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Interaction Characteristics of Laser and Plasma Energy Sources in Welding Processes of Steels and Alloys. Review

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This work reviews the current state of development in laser-plasma welding processes for steels and alloys. The novelty of the work lies in revealing the effectiveness of the combined effect of compressed arc plasma and laser radiation with a wavelength of 1.03 – 1.07 μm (mainly from fiber lasers) on steels and alloys and analyzing the possibilities of industrial application of laser-plasma welding, in particular in the pipe industry. Also, for the first time, several scientific papers have been compared, revealing the physical mechanisms underlying the synergistic (hybrid) effect of combining laser and plasma. Specifically, it was determined that increasing the efficiency of the synergistic effect is related to improved plasma arc combustion within the ionized vapor plume generated by focused laser radiation, and also to simplified laser keyhole formation due to plasma arc.

Keywords: laser-plasma welding, synergistic effect, process efficiency, steel, aluminum alloys, industrial applications.

1. INTRODUCTION

The development of hybrid laser-arc and laser-plasma processes began in the late 1970s, attributed to the work of the English scientist W. M. Steen [1]. Subsequently, the concept of combining laser radiation and an electric arc for welding and related processes was further developed in numerous theoretical and practical studies by leading scientists such as A.G. Grigoryants, K. Paul, F. Riedel, I.V. Krivtsun, V.M. Korzhik, and others. In addition to welding, laser-plasma technologies have been used for applying functional coatings [2, 3]. The development of these technologies is based on theoretical and experimental studies of heat conduction processes [4 – 6]. These developments consider not only the technological aspects of laser and plasma processes (e.g., [7 – 9]) but also the metal-physical properties of the materials being welded or deposited [10 – 12]. The influence of laser and plasma process characteristics on the physico-mechanical properties of the resulting structures was also considered [13 – 15], focusing primarily on mechanical [16, 17] and corrosion resistance [18, 19]. The effect of these energy sources on the residual stress-strain state of the resulting products was also considered [20, 21].

However, laser-arc and laser-plasma technologies yielded the best results when applied in welding processes. To date, hybrid welding processes have found both research and industrial applications. For example, they are used in automotive and shipbuilding industries, the production of pipes of various diameters, etc. [22, 23]. In particular, the work [23] demonstrates the potential of laser-arc welding in the automotive industry due to a significant reduction in the susceptibility to hard quenching structure formation, elimination of undercuts, and bridging of weld edge gaps. Laser-plasma welding occupies a prominent position in hybrid welding processes. Most researchers, both in the late 20th century [24] and more recently [25], have considered this process to be quite promising. Therefore, the authors propose a review of its current status to forecast future development.

2. PROBLEM STATEMENT

Works [26 – 28] present the results of analytical modeling for laser-plasma welding and cladding processes, utilizing models of integrated coaxial heads. These studies attributed the enhanced efficiency of coaxial laser-arc discharge to the formation of a combined laser-arc discharge, resulting from the absorption of the CO_2-laser beam, which traverses the center of the arc column, by the compressed arc plasma. In this regard, the degree of laser radiation absorption by the arc plasma was identified as a critical parameter for discharge control. This approach largely established the foundations of hybrid welding 20–30 years ago [24]. Over the past 10 – 20 years, CO_2 lasers have confidently superseded fiber lasers, as their radiation exhibits negligible interaction with arc plasma [29]. This significantly altered the perspective on the hybrid laser-plasma process and the prospects for its industrial application. Modern approaches to the development of welding and related laser-plasma technologies are based on the application of radiation with wavelengths in the range of

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1.03 – 1.07 µm, specifically from fiber, disk, and Nd:YAG lasers. Many questions arise concerning the combined use of arc plasma and the radiation from these specified lasers, particularly fiber lasers, whose radiation can be focused into a spot on the order of 0.01 – 0.1 mm [30, 31].

3. PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of this work is to analyze the current state of scientific research directions and industrial applications of laser-plasma welding processes and to evaluate the effectiveness of the synergistic (hybrid) effect when employing laser radiation with a wavelength of 1.03 – 1.07 µm. To achieve this objective, the following tasks were addressed:

– establishment of contemporary research directions for laser-plasma welding processes;
– determination of the synergistic effect's efficacy in laser-plasma welding of steels and alloys;
– analysis of the laser-plasma process's influence on characteristic welding defects in steels and alloys;
– analysis of the current state of industrial application of laser-plasma welding.

