plasma arc burning conditions in the zone of ionized vapour plume, which forms under the impact of focused laser radiation, as well as simplification of laser keyhole formation due to plasma arc pressure.

KEYWORDS: laser-plasma welding, synergic effect, process efficiency, steels, aluminium alloys, industrial application

INTRODUCTION

Ideas of hybrid application of the laser radiation and the electric arc for welding and related processes, proposed by W.M. Steen, became developed in theoretical and practical works of such prominent scientists as U. Dilthey, K. Paul, F. Ridel, I.V. Krivtsun and oth. Modern hybrid welding processes have become accepted by industry to a certain extent. For instance, they are applied in car- and shipbuilding, production of pipes of different diameters, etc. In the opinion of a number of researchers, laser-plasma welding is quite promising among other laser-arc processes. Therefore, the authors propose a review of its state-of-the-art to predict its further development.

PROBLEM DEFINITION

The authors of works [2–4] conducted analytical modeling of the processes of laser-plasma welding and spraying with application of models of integrated coaxial heads. In these works, higher efficiency of the coaxial laser-arc discharge was attributed to occurrence of a combined laser-arc discharge through absorption of the CO_2-laser beam, passing through the center of the arc column, by constricted-arc plasma. Here, the degree of laser radiation absorption by the arc plasma was indicated as a key parameter of discharge control. Such an approach mainly defined the principles of hybrid welding 20–30 years ago. Over the last 10–20 years CO_2 lasers have confidently replaced fiber lasers, the radiation of which practically does not interact with arc plasma [5]. This has significantly changed the way we look at the hybrid laser-plasma process and prospects for its industrial application. Modern approaches to development of welding and related laser-plasma technologies are based on application of radiation with wave length in the range of 1.03–1.07 μm, i.e. of fiber, disc and Nd:YAG-lasers.

PURPOSE AND OBJECTIVES OF RESEARCH

The objective of the work is to analyze the current state of the directions of investigations and industrial applications of laser-plasma welding processes and to assess the efficiency of manifestation of the synergic (hybrid) effect at application of laser radiation with 1.03–1.07 μm wave length.

The following tasks were solved to achieve this purpose:

- establishing modern directions of investigations of laser-plasma welding processes;
- determination of the efficiency of synergic effect manifestation in laser-plasma welding of steels and alloys;
- analysis of laser-plasma process impact on the characteristic welding defects in steels and alloys;
- analysis of the state-of-the-art of industrial application of laser-plasma welding.

ANALYSIS OF LITERATURE SOURCES

Already at the start of the XXI century acad. I.V. Krivtsun stated that the main factor for determination of the nature of metal penetration in combined laser-arc welding is the thermal and dynamic influence of the used heat sources on the weld pool surface. Therefore, he developed a system of equations to describe the process of metal evaporation under the impact of multicomponent plasma forming above the weld pool in laser-plasma welding [6]. Such a system is the base for calculation of the characteristics of thermal and dynamic influence of arc, laser or combined plasma on the welding pool surface in the respective gas-shielded welding processes. His next step was to study the features of metal penetration in laser-arc welding using Nd:YAG-laser [7]. A mathematical model of thermal processes developed for this purpose allowed calculating the penetration profiles at a combined influence of the laser beam and the electric arc on the product, taking into account their interaction on the metal surface. Calculations showed the presence of a synergic (hybrid) effect, which is manifested in a non-additive increase of the volume of metal remelted by laser-plasma process, compared to metal volumes, remelted separately by the laser and plasma processes.

In order to analyze the synergic combination effect, arising during the process, laser-plasma welding can be divided into three zones [8]: I — plasma above the surface; II — weld pool surface and III — interaction occurring directly under the surface. Such factors, as a common welding source, relative position of the laser and plasma sources, as well as the role and influence of welding parameters, have a major impact on the extent of synergic effect manifestation.

