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Abstract

Over the past 20 years, laser beam–electric arc hybrid welding has gained popularity, enabling high quality and efficiency standards needed for steel welds in structures subjected to severe working conditions. This process enables single-pass welding of thick components, overcoming issues concerning the individual use of traditional processes based on an electric arc or laser beam. Therefore, thorough knowledge of both processes is necessary to combine them optimally in terms of efficiency, reduced presence of defects, corrosion resistance, and mechanical and metallurgical features of the welds. This article aims to review the technical and metallurgical aspects of hybrid welding reported in the scientific literature mainly of the last decade, outlining possible choices for system configuration, the inter-distance between the two heat sources, as well as the key process parameters, considering their effects on the weld characteristics and also taking into account the consequences for solidification modes and weld composition. Finally, a specific section has been reserved for hybrid welding of clad steel plates.

Keywords: hybrid welding; system configurations; welding parameters; solidification; steel; clad steel



Academic Editor: Dulce Maria Rodrigues

Received: 18 June 2025

Revised: 7 July 2025

Accepted: 17 July 2025

Published: 22 July 2025

Citation: Costanza, G.; Giudice, F.; Missori, S.; Scolaro, C.; Sili, A.; Tata, M.E. An Overview of the Working Conditions of Laser–Arc Hybrid Processes and Their Effects on Steel Plate Welding. *J. Manuf. Mater. Process.* **2025**, *9*, 248. <https://doi.org/10.3390/jmmp9080248>

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1. Introduction

Welded joints are key factors in the safety of steel structures, particularly for pressure vessels and devices in petrochemical and nuclear plants, as well as for shipbuilding, where severe operating conditions require the use of thick plates. In this case, traditional arc welding processes exhibit some limitations in achieving quality and efficiency levels required by standards, as well as, for other reasons, use of a laser beam. Recently, laser–arc hybrid welding (LAHW or HLAW) has proven to be a valid alternative solution, integrating the characteristics of the two processes and overcoming their respective shortcomings [1]. In this case, the term hybrid refers to the close and simultaneous action of a laser and an electric arc.

Since the 1990s, single-pass LAHW has been recognized as a useful method for joining thick sections due to its ability to achieve deep weld penetration into steel components. This type of process attracted the attention of the scientific community after the publication in 1978 of a research article by Steen et al. [2], who showed the advantages of combining the two heat sources, such as an appreciable increase in welding speed and penetration

depth along with increased process stability. However, only since the late 1980s has the development of high-power laser devices prompted researchers to investigate the various issues related to making the combined process applicable at the industrial level. Initially, the high cost of the apparatus and the large number of control parameters were the main limits to the use of this technique. Its diffusion occurred from 2000 onwards when an integrated welding system was developed by Fraunhofer ILT and utilized by a Germany company for oil tank manufacturing [3]. Since then, the diffusion of integrated welding systems has benefited from the falling costs of new high-power laser equipment.

The evolution of LAHW processes is graphically summarized in Figure 1. In particular, over the last 10 years, it has been supported by the use of solid-state lasers and the development of integrated laser–arc devices.

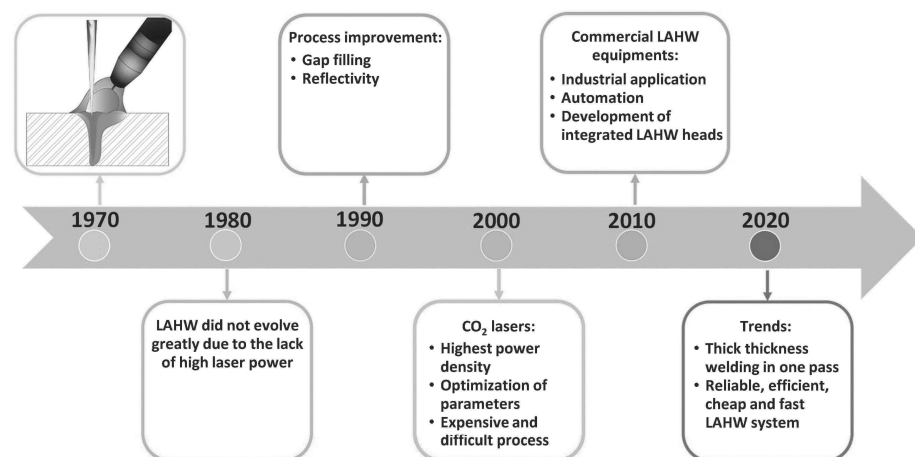


Figure 1. Evolution of LAHW processes. Reproduced from [4].

1.1. Arc Welding Processes

In general, it can be stated that arc welding involves high working time and costs, which is also because adequate preparation of the plates is required. In the case of thick steel plates, conventional arc welding methods consist of multiple passes where the filler metal is introduced by melting the continuous wire electrode [5]. In the case of large thicknesses, it is necessary to prepare the plates with chamfered edges and then fill the grooves with a low-speed arc process, which in turn determines high heat input and hence high residual stresses [6].

Each pass of arc welding can produce phase transformations and recrystallization processes in the fusion zone (FZ) of the previous passes; furthermore, due to distinct thermal histories of each pass, arc welding generates different structures in the heat-affected zone (HAZ) along fusion boundaries [7]. Thermal cycles of multi-pass welding lead to partial HAZ tempering, while the HAZ region close to the fusion line (namely, the coarse-grained heat-affected zone) exhibits significant grain growth and austenitization [8]. In this case, the application of preheating and post-weld heat treatments appears as a potential solution, even if it is expensive. Several studies showed that in electric arc-welded joints, mechanical properties are noticeably improved by pre- and/or post-weld heat treatments; for example, Vairamani et al. [9] reported their experimental investigations on the effects of heat treatments performed after gas metal arc welding (GMAW) of Corten steel, which enabled them to achieve better values of impact strength and hardness. More recently, Aninda et al. [10] demonstrated the advantages of post-weld heat treatments on mild steel joints by comparing their mechanical and microstructure features with those in the as-welded condition. For a detailed description of the various welding processes, see the current literature on this topic [11].