4. ANALYSIS OF LITERATURE DATA

4.1. Brief historical preview

As early as the beginning of the 21st century, Academician I.V. Krivtsun asserted that the primary factors determining the nature of metal penetration during combined laser-arc welding are the thermal and dynamic influences exerted by the utilized heat sources on the surface of the weld pool. Consequently, he developed a system of equations to describe the process of metal evaporation under the influence of the multicomponent plasma generated above the weld pool during laser-plasma welding [32]. Such a system forms the basis for calculating the characteristics of the thermal and dynamic impact of arc, laser, or combined plasma on the surface of the weld pool during corresponding welding methods in protective gases. As a next step, he investigated the characteristics of metal penetration during laser-arc welding using a Nd:YAG laser [33]. The developed mathematical model of thermal processes in laser-arc welding using a Nd:YAG laser and an argon arc allowed for the calculation of penetration profiles under the combined effect of a laser beam and an electric arc on the workpiece, considering their interaction on the metal surface. Calculations have demonstrated a synergistic (hybrid) effect, characterized by a non-additive increase in the volume of metal remelted by the laser-plasma method, in comparison to the volumes of metal remelted independently by laser and plasma methods.

4.2. Analysis of the manifestation of the synergistic effect

To analyze the synergistic coupling effect that emerges during the process, laser-plasma welding can be categorized into three distinct zones [34]: (I) plasma above the surface, (II) the weld pool surface, and (III) interaction occurring directly beneath the surface. Factors such as the combined welding source, the mutual arrangement of laser and plasma sources, and the role and influence of welding parameters, exert the primary influence on the degree of synergistic effect manifestation.

Reference [35] demonstrates that arc characteristics remain practically unchanged during interactions between a 'gas CO_2-laser and helium TIG arc' and a 'disk Yb:YAG-laser and argon TIG arc'. This is attributed to significant differences in the inverse absorption coefficients of bremsstrahlung radiation, stemming from varying electron densities in argon and helium arcs and distinct wavelengths of CO_2 and Yb:YAG lasers. Such research, to some extent, facilitates the partial application of experience gained with CO_2 lasers in hybrid processes involving solid-state laser radiation.

The results of research into the synergistic effect of hybrid laser-arc welding are presented in [36]. Experiments were carried out with a Nd:YAG laser with a power of $P_L = 500$ W in combination with standard equipment for TIG welding. Two aspects were investigated: heat transfer efficiency and melting efficiency. Heat transfer efficiency was determined using calorimetric measurements, and melting efficiency was determined by the cross-sections of weld seams obtained under various welding modes. The results indicate that the interaction between the laser and the arc does not lead to a noticeable alteration in heat transfer efficiency; however, it results in a significant increase in melting efficiency. The non-additive increase in the cross-sectional area of welds, achieved through the combination of two heat sources (laser and arc), signifies the presence of a synergistic effect and the hybrid characteristic of the welding process.

In investigating the manifestation of a synergistic effect during hybrid welding, spectral analysis of the hybrid plasma plume and high-speed photographic analysis of the process [37] serve as valuable tools. In this regard, to obtain accurate results, the selection of the structural research methodology and the determination of the physical and mechanical properties of materials are crucial [38 – 41]. As a result of conducting such investigations, the following has been established. Firstly, the principle of the synergistic effect posits that upon interaction with a constricted non-consumable electrode arc, the laser elevates electron energy to a higher level, thereby creating conditions conducive to a quantum transition. Consequently, more photons are emitted, which enhances the heat input to the material undergoing welding. The synergistic effect is quantitatively determined by the spectral intensity. It increases with escalating laser power and diminishes with the arc current. This effect is proportional to the weld seam's cross-section, particularly its upper portion. Secondly, the amount of spatter in hybrid laser-arc welding is significantly less than that observed in arc welding.

In work [42], a series of studies on laser-plasma welding were conducted following the scheme presented in Fig. 1. The welding efficiency η_W is proposed to be defined as the ratio of the theoretical power P_{FZ}, required for melting the material within the fusion zone (indicated by the index FZ), to the total supplied welding power P_W, as follows:

$$\eta_w = \frac{P_{FZ}}{P_W} = \frac{\rho \cdot w_{ch} \cdot A_{FZ} \cdot \Delta h_{FZ}}{P_W}, \quad (1)$$

where ρ is the mass density of the material being welded, w_{ch} is the travel speed, A_{FZ} is the cross-sectional area of the fusion zone, and $\Delta\eta_{FZ}$ is the required increase in specific enthalpy for melting.