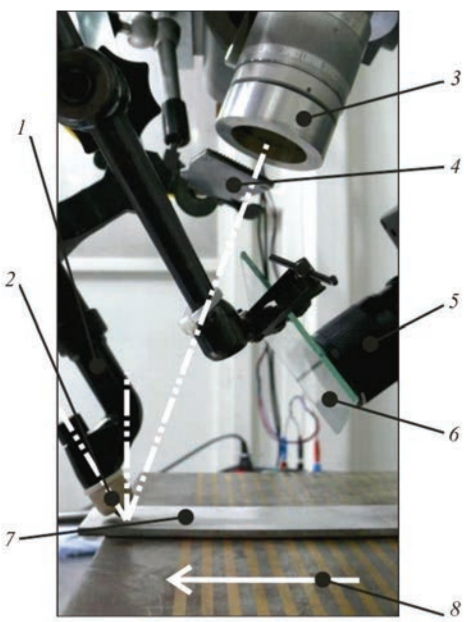


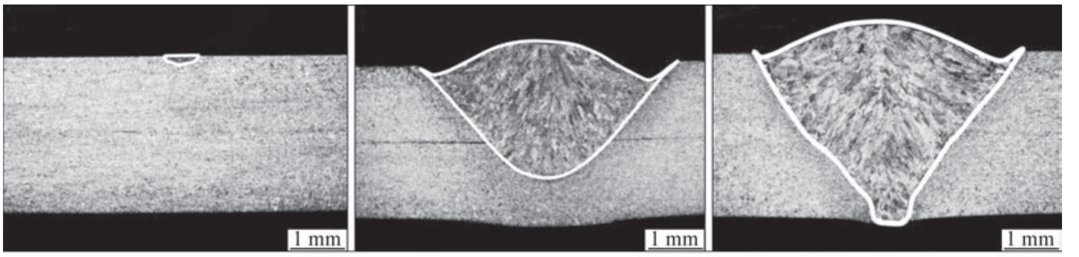
Figure 1. Experimental set-up with separate arrangement of the plasmatron and the laser beam [12]: *1* — plasma torch mounted at angle α = 35° (forward inclined); *2* — plasma nozzle (distance to sample L = 2 mm); *3* — laser beam directed at angle β = 20° (backward inclined); *4* — cross-jet (air knife); *5* — high-speed camera; *6* — protective glass; *7* — sample; *8* — direction of work table (sample) movement

In work [9] it is shown that the arc characteristics practically do not change in cases of interaction of "gas CO_2-laser – helium TIG arc" and "disc Yb:YAG-laser – argon TIG arc". The reason is that the inverse bremsstrahlung coefficients differ markedly, because of different electron density of argon and helium arcs and different wave lengths of CO_2 and Yb:YAG lasers. Such a study to a certain extent promotes partial application of the experience of the use of CO_2-laser in hybrid processes with solid-state laser radiation.

Work [10] presents the results of investigation of the synergic effect in hybrid laser–arc welding. Experiments were conducted with Nd:YAG-laser of power P_L = 500 W in combination with standard TIG-welding equipment. Two aspects were studied: heat transfer efficiency and melting efficiency. Heat transfer efficiency was determined by calorimetric measurements, and melting efficiency — by cross-sections of welds produced in different welding modes. Results show that laser-arc interaction does not lead to any noticeable change in heat transfer efficiency, but results in a significant increase in melting efficiency. Non-additive increase of the cross-sectional area of welds produced with addition of two heat sources (laser and arc) is indicative of the presence of a synergic effect and hybrid mode of welding.

Spectral analysis of the hybrid plasma plume and high-speed photographic analysis of the process in hybrid welding revealed the following. First, the principle of the synergy effect consists in that at interaction with the nonconsumable electrode constricted arc the laser transfers the electron energy to a higher level, and creates the conditions for quantum transition. Due to that more photons are emitted, which increase the heat input into the material being welded. The synergic effect is enhanced with increase of laser power and is decreased with the arc current. This effect is proportional to the weld cross-section, particularly in its upper part. Secondly, the amount of spatter at hybrid laser-arc welding is much smaller than in arc welding.