1.2. Laser Beam Welding

Industrial laser devices operate in continuous or pulsed mode, and their classification into two macro-categories is based on the wavelength of the incident radiation. The laser beam generated by a CO₂ apparatus has a wavelength of 10.6 μm , the solid-state Nd:YAG laser works with a wavelength of 1.06 μm , and other fiber lasers work in the range of 1–2 μm [12]. Consequently, the last two result in lower reflectivity of metal surfaces, improving their effectiveness at absorbing energy. Therefore, they have become more widespread than CO₂ devices. For this reason, over the last 10 years, the use of CO₂ lasers has been progressively reduced, and the production of hybrid joints has been carried out using predominantly solid-state lasers with wavelengths between 1.03 and 1.07 μm [13].

Due to the high levels of energy density, laser beam welding (LBW) enables deep penetration, representing a valid solution to overcome issues due to the multiple pass procedure required for joining thick plates [14]. It is a faster and cleaner process in comparison with conventional arc welding. However, LBW requires significant investment, and it does not allow for a wide range of workpiece positions. Furthermore, its ability to fill gaps is poor, and, consequently, high precision in the preparation of the edges is required [1].

LBW has spread due to its high welding rate and power density [15]. Working in the keyhole mode, the FZ area can be minimized; in this way, narrow, high-quality welds with reduced chances of thermal distortion can be obtained. However, cooling rates of LBW, associated with low heat input but concentrated in a small volume [16], are faster than those of arc welding. Therefore, they can give rise to hard martensitic microstructures. In addition, this technique can also lead to other issues, such as high-temperature cracking, underfill, porosity, and other defects, associated with rapid cooling and solidification [17]. For a comprehensive review of LBW issues, see the recent guide edited by Pereira et al. [18].

1.3. Laser–Arc Hybrid Process

The typical defects of welding carried out individually with an electric arc or laser beam can be overcome by developing laser–arc integrated processes. Nowadays, they are widespread due to their capability of combining the low power and high energy density of the laser beam with the opposite features of the electric arc (high power and low density). In this way, the drawbacks of each are mutually compensated for, while the advantages are maximized, thus improving welding quality [19]. Effectively, the penetration depth achievable with a given laser beam power can be increased by the synergetic contribution of the electric arc, whose improving effect is also reflected in other aspects listed below.

- Laser power is the main parameter affecting the penetration depth. The electric arc increases both penetration depth and width for all levels of applied laser power [20]. As such, LAHW can be performed at higher welding speeds than those of traditional processes [21].
- Thick plates can be joined using single-pass LAHW [22], overcoming the re-heating and re-melting issues that affect the multiple passes of a typical arc welding process.
- The upper zone of the weld is predominantly influenced by the electric arc, while deep penetration is due to the keyhole action of the laser [23].
- LAHW results in high filling efficiency of the consumable electrode, and, in general, the welds exhibit better properties in comparison to technologies adopting only one heat source [24].
- Given the greater tolerance for misalignments exhibited by the electric arc, LAHW demonstrates superior bridgeability in comparison to LBW [25].
- The heat input due to the electric arc lowers the cooling rate, leading to reduced hardness compared to autogenous LBW [1].

- Residual stress can also be significantly reduced in comparison with the traditional arc welding techniques [26].

Regarding the last point, the comparisons of the characteristics of hybrid welded joints (gas metal arc followed by laser beam) and submerged arc welded joints of high-strength thick steel plates conducted through numerical–experimental investigation clearly highlighted a substantial decrease (10–15%) in the longitudinal residual stresses due to the hybrid welding process [27]. This result has been substantially confirmed by other authors, who compared the effects due to the same type of welding setups (metal gas arc leading configuration with trailing laser beam vs. submerged arc) on carbon steel, with more detailed findings [28]. LAHW produced a wider distribution of the longitudinal residual stresses than the submerged arc, with a lower maximum value for the tensile stresses and higher values for the compressive ones. The transverse stresses were comparable, and the normal stresses were higher for the submerged arc. Analogously, according to Ragavendran et al. [29], both laser–TIG and laser–MIG hybrid welding produced smaller heat-affected zones and lower residual stress distributions in the weld region of austenitic stainless steel compared to laser welding.

As a general result, numerical simulations demonstrated a more uniform distribution of residual stresses in joints obtained using LAHW [26]. Table 1 summarizes a qualitative comparison of the residual stress distribution in arc, laser, and hybrid welding and their correlation with heat input, the cooling rate, and the width of HAZ.

Table 1. Comparison of residual stress distribution with correlated parameters [26].

Parameter	Arc Welding	Laser Welding	Hybrid Welding
Heat input	High	Low	Medium
Cooling rate	Slow	Very fast	Intermediate
HAZ	Large	Small	Medium
Residual stress	High (tensile in weld zone)	Localized (high near weld)	Moderate (uniformly distributed)

By integrating laser technologies with any arc systems, such as gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), submerged arc welding (SAW), cold metal transfer (CMT), and plasma arc welding (PAW), it is possible to develop different technical solutions for combined laser–arc processes. This allows for the satisfaction of a wide variety of operational requirements of the welds, meeting requirements for good mechanical properties and corrosion resistance for chemical, petrochemical, and power generation industries. A detailed review of the key characteristics of the different LAHW processes, as well as their industrial relevance, was proposed by He et al. [30].