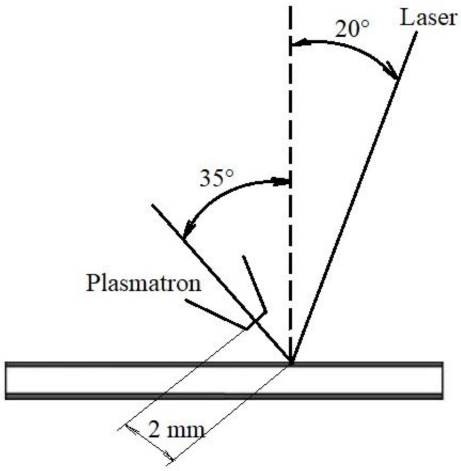


Fig. 1. Scheme of the experimental setup with separate arrangement of the plasmatron and laser beam

Eq. 1 can be considered as the basis for determining the relative welding efficiency, which compares the efficiency of the combined laser-plasma process with the efficiency of individual processes. In this case, we obtain:

$$\eta_{rel} = \frac{\eta_{PL}}{\eta_{P+L}} = \frac{\rho \cdot w_{ch} \cdot A_{FZ,PL} \cdot \Delta h_{FZ}}{P_p + P_L} \cdot \frac{P_p + P_L}{\rho \cdot (A_{FZ,P} + A_{FZ,L}) \cdot \Delta h_{FZ} \cdot w_{ch}} = \frac{A_{FZ,PL}}{A_{FZ,P} + A_{FZ,L}}. \quad (2)$$

In this regard, $A_{FZ,PL}$ denotes the cross-sectional area of the weld seam in the combined laser-plasma process, while $A_{FZ,P}$ and $A_{FZ,L}$ are the cross-sectional areas of the seams individually produced by plasma and laser welding. Calculated values of the measured weld seam cross-sectional areas and their corresponding relative efficiencies are presented in Table 1 for ASTM A284 medium carbon steel, AISI 304 stainless steel, and 6082 aluminum alloy.

One potential reason for the enhanced efficiency of laser-plasma welding, compared to standalone processes, is the alteration of arc voltage when laser radiation is introduced into the plasma-arc process. Specifically, characteristic differences in arc voltage were identified during the welding of steels and aluminum alloys. For aluminum welding, a noticeable decrease in arc voltage, ranging from –2 to –3 V, was observed upon activation of the laser beam. Conversely, for steel welding under identical conditions with a highly focused laser beam, a moderate increase in arc voltage, between 0.15 and 0.6 V, was detected.

If the synergistic effect of hybrid laser-arc processing is understood as an increase in energy transfer from heat sources to the material, then the thermal efficiency or overall process efficiency η_T corresponds to the ratio of power P_U, which is required to melt the welded material per unit of time (without losses), to the total applied power P_A [43]. This quantity can be segmented, in accordance with Eq. 3, into melting efficiency η_M (representing energy utilization within the base material) and energy coupling efficiency η_C (denoting energy input from heat sources) using the power P_T transferred from the heat sources to the workpiece [43]:

$$\eta_T = \frac{P_U}{P_A} = \eta_M \cdot \eta_C = \frac{P_U}{P_T} \cdot \frac{P_T}{P_A}. \quad (3)$$

Considering the heat flux supplied to the workpiece during welding and the dependent energy coupling efficiency η_C, the thermal efficiency η_T is determined by utilizing the evaluated cross-sections of the weld seam in conjunction with Eq. 4 [43]:

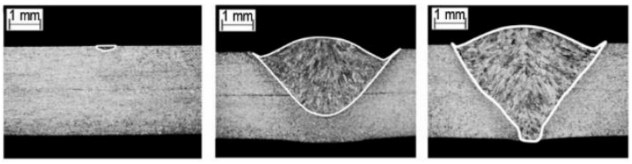
$$\eta_T = \frac{P_U}{P_A} = \frac{v_x \cdot A_S \cdot \rho \cdot (c_\rho \cdot (\vartheta_S - \vartheta_\infty) + h_S)}{U_{Arc} \cdot I_{Arc} + P_L}, \quad (4)$$

where v_x is the welding speed, A_S is the weld seam area, probe density, c_ρ is the specific heat capacity, ϑ_S and ϑ_∞ are the melting and ambient temperatures, h_s is the enthalpy of melting, P_L is the laser power, and U_{Arc} and I_{Arc} are the arc voltage and current, respectively. The melting efficiency η_M is then derived from the application of Eq. 3.