In work [12] a number of investigations of laser-plasma welding were conducted by the scheme in Figure 1. It is proposed to define welding efficiency η_W as a ratio of the theoretical power P_{FZ} required for melting the fusion zone material (FZ index), to the total input welding power P_W according to



	Laser	Plasma		Laser–plasma
Energy combination efficiency, %	29.5	67.2	+9.9	71.6
Melting efficiency, %	5.8	10.6	+53.4	15.8
Thermal efficiency, %	1.7	7.1	+68.7	11.3

Figure 2. Transverse sections in welding AISI304 steel (δ = 1 mm) by the laser beam (P_L = 200 W, ω_0 = 200 μm), plasma welding (Q_p = 1.8 l/min; d_W = 5 mm) and laser-plasma welding (laser-plasma) (P_L = 200 W, ω_0 = 200 μm, Q_p = 1.8 l/min; d_W = 5 mm) with the respective efficiency values [14]

$$\eta_W = \frac{P_{FZ}}{P_W} = \frac{\rho w_{ch} A_{FZ} \Delta h_{FZ}}{P_W}, \qquad (1)$$

where ρ is the density of the material being welded; w_{ch} is the movement speed; A_{FZ} is the cross-sectional area in the fusion zone, and Δh_{FZ} is the required increase of specific enthalpy for melting. Relationship (1) can be considered as the basis for determination of relative welding efficiency, which compares the efficiency of combined laser-plasma process with that of individual processes.

A change in arc voltage at introduction of laser radiation into the plasma-arc process can be one of the causes for improvement of laser-plasma welding efficiency compared to individual processes. In case of aluminium welding, a marked voltage drop in the range from –2 to –3 V is observed at switching on the laser beam. In welding steel under the same conditions of a highly focused laser beam, a moderate increase of arc voltage between 0.15 and 0.6 V was found. Calculations showed [12] that the efficiency of laser-plasma welding can change from 1.5 (for 6082 aluminium alloy) to 2.4 for AISI304 steel.

If the synergic effect of hybrid laser-arc treatment is interpreted as increase of energy transfer from the heat source to the material, then the thermal efficiency η_T of the process corresponds to the ratio of power P_U, which is required for melting the material being welded per a unit of time (without losses), to total applied power P_A [13]. In keeping with equation (2), this value can be divided into melting efficiency η_M (energy consumption within the base material) and energy combination efficiency η_C (energy input from the heat source), using power P_T, transferred from the heat source to the blank [13]:

$$\eta_T = \frac{P_U}{P_A} = \eta_M, \; \eta_C = \frac{P_U}{P_T}\frac{P_T}{P_A} \qquad (2)$$

A method and model of efficiency determination were applied in work [14]. While the laser beam of power P_L = 200 W and focal point diameter of 200 μm barely melts the material, the process of plasma welding with arc power of about 2 kW reaches weld penetration through approximately 2/3 of the blank thickness for the applied set of parameters (Figure 2). A combination of both the processes provides complete penetration welding. While energy combination efficiency η_C rises by just ~10 % compared to arithmetic effectiveness of combining energy η_C of individual processes, melting efficiency η_M of the combined process is approximately 1.5 times higher than that of melting η_M of the plasma-arc process. It can be assumed that the heat flow in the weld pool, controlled by the conductive and/or convective transfer mechanisms, changes favourably to create the resulting cross-section of the weld with increased penetration due to more advantageous thermal and/or hydrodynamic boundary conditions. The authors of work [14] propose to regard it as a clear proof of the hypothesis that the secondary, i.e. thermal effects are responsible for synergic advantages of laser-arc treatment efficiency.

In work [15] it was determined that synergic effect manifestation depends on welding speed. At 2 m/min speed of welding AISI304 steel (δ = 4 mm) exceeding of the hybrid penetration cross-sectional area is equal to the sum of areas produced by laser and plasma processes (~2 kW each), and it reaches 30 %, while for 4 m/min speed it is ~20 %. In work [16] the quantitative evaluation of the synergic effect in laser-arc hybrid welding was performed using a dimensionless parameter of melting energy increment ψ:

$$\psi = \frac{S_H - (S_L + S_A)}{S_L + S_A} \cdot 100\%,$$

where S_H, S_L, S_A are the cross-sectional areas of welds in hybrid, laser and arc welding, respectively.