At the same time, the need for a fair balance between materials properties and production costs has been considered. Concerning the economic benefits of LAHW, the reduction in the number of layers and the lower consumption of filler material and energy have enabled increased productivity in heavy industry. Recently, Zhang et al. [31] joined two plates of Q355B steel, 20 mm thick, performing only three passes of LAHW using the arc-leading configuration. In [22], Acherjee demonstrated that steel plates up to 25 mm thick can be joined through single-pass LAHW at a welding speed of 1 m/min. Brunner et al. [32], performing LAHW of the steel structures (25 mm thick) of a wind tower in a single pass, showed the possibility of reducing the processing time, thus increasing productivity. For example, by comparing LAHW with SAW of 25 mm thick steel plates in five to six layers, the processing time was reduced more than 80%, saving up to 90% of the processing cost (Figure 2).

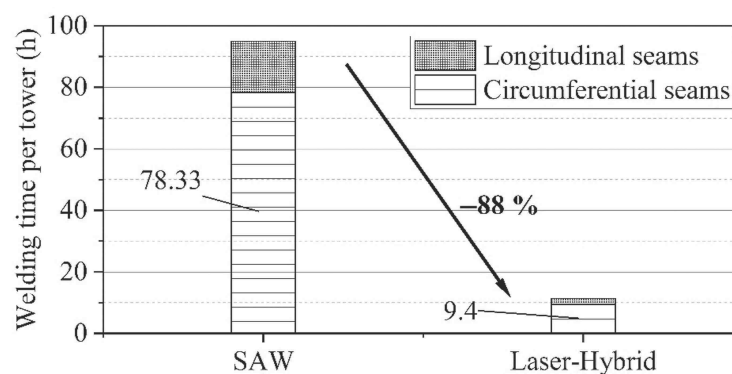


Figure 2. Welding times for comparison of multilayer SAW and single LAHW of a steel tower (length 120 m, diameter 5 m, plate thickness of 25 mm). Reproduced from [32].

Due to high penetration depth, which allows for welding in a single pass, LAHW consumes less energy and requires less working time than GMAW, as shown in a comparative study carried out by Bunaziv et al. [33]. The results of their experiments are summarized by the diagram in Figure 3, which illustrates the time required for producing a weld bead that is 1 m long to join 40 mm thick steel plates using GMAW, LAHW combined with arc capping, and pure LAHW with two different welding speeds. LAHW with higher speed increases productivity 24 times compared to conventional GMAW. In addition to the achievement of greater productivity, LAHW requires lower filler consumption than GMAW (due to much less beveling of the plates).

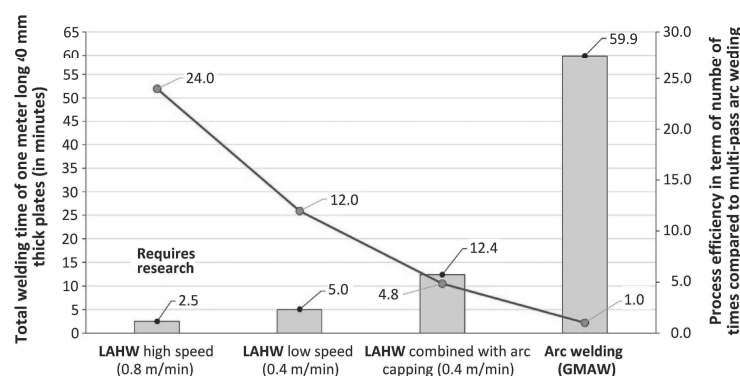


Figure 3. Productivity comparison of different welding processes. Reproduced from [33].

In this regard, in recent times, these aspects related to process efficiency and their implications in terms of environmental protection have received increasing attention from a sustainability perspective, along with other more specific factors. Therefore, the consumption of resources and energy, emissions, and various categories of environmental impacts tend to increasingly acquire a prominent role among the decision making criteria in the selection of welding processes, which is traditionally based on the required function of the joint and the cost [34], and general methodologies specifically conceived for sustainability assessments of welding processes have been proposed [35].

In this field, LAHW appears to be an application of particular interest, as in the case of the definition of energy efficiency metrics [36], as it involves a greater complexity in terms of assessment efforts, being a process based on combined technologies. This could lead to addressing specific environmental aspects, such as fume emission rates, limiting the evaluation to a direct sum of the effects of the two coupled welding systems [37]. Actually, more exhaustive environmental investigations, which contemplate the use of structured methods, such as Life Cycle Assessment (LCA), must be used to reach quantitative assessments taking into account the various factors that contribute to the overall impact on the environment.

With this comprehensive approach, a tendency towards greater environmental efficiency of LAHW processes has been demonstrated. Among the most significant experiences, Sproesser et al. [38] performed LCA evaluations by comparing the environmental impacts of arc welding technology in different configurations (manual metal arc welding, standard and modified gas metal arc welding) with laser–arc hybrid welding used to join a 20 mm thick plate of structural steel. The results showed that the hybrid process involved lower environmental impacts (evaluated in terms of eutrophication, acidification, photochemical ozone creation, and global warming potential) as a consequence of the higher process performance and limited overall weld volume.

The need to fulfill multiple tasks to achieve the operational requirements of the joint has pushed the manufacturing industry to address the issue of welding thick metal plates, developing suitable methods. This is confirmed by research dealing with hybrid welding, which needs to combine the numerous parameters involved, including those of each process and those resulting from their integration (Figure 4).