The method and model for efficiency determination were applied in this work [44]. While a laser beam with a power of P_L = 200 W and a focal spot diameter of 200 µm barely melts the material, the plasma welding process, utilizing an arc power of approximately 2 kW, achieves weld seam penetration to approximately 2/3 of the workpiece thickness for the given set of parameters (Fig. 2, Table 2). The combination of both processes results in full-penetration welding. While the energy coupling efficiency η_C is only moderately increased by approximately 10 % compared to the arithmetic energy coupling efficiency η_C of individual processes, the melting efficiency η_M of the combined process is approximately 1.5 times higher than the melting efficiency η_M of the plasma arc process. It can be hypothesized that the heat flux within the weld pool, governed by conductive and/or convective transfer mechanisms, is favorably altered to produce a resultant weld seam cross-section with enhanced penetration, owing to more favorable thermal and/or hydrodynamic boundary conditions. The authors of [44] propose that this be considered clear evidence supporting the hypothesis that secondary, i.e., thermal, effects are responsible for the synergistic performance advantages observed in laser-arc processing.

Table 1. Cross-sectional areas of the weld bead, A_{FZ}, and relative efficiency, η_W, in plasma, laser, and laser-plasma welding of plates (P_L=600 W, I_P=100 A) [42]

No.	Materials	Thickness δ, mm	Welding speed *V*, m/min	$A_{FZ,P}$, mm^2	$A_{FZ,L}$, mm^2	$A_{FZ,PL}$, mm^2	η_W
1	ASTM A284	10.0	0.5	0.4	1.5	3.3	1.74
2	AISI 304	1.5	1.5	0.1	0.7	1.9	2.38
3	6082	2.5	1.5	2.2	1.8	6.0	1.50



a b c

Fig. 2. Cross-sections of AISI304 steel welding (δ = 1 mm) performed by laser ($a – P_L$ = 200 W; ω_0 = 200 µm), plasma ($b – Q_P$ = 1.8 l/min; d_W = 5 mm), and laser-plasma welding (LaPAW) ($c – P_L$ = 200 W; ω_0 = 200 µm; Q_P = 1.8 l/min; d_W = 5 mm) with the efficiency values given in Table 2 (Adapted from [44], under CC BY 4.0 license)

Table 2. Welding efficiency values of AISI304 steel [44]

Efficiency	Values, %			Efficiency gain, %
	Laser	Plasma	LaPAW	
Coupling	29.5	67.2	71.6	9.9
Melting	5.8	10.6	15.8	53.4
Thermal	1.7	7.1	11.3	68.7

In this work [45], the presence of a synergistic effect in laser-plasma welding utilizing a fiber laser was confirmed by comparing the cross-sectional areas of welds. These welds were executed on TC4 titanium plates of the Ti-6Al-4V system (δ = 3 mm) and AISI 304 stainless steel (δ = 4 mm) using laser, plasma, and hybrid methods, under comparable power levels for both laser radiation and the plasma arc (approximately 2 kW each). It was determined that the manifestation of this effect depends on the welding speed. At a welding speed of 2 m/min, the cross-sectional area of the hybrid weld fusion zone exceeds the sum of the areas obtained by laser and plasma methods by 30 %, while at 4 m/min, this excess is approximately 20 %.

In [46], a dimensionless parameter of melting energy gainψ ($\psi = \frac{S_H-(S_L+S_A)}{S_L+S_A} * 100\%$, where S_H, S_L, and S_A denote the cross-sectional areas of hybrid, laser, and arc welding seams, respectively. A higher value of ψ indicates a stronger synergistic effect. The ψ values were calculated and compared for various parameters of laser-TIG and laser-MIG hybrid welding processes. Laser-TIG exhibited a more pronounced synergistic effect (ψ = 59.3 – 83.6 %) compared to laser-MIG (ψ = 1 – 23 %). It is anticipated that incorporating arc plasma (i.e., a compressed electric arc) into the hybrid process will yield an even greater synergistic effect than that observed in laser-TIG welding [47].

4.3. Analysis of experimental studies

For the implementation of laser-plasma welding processes, a focused laser beam can be directed to the point of interaction with the material at a specific angle, i.e., using a paraxial scheme (Fig. 1) (e.g., [48]), or perpendicularly to the surface of the workpiece, i.e., using a coaxial scheme (e.g., [28, 49]). Structurally, a laser-plasma welding head may consist of discrete elements, namely a laser focusing system and a plasmatron, or be integrated within a single housing. The plasma torch is typically angled at a specific (minimally attainable) inclination relative to the axis of the focused laser beam [50]. The filler wire can be introduced counter to the plasma jet or entirely omitted. Additionally, metal and alloy powders [51, 52] can be utilized as filler materials. When employing powdered filler materials, crucial technological parameters for welding include the distance between the workpiece and the laser-plasma head, as well as the arc current [52]. The arc current primarily governs the formation of the top bead, whereas the laser radiation power dictates the depth of penetration (Fig. 3).