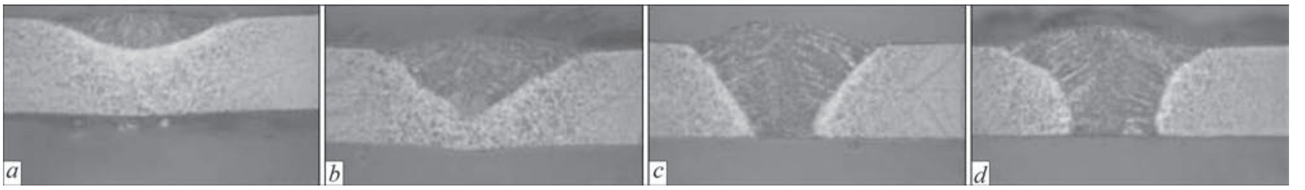


Figure 3. Penetration formation in sheets of S235JR steel 3 mm thick, due to a change of laser radiation power: *a* — 0; *b* — 200; *c* — 330; *d* — 440 W (unchanged parameters: $I = 150$ A; $V = 1000$ mm/min; $Q_P = 0.8$ l/min; $L = 8$ mm, $\beta = 3°$) [17]

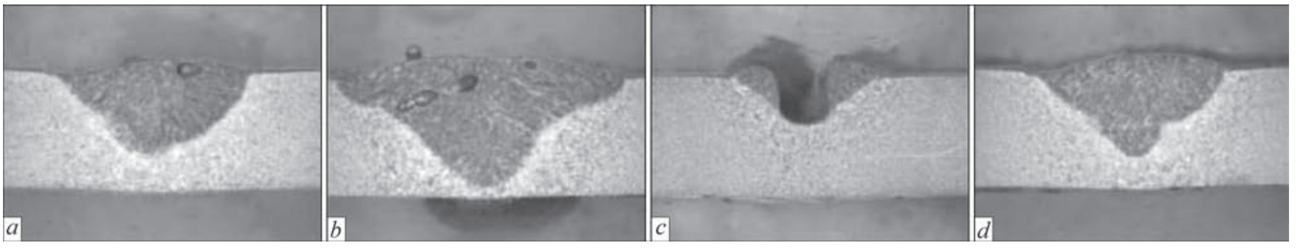


Figure 4. Penetration formation in sheets of S235JR steel 4 mm thick due to a change in laser radiation power: *a* — 0; *b* — 440; *c* — 0; *d* – 440 W and welding speed: *a, b* — 200; *c, d* — 250 mm/min (unchanged parameters: $I = 150$ A; $Q_P = 0.4$ l/min, $L = 8$ mm, $\beta = 19°$) [17]

The larger ψ value, the stronger is the synergic effect. It was calculated that in hybrid laser-TIG welding ψ = 59.3–83.6 %, and at laser-MIG welding ψ = 1–23 %. It can be anticipated that in case of constricted electric arc application in the hybrid process the synergic effect will be even greater than in laser-TIG welding [17]. For laser-plasma welding using Nd:YAG laser this effect can be evaluated by transverse microsections, given in Figures 3 and 4, in keeping with the specified mode parameters.

For realization of laser-plasma welding processes, the focused laser beam can be aimed at the point of interaction with the material at a certain angle, i.e. by the paraxial scheme (Figure 1) (for instance, [18]), or normal to the surface of the product being welded, i.e. by the coaxial scheme (for instance, [4, 19]). The nonconsumable electrode is usually inclined at a certain (minimal possible) angle to the focused laser beam axis [20]. Filler wire can be fed in the direction towards the plasma jet or not fed at all. Metal and alloy powders can be also used as filler materials [21, 22]. Influence of arc current predominantly ensures upper bead formation, while laser radiation power is responsible for penetration depth.

Figure 5. Head for laser-plasma microwelding and cutting of thin metals (radiation power of 100 W, welding current of 40 A) [24]

To achieve the greatest effect from simultaneous application of the laser and plasma, specialists of the Institute for Production Technology together with specialists of the Institute for Material and Beam Technology (Dresden, Germany) developed a hybrid laser-plasma head, designed for up to 100 W radiation power and up to 40 A welding current (Figure 5) [23–26]. During investigation of stainless steel welding by this method it was found [25] that laser beam activation causes an abrupt drop of arc voltage by approximately 1 V (Figure 6, *a*). This phenomenon was observed only in the case of low arc currents. For higher arc currents this effect disappeared (Figure 6, *b*).