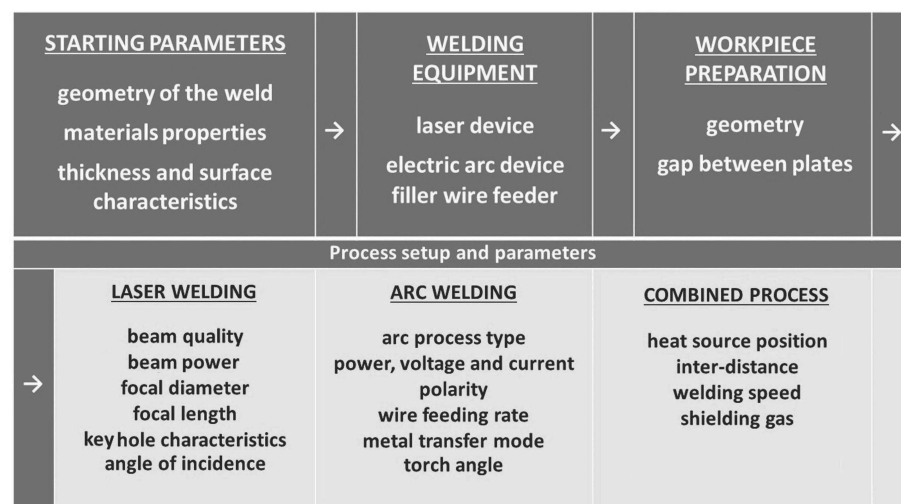


Figure 4. Flow chart of the combined process setting.

The basic issues that emerge from the analysis of the existing literature highlight the key role of process setup and its effect on the interaction between the two sources, depending on the configuration (laser- or arc-leading) and the inter-distance between the laser impact point and the tip of the electrode wire. This parameter, together with welding speed and power, determines the transition from a “full hybrid” (characterized by a shared melt pool) to a “tandem” welding mode (with the heat sources interacting indirectly) [1]. Starting from this consideration, the present article focuses on a review of the key issues that emerge from the different working conditions of LAHW based on the possible combinations between configurations and operating modes of the system, with particular attention paid to welding parameter settings, as well as some significant implications of the solidification modes and applications in clad steel welding.

The process configurations will be discussed in Section 2 with reference to their peculiarities. As documented in the literature, the different industrial applications have led to a multiplicity of values of the welding parameters. Some values are due to the equipment available, while for others the operators have a wide range of choices. Section 3 is dedicated to the effects that the main process parameters, such as the inter-distance between the heat sources, the heat input, the voltage and current, the welding speed, and the wire feed rate, have on the welded joint. Section 4 deals with their consequences for weld solidification, focusing on morphological aspects and composition changes along

with thickness. Finally, in Section 5, the current use, due to their many advantages, of laser-arc processes for joining clad steel plates is discussed.

2. System Configuration (Laser- or Arc-Leading)

In the hybrid mode, the concurrent action of two heat sources exerts a significant influence on the formation of the weld pool (Figure 5a), thereby enabling single-pass welding of thick plates (see Figure 5b for a comparison of the typical cross-sections obtained through arc welding, LBW, and LAHW).

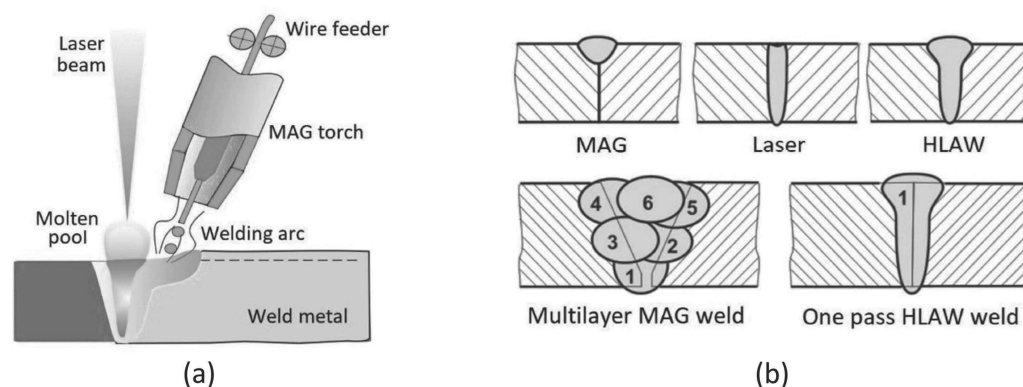


Figure 5. Hybrid laser-metal active gas (MAG) system: (a) setup; (b) comparison of weld shapes and geometric features obtained through different processes. Reproduced from [25].

Figure 6 shows the macrograph of a weld cross-section obtained through single-pass LAHW. Here, the laser beam preceded the electric arc; therefore, first, a deep keyhole was created, and then the weld bead was completed through metal inert gas welding (MIG). In this case, the large upper zone, mainly due to the action of the arc, is affected by the alloying action of the filler wire, which decreases along the keyhole [39].

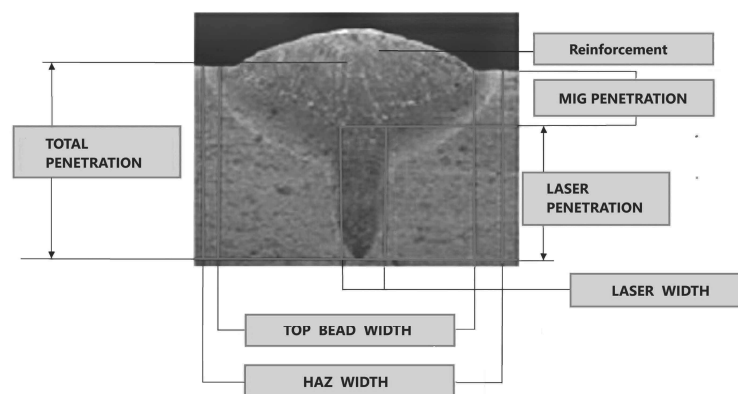


Figure 6. Bead geometry nomenclature for hybrid welding (low-carbon steel plate, 10 mm). Reproduced from [40].

The LAHW devices commonly use a solid-state laser (only in some cases a CO₂ laser), mainly combined with GMAW, in which the consumable electrode wire facilitates the introduction of the filler metal. Otherwise, GTAW, using a non-consumable tungsten electrode, requires the addition of a certain amount of filler material and, consequently, more energy for fusion. Recently, new technologies of arc welding, such as CMT and PAW, have also been considered.