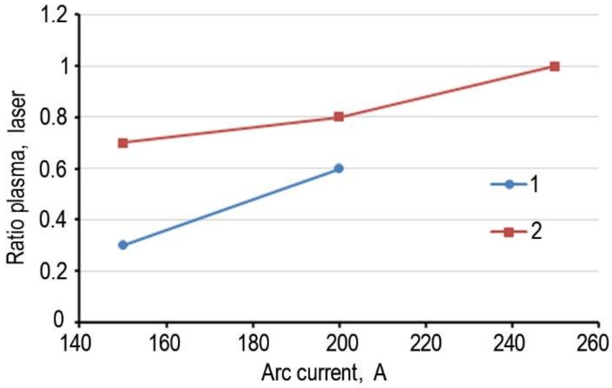


Fig. 3. Laser-plasma welding with powder additive: the ratio of the areas of remelted metal in the cross-section of the weld seam obtained by the plasma and laser components, depending on the plasma arc current for two different welding speeds: 1 – vs 2.5 m/min; 2 – vs 2 m/min

To maximize the synergistic effect of combined laser and plasma application, experts from the Institute of Manufacturing Technology, in collaboration with specialists from Fraunhofer IWS Dresden (Dresden, Germany), developed a hybrid laser-plasma head (Fig. 4) [29 – 56].

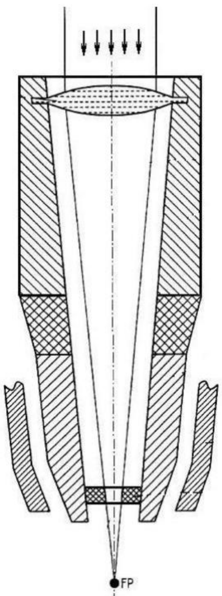


Fig. 4. The design of an integrated plasma torch with a hollow cathode that allows laser radiation to be fed coaxially and perpendicular to the surface of the product being welded (Adapted from [54], Patent)

This head is designed for laser radiation power up to 600 W and welding current up to 100 A, intended for microwelding of thin metals. During the investigation of stainless steel welding using this method, it was observed [42] that laser beam activation causes a sharp drop in arc voltage of approximately 0.5 – 1 V for a given set of parameters. However, this phenomenon was noted only at low arc current values. For higher arc currents, the effect diminished.

In this work [56], it was found that under stable arc combustion conditions, the measured voltage drop following the activation of a laser beam (with a power of 100 W) is closely correlated with the displacement of the arc's active zone from a position posterior to the beam's focal point to the laser-irradiated point. In the pure plasma process, the arc deviates above the workpiece surface, and the anode region of the arc distinctly lags behind the axis of the arc column.

Conversely, with the inclusion of laser radiation, this lag is diminished, and the anode region of the arc becomes stably anchored within the beam's focal zone. Concurrently, an increase in arc voltage of 0.4 – 0.6 V was observed. A similar activation effect was not observed when the arc acted at the same location without the support of a laser beam. The authors of [56] posit that the primary mechanism for arc stabilization is a surface effect, unrelated to changes in the bulk properties of the arc plasma, whether through direct interaction between laser radiation and arc plasma, or through a potential alteration of plasma composition resulting from laser-induced evaporation.

In this work [57], a model is proposed detailing the action of both laser radiation and combined radiation with an electric arc (plasma jet). The prospects of the laser-plasma process are demonstrated through the lens of hybrid thermal cycle characteristics impacting material microstructure. The model was validated through experimental laser welding of automotive body steels.

Experiments involving the laser-plasma welding of 6 mm thick low-carbon steel plates, utilizing a laser power of up to 5 kW and an arc current of up to 150 A, demonstrated a 100 % increase in welding speed with full penetration, or a 25 – 100 % increase in penetration depth, when compared to the use of laser alone [58]. It has also been established that full penetration in laser-plasma welding leads to significant energy losses due to its escape through the keyhole root. All advantages of the hybrid process are manifested only when the keyhole root is closed (within the workpiece).

A three-dimensional nonlinear finite element method, combined with a Monte Carlo model, was developed in work [59] to investigate the temperature field and grain growth in the heat-affected zone (HAZ) during 3D printing of thin-walled metal parts using a hybrid laser-plasma method. Numerical research indicates that the temperature gradient directly determines the grain growth rate within the heat-affected zone (HAZ) of the deposited wall. In this work [60], the fundamental feasibility of real-time monitoring of vapor-gas channel parameters and the weld pool during laser and laser-arc welding is demonstrated through the registration of indirect informational signals from the active zone.

Research findings by the authors in [61, 62] demonstrate the promise of hybrid laser-plasma welding for industrial applications involving the joining of thin-sheet (up to 3 – 4 mm) austenitic and ferritic stainless steels. It has been established that the application of filler materials is not required for the hybrid welding of these steels. Joints produced by this method are not inferior to the quality of laser welding in terms of their mechanical properties; in some cases, they surpass it, and they significantly exceed the quality achieved by plasma welding.