In work [26] it was found that under stable arc burning conditions the measured voltage drop after laser beam activation (100 W), is closely related to shifting of the arc impact zone from the position behind the beam focal point to a point irradiated by the laser. In the case of a pure plasma process, the arc is deflected backwards, and the anode region evidently lags behind the arc column axis (Figure 7, *a*). In the case of a variant with laser radiation, this lagging behind becomes smaller, and the arc anode region is stably rooted in the beam focusing zone (Figure 7, *b*). At the same time, an increase of arc voltage by 0.4–0.6 V was observed. The authors of work [26] believe that the main mechanism of arc stabilization should be the surface effect, which is unrelated to changes in arc plasma volume properties, either through direct interaction of laser radiation and arc plasma, or due to a possible change of plasma composition as a result of laser-induced evaporation.

In work [27] a mathematical model was proposed, which showed the potential of laser-plasma process

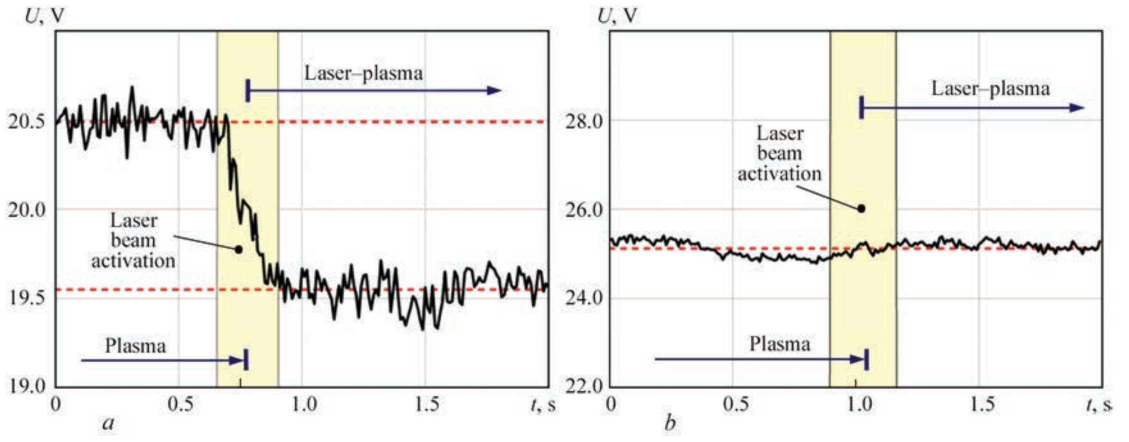


Figure 6. Arc voltage during bead deposition on a plate from AISI304 stainless steel with laser beam support and without it under different welding conditions: *a* — arc current $I = 40$ A; laser power $P = 100$ W, welding speed $V = 0.75$ m/min and sheet thickness $\delta = 1$ mm; *b* — arc current $I = 160$ A; laser power $P = 400$ W, welding speed $V = 2.00$ m/min and sheet thickness $\delta = 3$ mm [25]

in terms of peculiarities of the influence of hybrid thermal cycles on the material microstructure. The model was verified by experiments on laser welding of car body steels. Work [28] describes laser-plasma welding of low-carbon steel plates 6 mm thick at up to 5 kW laser power and up to 150 A arc current, which ensured a 100 % increase of the speed of complete penetration welding or increase of penetration depth by 25–100 %, compared to application of just the laser. It was also found that complete penetration in laser-plasma welding leads to considerable energy losses, because of its release through the keyhole root. All the advantages of the hybrid process are revealed only when the keyhole root is enclosed (in the blank).

Numerical study of the temperature field during 3D printing of thin-walled metal parts by hybrid laser-plasma method shows that the temperature gradient directly determines the grain growth rate in the HAZ of the built-up wall [29]. In work [30] a real-time observation of the parameters of the vapour-gas channel and the weld pool at laser and laser-arc welding was performed. Authors of works [31, 32] showed the good prospects for application of hybrid laser-plasma welding method for joining thin sheet (up to 3–4 mm) stainless steels of austenitic and ferritic grades without filler material application.

In work [33] it was established that in laser-microplasma welding of 7075 alloy ($\delta = 1.5$ mm) the volume fraction of remelted metal defects in the form of pores of 15–25 μm size decreases, compared to microplasma welding, to the level characteristic for laser welding (~5 %). Remelted metal hardness decreases by 15–20 % at HAZ metal hardness close to that of the base metal. For comparison, in the laser process the remelted metal hardness is decreased by ~15 %, and in the microplasma process it is ~30 % (relative to base metal). Obtained data confirm the advantage of the laser-microplasma process, proved in [34]. This method reduces the use of laser energy to 40–50 %, the time of weld pool existence (0.03–0.05 s) becomes close to laser welding, and the risk of alloying element burn-out is eliminated.