CMT is an emerging process based on pulsed wire feeding achieved by retracting the wire during the short-circuit phase. In this way, CMT provides lower heat inputs than GMAW, with best results in terms of FZ microstructure and reduced effects on the HAZ [41].

Due to the lower heat input of laser–CMT hybrid welding, joints with higher properties and uniform microstructures can be obtained, making this technology suitable for laser hybrid welding [42].

Plasma Arc Welding (PAW) uses a high-melting-point tungsten electrode to obtain a high-current-density arc, generating plasma through electric discharge with the base metal. The tungsten electrode is placed behind the nozzle, which provides an adequate plasma jet (see [43] for a review of the interaction mechanisms in PAW). Integration with this process leads to hybrid welding with lower laser energy demand, minimizing the energy input and enabling higher welding speeds [13].

In any case, process configuration is a primary issue in LAHW. The torch is usually tilted at $65\text{--}70^\circ$ to the metal surface, and the laser beam is perpendicular to the surface, in some cases inclined $6\text{--}7^\circ$ with respect to the normal direction, to avoid high back reflections. Figure 7 shows the possibility of two different configurations, depending on whether the laser beam precedes the electric arc (laser-leading mode) or vice versa (arc-leading mode). The selection of either one of these two variants gives rise to distinct weld geometry features, penetration depths, and microstructural properties of FZ and HAZ.

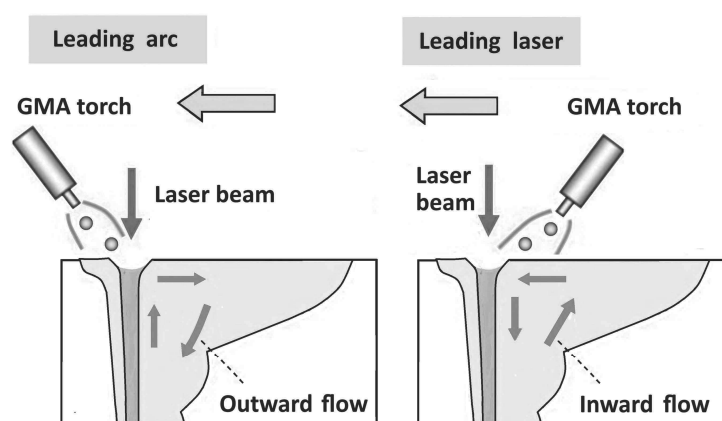


Figure 7. Laser-leading and arc-leading configurations. Reproduced from [44].

There are conflicting opinions among researchers regarding the opportunity to adopt the laser-leading or arc-leading configuration, as documented in [45]. Therefore, the characteristics of each will be analyzed in Sections 2.1 and 2.2. Further consideration of the effects of process configuration will be made by dealing in detail with the welding parameters in Section 3.

2.1. Laser-Leading Configuration

In [40], both laser-leading and arc-leading configurations were tested for single-pass butt welding of 10 mm thick mild steel plates (Figure 6). Better bead characteristics were achieved in the laser-leading mode. This is because when the laser beam precedes, the molten metal flows inward (from the rear end of the pool surface to the keyhole and then down just behind the keyhole itself). Therefore, the alloying elements of the filler wire are dispersed towards the bottom of the keyhole, finally improving the homogeneity of the weld metal. Muhammad et al. [46] observed in the arc-leading configuration an absence of melt recirculation at the weld root, which is the main reason for low mixing. In their experiments, they demonstrated more pronounced flow recirculation in the laser-leading condition and, consequently, more efficient mixing of alloy elements.

Several authors have demonstrated that the laser-leading configuration is advantageous for obtaining good metallurgical characteristics of the welds and reducing the presence of some defects, such as porosity, when carried out with the right process parameters. In [47], the authors used the laser-leading setup to weld 6 mm thick plates made

of high-nitrogen austenitic steels. They obtained welds without defects, such as pores and solidification cracks, with the presence of only a few micro-voids. In comparison, the specimens obtained with hybrid welding showed higher nitrogen content and impact energy than those produced through the MIG process (Figure 8).

Specimens	Impact energy A_k (J)	Fracture
BM	34.95	Breaking
MIG	39.01	Breaking
Hybrid	46.86	Breaking

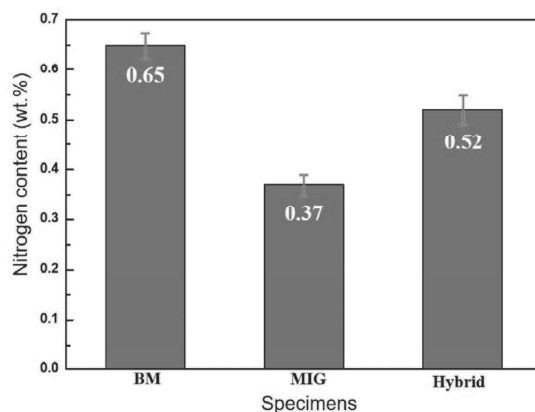


Figure 8. Impact energy and nitrogen content in base metal (BM) specimens and after MIG or hybrid welding process. Reproduced from [47].

In [48], the authors investigated the feasibility of using laser–CMT hybrid welding to join X80 steel plates (21.4 mm thick) through multiple passes. They used a system equipped with a fiber laser device (maximum power 10 kW) and a CMT welding machine (maximum power 4000 kW) working in the laser-leading configuration. Under this condition, the heat input was efficiently reduced, preventing the formation of defects, such as lack of fusion, and reducing the number of pores.