In this work [63], the structural characteristics of butt-welded joints in 1.5 mm thick plates of high-strength aluminum alloy 7075 (Al-Zn-Mg-Cu system) were investigated. Welding was performed using three methods: laser, microplasma, and hybrid laser-microplasma. It was determined that in laser-microplasma welding, the volumetric fraction of defects in the remelted metal, specifically pores ranging from 15 to 25 μm in size, decreases to a level characteristic of laser welding (~ 5 %), relative to microplasma welding. The hardness of the remelted metal decreases by 15 – 20 % when the heat-affected zone (HAZ) metal's hardness is comparable to that of the base metal. For comparison, the laser welding method yields a reduction in remelted metal hardness of approximately 15 %, whereas the microplasma method results in a reduction of approximately 30 % (relative to the base metal). Microcracks were not detected in the weld metal. Overall, the analysis of the research results confirmed the advantage of the laser-microplasma method, as previously demonstrated in reference [64]. This method reduces laser energy consumption by 40 – 50 %, the weld pool existence time (0.03 – 0.05 s) approximates that of laser welding, and the risk of alloying element burnout is eliminated.

Beyond welding processes, the laser-plasma method of material processing can be applied for the thermal modification of surfaces, including alloying. Thus, work [65] demonstrates that laser-plasma alloying regimes contribute to an increase in strength characteristics (by an average of 20 %) compared to alloying with laser radiation. In work [66], utilizing the example of laser-plasma strengthening, the influence of concentrated energy fluxes on materials is examined, and the possibility of forming nanostructured layers has been established. Ultrathin coatings can be formed on the working surfaces of components through an optical pulsating discharge generated by a laser-plasma method [67]. In this work [68], it is demonstrated that when a laser heating source interacts with the surface of a plate, an intense (~50 cm/s) near-surface melt flow is generated within the molten zone. This phenomenon is attributed to the dominant effect of thermocapillary forces, which arise from a high-temperature gradient (~7000 °C/cm) at the free surface of the metallic melt pool. This flow, directed from the axial region of the weld pool towards the melting front, intensifies energy transfer from the superheated axial area of the pool to its peripheral region, thereby contributing to an increased width of the melted zone. The influence of convective mixing within the weld pool on the depth of penetration is significantly diminished due to the predominantly near-surface flow of the melt.

5. DISCUSSION OF THE RESULTS FROM LITERATURE ANALYSIS

During the welding of steels and alloys with highly concentrated heat sources, characteristic defects such as hot cracks, internal pores, softening of the heat-affected zone, weld sagging, undercuts, and irregular reinforcement bead formation may occur [45, 63, 69]. To minimize the susceptibility to the formation of the aforementioned defects and to achieve high-quality joints, it is advisable to carefully select welding parameters, remove oxide film from the surface of workpieces before welding, ensure reliable protection of the weld pool from atmospheric exposure, and, in certain cases, utilize filler materials and pre- or concurrent heating. One progressive method for eliminating these defects involves the application of hybrid laser-arc and laser-plasma welding techniques [69]. Consequently, in laser-plasma welding, the laser component primarily dictates the speed, precise joint positioning, and root bead formation. Conversely, the plasma component predominantly ensures the elimination of undercuts along the weld, bridging of joint gaps, penetration depth, and the formation of the upper reinforcement bead [22, 45, 46].

One of the most critical aspects of deep penetration laser welding is the formation and sustained existence of the laser vapor-gas channel, commonly referred to as a keyhole [71]. The influence of the plasma component in laser-plasma welding can be evaluated through findings presented in [47]. This research demonstrates that even in the absence of laser radiation, the inherent pressure exerted by the arc plasma on the molten metal within the weld pool generates a discernible depression, which constitutes a rudimentary keyhole. It is evident that when laser radiation impinges upon this depression in the liquid metal, the conditions for keyhole formation are significantly enhanced. It can be hypothesized that the synergistic (hybrid) effect observed when utilizing laser radiation with a wavelength of 1.03 – 1.07 µm results both from improved absorption of laser radiation by the liquid metal, pre-melted by the plasma source, and from the formation of a metal depression in the weld pool by the plasma source.

According to the high-speed video recording results detailed in this work [56], following the activation of focused laser radiation, the plasma arc contracts. This contraction is attributed to the proximity of the ionized metal vapor plume, a region of enhanced electrical conductivity, to the laser plume zone. This phenomenon contributes to the contraction of the plasma arc and the corresponding voltage drop across the arc, as described in this work [56]. Should the plasma arc penetrate deeper into the laser keyhole, its elongation may occur, resulting in a consequential increase in arc voltage.