The laser-plasma method of material treatment can be used for thermal surface modification, alongside the welding processes, in particular for alloying. In work [35] it is shown that the modes of laser-plasma alloying promote an increase of strength characteristics (by 20 % on average), compared to laser alloying. In work [36] the influence of concentrated energy flows on the materials is considered in the case of laser-plasma hardening, and the possibility of nanostructured layer formation is established. Superthin coatings can be deposited on the part working

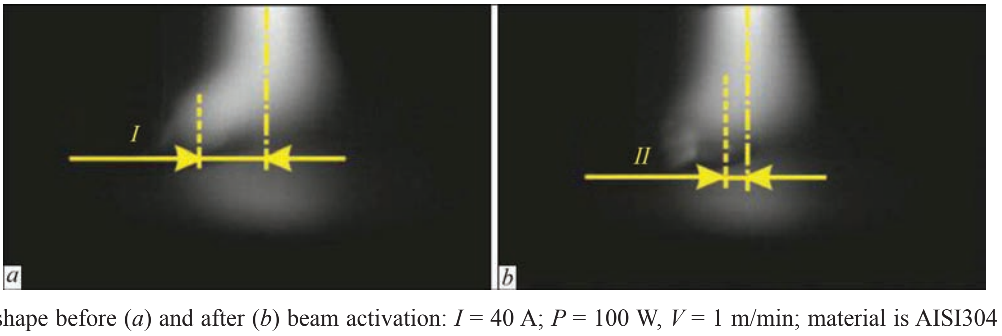


Figure 7. Arc shape before (*a*) and after (*b*) beam activation: $I = 40$ A; $P = 100$ W, $V = 1$ m/min; material is AISI304 stainless steel ($\delta = 1$ mm) [26]

surfaces by an optical pulsed discharge, created by laser-plasma method [37]. In work [38] it is shown that at plate surface exposure to a laser heat source, an intensive subsurface melt flow (~50 cm/s) forms in the molten zone, owing to the dominating impact of the thermocapillary force, generated as a result of a high temperature gradient (~7000 °C/cm) on the metal pool free surface. This flow, directed from the pool axial part towards the melting front, intensifies energy transfer from the pool overheated axial portion to its periphery region, and promotes widening of the melted zone. Influence of convective stirring of the pool on penetration depth is essentially smaller due to a predominantly subsurface melt flow.

DISCUSSION OF THE RESULTS OF LITERATURE SOURCE ANALYSIS

Welding of steels and alloys by highly concentrated heat sources can lead to formation of such characteristic defects as hot cracks, internal pores, softening of the near-weld zone, weld sagging, undercuts and irregular nature of reinforcement bead formation [15, 33, 39]. One of the advanced methods to eliminate the above defects is application of hybrid laser-arc and laser-plasma welding processes [39]. In laser-plasma welding the penetration depth and root bead formation are predominantly ensured by the laser component, and elimination of undercuts and formation of the upper bead are provided by the plasma component [15].

One of the more important aspects of laser welding with deep penetration is formation and containment of the laser vapour-gas channel — the so-called keyhole [40]. The influence of the plasma-component in laser-plasma welding can be assessed by Figure 4, *c*. From this Figure one can see that even in the absence of laser radiation the arc plasma creates a certain sagging due to its own pressure on the weld pool liquid metal, which is a certain keyhole nucleus [17]. It is obvious that in the case of laser radiation penetration to this liquid metal sagging, the conditions for keyhole formation are greatly improved. It can be assumed that formation of the synergic (hybrid) effect in the case of application of laser radiation with λ = 1.03–1.07 μm, occurs both through improvement of laser radiation absorption by liquid metal, molten by the plasma source, and due to formation of weld pool metal sagging under the plasma source impact.