2.2. Arc-Leading Configuration

In the arc-leading configuration, the molten metal flows outward (Figure 7), causing variations in the solidification front that determine the lack of homogeneity of the weld. However, in other respects, the arc-leading configuration is advantageous. In effect, this arrangement provides a more stable arc and deeper penetration, probably because the laser beam impinges the FZ (already molten by the electric arc), enhancing its absorption in comparison to a solid surface and thereby minimizing energy dissipation [44].

Also, in [49], the arc-leading configuration is recommended for full penetration, single-pass welding. However, an excess of energy input can result in root imperfections, such as undercutting and humping. Therefore, penetration efficiency emerges as a key factor limiting the formation of weld bead undulations (root hump) and increasing the maximum single-pass weld thickness. In this regard, Tang et al. [6] proved, using 12 mm thick high-strength bainitic steel plates, that the arc-leading configuration makes it possible to avoid hump formation at the weld root and results in higher electrical stability than the laser-leading configuration under optimal process conditions. They concluded that compared with the laser-leading configuration, the arc-leading droplet transfer cycle is longer, involving a smaller droplet diameter, and the weight accumulation in the molten pool is slower. Consequently, it helps to slow down the increase in gravity at the root of the bath, suppressing the occurrence of a hump. For a detailed review of humping formation, see the article by Liu et al. [45].

In any case, an adjustment of many process parameters is necessary, because LAHW can promote humping, as verified in [50] for LAHW of thick structural steel; humping was avoided by balancing the welding parameters in butt-positioned plates with gaps and chamfered edges.

For an accurate evaluation of the process parameters' effects on the formation of humping and other defects, see also the article by Kim et al. [19], who addressed this problem by optimizing the LAHW process with a leading arc to join in a single pass two 15 mm thick high-Mn steel plates. Peli et al. [51] obtained sound welds between EH40 steel plates (20 mm thick), providing a gap of 0.5 mm and a proper set of welding parameters.

In the study by Silva et al. [20], the microstructures of structural steel joined through LBW and LAHW were compared, demonstrating the metallurgical and operational advantages of hybrid technology. They welded 25.2 mm thick plates made of ASTM A516 GR70 steel through an arc-leading setup, showing that an increased penetration depth can be achieved through the LAHW process using same laser power values as the LBW process. This result is due to the higher absorbcency of the laser beam in the metal preheated by the electric arc. Furthermore, the increased weld width contributes to achieving a better bridgeability in LAHW. The heat input coming from the electric arc is another advantage, as it acts as a cooling retarder, particularly in the upper portion of the weld bead.

In [25], the authors welded two low-carbon steel plates (5 and 7 mm thick, respectively) using the arc-leading configuration. They demonstrated the high bridgeability of the hybrid process, namely, the ability to connect highly misaligned plates (Figure 9). The resulting joints showed high quality, exhibiting both notable mechanical strength and plasticity. Specifically, the hybrid process did not result in a weld with tensile strength reduction compared to the base material.

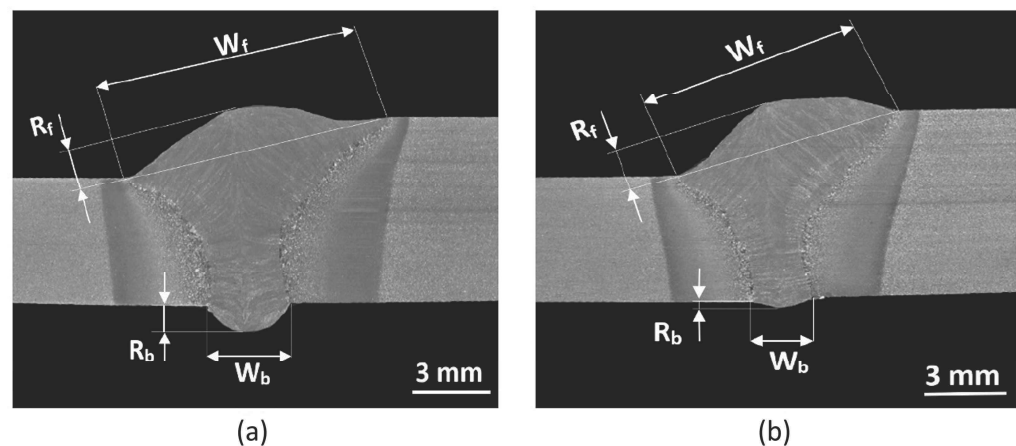


Figure 9. Macrographs of the welds obtained with the laser-leading configuration: (a) flat position; (b) horizontal position. Reproduced from [25].

Hao et al. [52] tested a setup with a beam oscillating system applied for LBW and LAHW of Q235 steel plates (Figure 10). They carried out a comparison between the welds obtained with and without beam oscillation. Both LBW and LAHW benefited from beam oscillations, resulting in an increase in weld width, as shown by the macrographs in Figure 10. Beam oscillations eliminated any preferred orientation assumed during grain growth, and elongation was also improved without significant changes in tensile strength, while the microhardness values are lower than those of welds without beam oscillation and significantly lower than those of welds obtained by using only the laser.