In this work [52], it is demonstrated that acceptable welds can be achieved through the application of laser-plasma powder hybrid welding in both vertical-up and vertical-down positions. Researchers' interest in this welding method stems from two primary factors: the decoupling of filler material supply from the arc energy, and the mitigation of energy losses attributable to heat dissipation into the filler material. Consequently, this technology has garnered interest from researchers for its potential implementation in shipbuilding [72]. Furthermore, laser-plasma welding, without the application of filler materials, is actively utilized in automotive manufacturing [73]. It is employed for the fabrication of tailor-welded blanks, the lap welding of zinc-coated steel (with a specified gap), and welding processes incorporating additional material.

Compared to laser welding (LW), plasma arc welding (PAW), and conventional arc welding methods (TIG, MIG/MAG), hybrid laser-plasma and laser-arc welding processes exhibit specific advantages and characteristics that facilitate their application in distinct industrial sectors. The corresponding comparative characteristics of these welding methods are presented in Table 3.

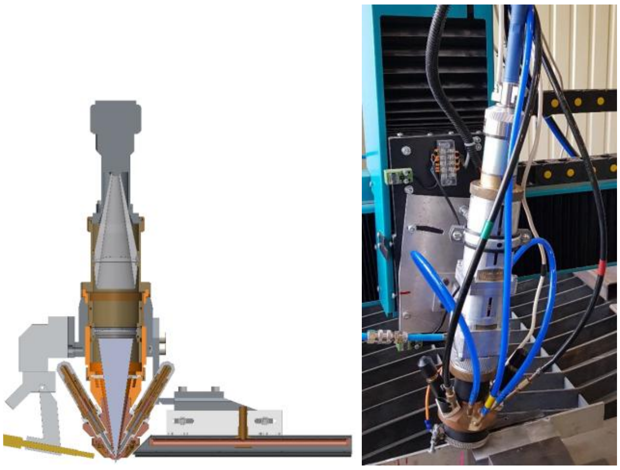
Table 3. Comparison of applicable materials and characteristics for various welding methods [22]

Method	Applicable materials	Process overview	Advantages	Disadvantages	Best application scenarios
Hybrid laser-plasma (laser-arc) welding	Stainless steels, aluminum, titanium, and high-strength steels	Combines laser and arc welding for deep penetration and high precision	High speed, deep penetration, smaller HAZs	Complex control, high equipment cost	Suitable for welding medium-thick and thick plates, providing excellent weld formation with minimal defects and a wide range of industrial applications
LW	Thin metals, high-strength steels, aluminum, and non-ferrous alloys	Uses a focused laser beam for high precision with minimal heat distortion	High precision, low distortion, fast	Limited to thin materials, high initial cost	Ideal for welding thinner plates because of its high precision and low heat input, commonly used in industries such as electronics and aerospace
PAW	Stainless steels, titanium, nickel alloys, and non-ferrous metals.	Uses a focused plasma arc for high energy density and deep penetration	High precision, deep penetration, clean welds	Complex process, high operational costs	Well suited for welding difficult materials (such as titanium and nickel alloys) that require deep penetration, particularly in aerospace and high-end manufacturing sectors
TIG	Stainless steels, aluminum, copper alloys, etc	Non-consumable tungsten electrodes with optional filler materials	Clean, precise welds, good for thin metals	Slow speed High skill required Porosity risk	Optimal for welding lightweight materials, thanks to its high precision, and frequently applied in aerospace, automotive, medical, and other industries
MIG / MAG	Carbon steels, stainless steels, aluminum, etc	Uses an electric arc and consumable electrode with shielding gas	Versatile, high deposition rate, easy automation	Larger HAZs, less precise, more spatter	Ideal for thick plate welding and large-scale production, with high deposition rates, and commonly used in shipbuilding and heavy industries

This table demonstrates that hybrid welding processes can be successfully implemented in the aerospace, automotive, railway, and shipbuilding industries.

An example of the industrial application of laser-plasma welding without filler material is the laser-plasma welding of small-diameter stainless steel pipes [74]. The efficiency of such a process is determined by the multiple reflection of the laser beam within the V-shaped groove, which is formed during the rolling of a thin stainless steel strip into a welded pipe. Concurrently, the additional energy from the plasma arc enhances the overall welding speed and reduces sensitivity to the joint gap.