According to the results of high-speed filming described in work [26] (Figure 8), after activation of focused laser radiation, the plasma arc is shortened due to approaching the zone of the laser plume ionized by metal evaporation (i.e. more electrically conductive zone). It promotes a shortening of the plasma arc and arc voltage drop described in work [26]. In the case of plasma arc immersion into the laser keyhole, its elongation can occur, which will lead to a certain increase of arc voltage.

In case of application of laser-plasma powder hybrid welding, energy losses for heat removal into the filler material are eliminated [22]. It promoted introduction of such a technology into shipbuilding [41]. Laser-plasma welding without filler material application is actively used in automotive manufacturing [42]. It is applied for manufacturing tailor welded blanks, overlap welding of zinc-coated steel (with a gap), welding using additional material. Welding of stainless tubes is an example of industrial application of laser-plasma welding without filler material [43].

The future of laser-plasma welding as an independent process is associated with development of an integrated head, which combines two energy sources by a coaxial scheme [42]. One of the examples of such an integrated welding head is the coaxial head shown in Figure 8, *a*, which was developed at the Bremen Institute of Applied Beam Technology (Germany) [44]. This head was later upgraded and fitted with a system of filler wire feed (Figure 8, *b*) [45]. Another example,

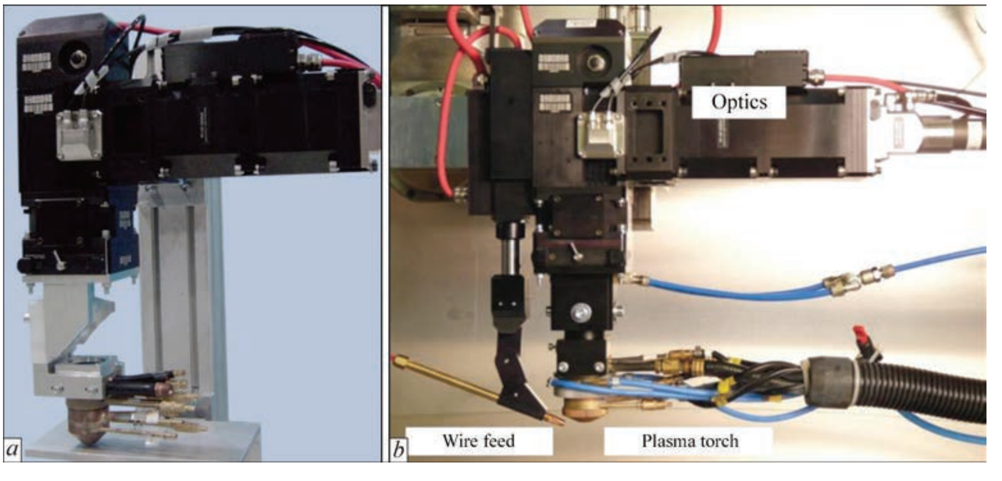


Figure 8. Integrated head for laser-plasma welding: without (*a*) [44] and with (*b*) [45] filler wire feed

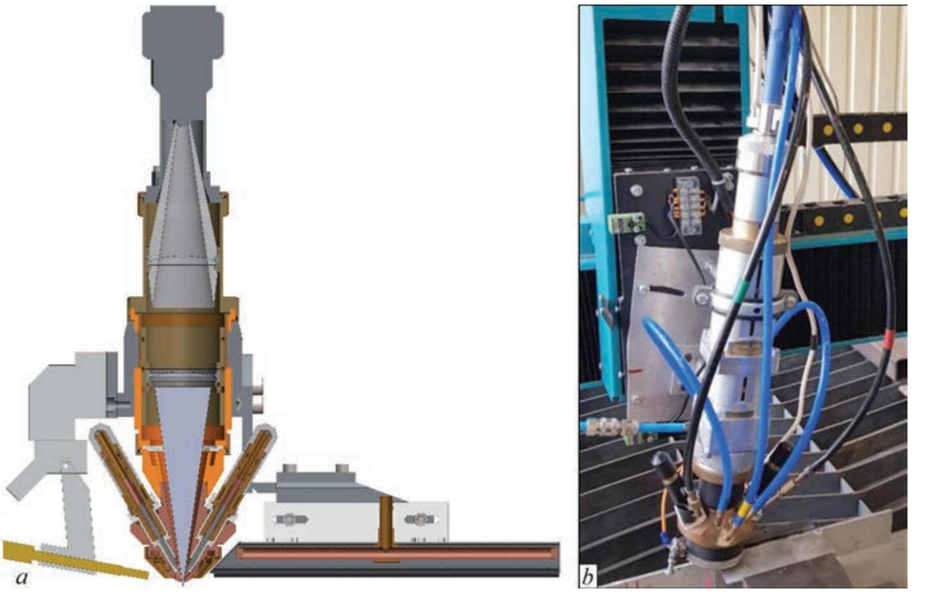


Figure 9. 3D-model (*a*) and appearance (*b*) of the head for laser and laser-plasma welding, developed at PWI [46]