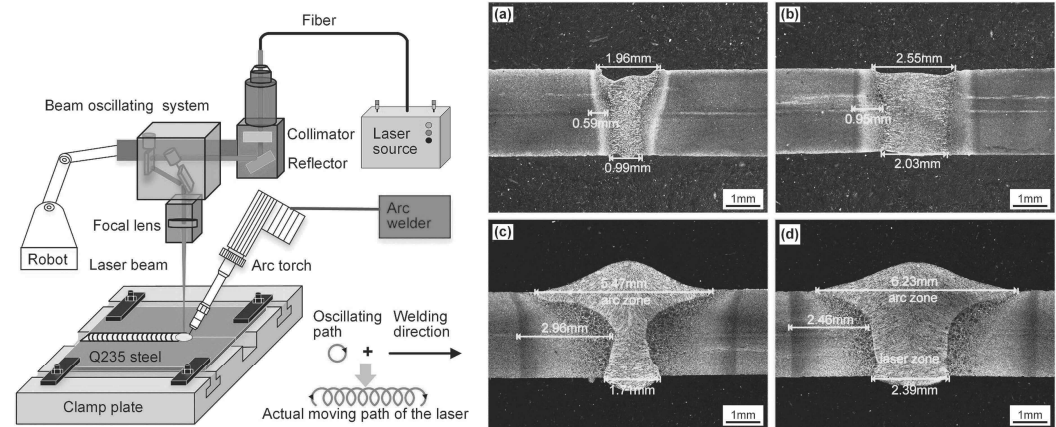


Figure 10. Experimental setup (trailing laser with beam oscillating system) and macrographs of the weld cross-sections in comparison: (a) LBW; (b) LAHW; (c) LBW with beam oscillation; (d) LAHW with beam oscillation. Reproduced with permission from [52].

3. Effects of Welding Parameters

Several combinations of values of the welding parameters are reported in the literature because their choice needs to be appropriate for each specific case. In the following subsections, the influences of the different parameters will be analyzed.

3.1. Effects of Laser–Arc Inter-Distance

Low values of the inter-distance enable synergy between the heat sources producing a single melting pool. For example, with reference to the scheme in Figure 11, the values considered by Gook et al. [39] for LAHW 14.5 mm thick steel plates were $a = 4$ mm, $\Delta z = -3$ mm, $\gamma = 25^\circ$, and $S = 16$ mm.

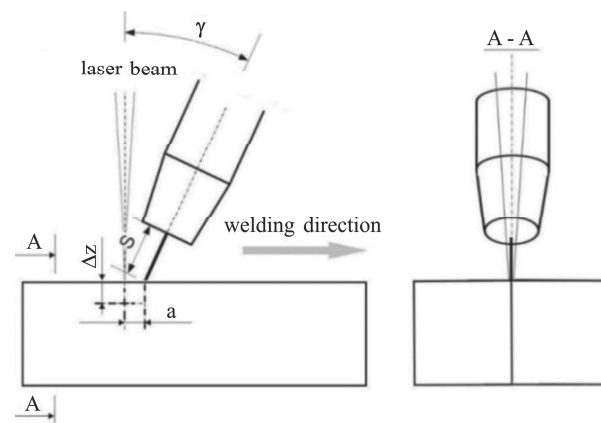


Figure 11. Sketch of a welding setup indicating the inter-distance between the electric arc and the laser beam. Reproduced from [39].

Conversely, when the two heat sources are spaced so far away that the molten pool due to the arc does not interfere with the keyhole, the process turns into tandem mode [23]. In general, the threshold value of the inter-distance that leads to distinct melt pools, depending on the heat input of the two sources, is specific to the case considered.

The inter-distance between the two sources has more significant effects than those due to the choice between laser- and arc-leading configurations, as demonstrated in [53], who performed LAHW tests on 10CrNi3MoV steel plates (8 mm thick) with different values of this parameter up to 10 mm. The authors obtained satisfactory welds when the inter-distance values were in the range of 2–4 mm due to the optimum synergy between the heat sources. For smaller values, the two sources interfere, leading to the formation of

spatters; for larger values, pores and undercuts were generated in the case of the arc-leading configuration and spatters in the case of the laser-leading configuration. In particular, if the laser–arc distance is too short, the molten pools formed by the two heat sources may collide, causing the keyhole to collapse [17]. Therefore, maintaining a certain distance between the sources helps with defect control.

3.1.1. Low Inter-Distance (Hybrid Mode)

Low values in the range of 2–4 mm are usually considered in the literature (see [25,39] for arc-leading configuration and [6,40] for both arc- and laser-leading configurations).

In any case, the inter-distance must be recalibrated for each distinct welding case, depending on the properties of the material involved and several welding parameters, such as joint type, welding configuration, heat sources' speed, arc mode and power, and shielding gas. In [54], the authors used the arc-leading configuration for welding steel plates (7 mm thick), and a clear synergy between the laser and the arc was identified in the formation of the melt pool when the inter-distance did not exceed 5 mm.

Gao et al. [55] demonstrated, working with the arc-leading configuration on 7 mm thick steel plates, that when the inter-distance is lower than 4 mm, the interaction between the laser-induced plasma and the arc plasma is dominant; conversely, as the inter-distance increases, the role of preheating due to the electric arc becomes more prominent.

In [56], the authors butt welded thick HSLA steel plates under a variety of conditions in order to develop generalizable considerations. In this way, it was demonstrated that the laser–arc inter-distance is a crucial parameter; in particular, for the deep penetration mode, its optimal values vary depending on whether the laser-leading or arc-leading configuration is used. Furthermore, the authors also experimentally verified that with a leading pulsed arc, an inter-distance ranging from 4 to 8 mm is associated with increased penetration depth [57]. Instead, with a leading laser, lower values are preferable because they enable enhanced melting flows that, in turn, facilitate the inward motion of the alloying elements. In this case, inter-distance values greater than 2 mm reduce the depth of the zone affected by alloying due to the filler metal. For more details on the choice of inter-distance, see the review by Liu et al. [21].

3.1.2. High Inter-Distance (Tandem Mode)

At high inter-distance between the laser and the arc sources, the process conditions turn from a hybrid mode with a shared melt pool into a so-called tandem mode. This results in a loss of hybridization, as the heat sources give rise to distinct weld pools [1]. Greater values of the inter-distance lead towards a configuration where the electric arc does not directly affect the keyhole; in the case of a leading laser beam, the trailing arc produces a short-time post-heating treatment of the weld that can improve the microstructure [44].