Overall, the application of laser-plasma welding is associated with sectors of welding technologies where the process offers distinct advantages, such as the fabrication of customized welded blanks, lap welding of coated steel, and the joining of workpieces with varying thicknesses [73]. The future of laser-plasma welding as an independent process is contingent upon the development of an integrated head that coaxes two energy sources. According to reference [73], this configuration ensures high welding productivity and a more compact physical realization. One example of such an integrated welding head is the coaxial head which was developed at the Bremen Institute of Welding (Germany) [75]. This head was subsequently modernized and equipped with a filler wire feeding system [76]. Another example is the coaxial head for laser-plasma welding developed at the E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine (Fig. 5).



a b

Fig. 5. a – 3D model; b – external view of the head for laser and laser-plasma welding, developed at the E.O. Paton Electric Welding Institute

The analysis of literature data allows for the formulation of the following primary advantages of the hybrid laser-plasma process compared to laser welding:

– the combined utilization of laser and plasma energy facilitates a reduction in laser power requirements and a corresponding decrease in equipment costs (estimated at up to 40 – 50 %);
– the plasma component inherent in laser-plasma welding mitigates the stringent requirements for the preparation and assembly of welded edges;
– enhanced productivity is achieved through an increased welding speed;
– a reduction in energy intensity is realized by improving process efficiency;
– expansion of the deposited bead during laser-plasma surfacing and an increase in penetration depth during welding due to alterations in hydrodynamic flows within the weld pool.

Further prospects for the development of laser-plasma welding and related processes are linked to the reduction of process and equipment costs, alongside an increase in productivity. Recently, fiber lasers have achieved widespread industrial adoption, with their cost progressively decreasing and becoming increasingly accessible to a broad spectrum of manufacturers [77]. Consequently, among all solid-state lasers operating within the 1.03 – 1.07 μm wavelength range, fiber lasers (λ = 1.07 μm) exhibit the greatest potential. These systems should be considered as the laser component for subsequent investigations into hybrid laser-plasma processes. The characteristics of the plasma component are contingent upon the specific metal being welded. For instance, direct current polarity suffices for welding steels, whereas for welding aluminum alloys, the application of an asymmetric alternating current is advisable [78]. The enhanced productivity of laser-plasma welding is primarily attributable to the potential for increased welding speed and diminished requirements for welded edge preparation, in comparison to conventional laser welding. In contrast to plasma welding, laser-plasma welding not only augments processing speed but also substantially mitigates residual deformations [79]. Consequently, a trend towards the industrial adoption of laser-plasma welding, replacing separate laser and plasma welding processes, can be anticipated. Overall, by achieving sufficiently high speeds (up to 10 m/min and beyond), laser-plasma welding is applicable for the serial production of thin-walled products and structures made from steels and alloys, including conventional and profiled pipes, automotive and railway vehicle body components, and articles for the food and chemical industries, among others.

Considering the described prospects for the industrial development of laser-plasma welding, it can be assumed that research and development efforts should primarily focus on the mutual influence of fiber laser radiation and a constricted arc on steel and alloys. The prospect of this research is to identify the characteristics, advantages, and disadvantages of such a process to establish the boundaries for the emergence of a synergistic effect, the possibilities for enhancing its action, and avenues for future application.

6. CONCLUSIONS

1. The key feature of hybrid laser-plasma welding is the stable synergistic effect of the interaction of its energy components. It has been established that the enhancement of this synergistic effect is due to improved plasma arc combustion conditions in the ionized vapor plume generated by focused laser radiation, as well as to the simplification of the laser channel formation process under the influence of plasma arc pressure. Prospects for further research in laser-plasma welding lie in studying the emergence of a stable synergistic effect using fiber laser radiation.

2. The efficiency of the synergistic effect in laser-plasma welding of steels and alloys is proposed to be determined as the ratio of the theoretical power required to melt the weld material to the total applied welding power, or as the ratio of the cross-sectional area of the laser-plasma weld to the sum of the cross-sectional areas of welds separately produced by plasma and laser welding. It has been established that the efficiency of laser-plasma welding can vary from 1.5 (for aluminum alloy 6082) to 2.4 (for AISI304 steel). The presence of a steady-state synergistic effect in laser-plasma welding can also be determined by an arc voltage drop of 1 V or more, compared to plasma welding.
3. The industrial application of high-speed laser-plasma welding is associated with a reduction in laser energy (up to ~50 % compared to laser welding), diminished requirements for the preparation and assembly of welded edges, an increased welding speed, and a minimization of the specific energy consumption of the process. This technology holds significant promise for extensive industrialization in the mass production of thin-walled products and structures (primarily from stainless steels, titanium, and aluminum alloys). Examples include structures fabricated from conventional and profile pipes, body components for railway transport, long welded panels for aerospace and marine applications, and critical equipment structures for the food and chemical industries, among others.

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