developed at PWI, is the coaxial head for laser-plasma welding (Figure 9) [46].

Conducted analysis of literature data allows defining the following main advantages of the hybrid laser-plasma process, compared to laser one:

● simultaneous use of laser and plasma energy allows reducing the laser power and lowering the equipment cost (estimated up to 40–50 %);

● plasma component of laser-plasma welding allows lowering the requirements to preparation and fit-up of the edges to be welded and removing the oxide film (for aluminium alloys);

● improvement of productivity due to increase of welding speed;

● reducing energy consumption of the process due to increase of its efficiency;

● widening of the deposited bead in laser-plasma surfacing and increase of penetration depth in welding due to a change in hydrodynamic flows in the weld pool.

Further prospects for development of laser-plasma welding and related processes are associated with application of fiber lasers (λ = 1.07 μm), as the most accessible ones for a wide range of users [47]. The plasma component characteristics are related to the metal being welded (straight polarity for steels and multipolar asymmetrical current for aluminium alloys) [48]. Compared to laser welding, laser-plasma process promotes lowering of the requirements to edge preparation, and compared to plasma welding it lowers the residual deformations [49]. Considering an increase in productivity, one can anticipate tendencies of separate laser and plasma welding processes being replaced by laser-plasma welding in industry. Due to ensuring rather high speeds (up to 10 m/min and higher), laser-plasma welding can be used for small-scale production of such thin-walled products and structures from steels and alloys, as regular and profile pipes, body elements of automotive and railway transport, products for food and chemical industry, etc.

One can assume that it is rational to predominantly focus further investigations of laser-plasma welding on relative influence of the radiation of fiber laser and constricted arc on steels and alloys. The prospect here is revealing the features, advantages and disadvantages of such a process with the purpose of establishing the limits of synergic effect manifestation, possibilities for enhancing it and ways to further use this effect.

CONCLUSIONS

1. Current directions of investigation of laser-plasma welding processes are focused predominantly on studying the features of simultaneous impact on steels and alloys of the constricted arc plasma and laser radiation with wave length of 1.03–1.07 μm (first of all, fiber laser), as well as studying the physical fundamentals of the synergic (hybrid) effect manifestation under such an impact, and determination of its possible practical applications. It was determined, for instance, that promotion of the synergic effect manifestation is associated with improvement of the plasma arc burning conditions in the zone of ionized vapour plume, which forms under the impact of focused laser radiation, as well as facilitation of laser keyhole formation due to plasma arc pressure.

2. It was proposed to define the effectiveness of the synergic effect manifestation in laser-plasma welding of steels and alloys as the ratio of the theoretical magnitude of power required for melting the weld material, to the total input welding power, or as a ratio of the cross-sectional area of the laser-plasma process weld

to the sum of the cross-sectional areas of welds, made separately by plasma and laser welding. It was established that the efficiency of laser-plasma welding can vary from 1.5 to 2.4.

3. Application of laser-plasma welding allows prevention of such defects characteristic for laser and plasma welding of high-strength steels and alloys as hot cracks, internal pores, near-weld zone softening, weld sagging, undercuts and irregular formation of the reinforcement bead.

4. Industrial application of high-speed laser-plasma welding is associated with reduction of laser energy (to ~50 %, compared with laser welding), lowering of the requirements to preparation and fit-up of the edges to be welded, increase of welding speed, and minimizing the process energy input. This technology has a considerable potential for industrialization in large-scale productions of thin-walled products and structures (first of all, from stainless steels, titanium and aluminium alloys), such as structures from regular and profile pipes, body elements of railway transport, extended welded panels of aviation and sea transport, critical structures of equipment for food and chemical industry, etc.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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