As tested by Reutzel et al. [58] by welding 6 mm thick steel plates with the laser-leading configuration, inter-distances that exceed 6 mm can lead to full penetration, resulting in the formation of two distinct fusion zones. The authors observed that at close range, the laser beam acts deep into the base metal, promoting the penetration of the alloying elements provided by the filler wire. However, under conditions of increased spacing (10 mm), the keyhole, due to the laser beam, precedes the arc puddle; this condition prevents the introduction of any additional material (Figure 12). Effectively, using a tandem configuration, the greatest effect is achieved when the laser beam acts to autogenously produce the root pass, while the arc with a consumable electrode fills the pass limited to shallow layers [23].

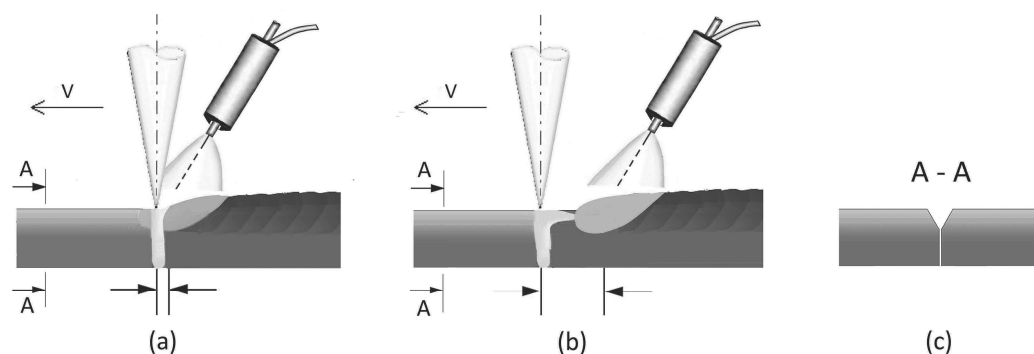


Figure 12. Effect of the inter-distance on melt pool formation: (a) 2 mm; (b) 10 mm; (c) plates' preparation.

In order to obtain a tandem configuration with a prevalence of electric arc effects, a high value of the inter-distance and a lower LBW/GMAW power ratio should be chosen [22]. In this specific condition, the thermal field of the laser beam exerts minimal influence on the operation of the electric arc, and the effects of the two heat sources do not overlap. This condition can allow for separation of the deep keyhole mode from the shallower action of the electric arc, maximizing the concentration of the alloying elements within the shallow layer. It can be particularly useful for clad steel welding, as evidenced in Section 5.

Gao et al. [59] used the tandem configuration with a leading laser, maintaining a heat source inter-distance of 40 mm and achieving the formation of two relatively independent molten pools. This value involved the formation of a shallow molten pool from the electric arc, which was clearly separated from the keyhole operating in depth along the thickness. In addition, the weld produced by the laser beam was heated by the trailing arc; in this condition, the latter serves as a secondary heat treatment source, leading to a reduction in the cooling rate and the residual stresses.

3.2. Effects of Heat Input and Power Ratio

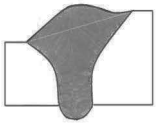
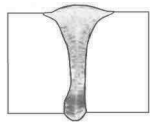
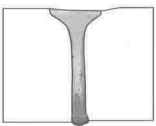
From a general point of view, the heat input (namely, the total heat power to welding speed ratio) should have a value that ensures welding along the entire thickness. In [40], the authors adopted a total value of 835 kJ/m for joining through LAHW carbon steel plates that were 10 mm thick, while in [60] the total heat input was 1820 kJ/m for each of the two opposite passes used for LAHW of 40 mm thick steel plates. In addition to the thickness, other aspects must also be considered; for example, in [61], a heat input of 892 kJ/m was used for LAHW of 8 mm thick plates prepared with a Y groove and a 0.6 mm gap.

The laser power/arc power ratio balances the effects of the two heat sources, influencing the shape and the microstructural characteristics of the FZ. Qualitatively, it can be stated that for high values of this ratio, the process is similar to laser welding, as fast cooling rates result in fine grains or harder microstructures, such as martensite or bainite. Instead, with low values of the laser power to arc power ratio, the process more closely resembles arc welding, attaining a coarse grain and pearlite with relatively low hardness [23]. High values of this parameter accentuate the prevalence of the laser beam, leading to a narrow shape of the weld towards the root. Conversely, when it decreases, the electric arc's effects prevail, and the difference in width and height between the upper and the root zone is reduced. In their experiment of LAHW of 12–15 mm thick steel plates, Bunaziv et al. [16] achieved narrow weld cross-sections using values of the power ratio greater than one; meanwhile, upon reducing its value, the weld's shape is characterized by a wide zone extending towards the upper surface of the weld.

Some examples of heat input and power ratio effects on the weld shape are shown in Table 2. For a useful comparison among plates with different thicknesses, the surface heat input, obtained by dividing the linear heat input by the thickness, is also considered. It can

be deduced that the power ratio determines the weld's shape (like a wine cup or triangular shape for high or low values of the power ratio, respectively), while the surface heat input affects its width. Other parameters, such as the distance between the plates to be welded and the edge geometry, can also have an effect, as will be shown in Section 3.9.

Table 2. Effects of heat input and laser/arc power ratio on weld shape and width.

Material/ Plate Thickness	Edge Geometry	Setup/ Inter-Distance	Total Linear Heat Input	Total Surface Heat Input	Laser/Arc Power Ratio	Weld Shape/ Reference
High-Ni steel 8 mm	Single-sided Y, 30° groove angle, 0.6 mm gap, 4 mm root face	GMAW (leading) + Nd:Yag 6 mm	892 kJ/m	111,500 kJ/m ²	0.327	 [61]
S960QL steel 5 and 7 mm	Square edge, 0 gaps	GMAW (leading) + disk laser 2 mm	534 kJ/m	89,000 kJ/m ²	0.479	 [25]
AISI 316L stainless steel 10 mm	Square edge, 0 gaps	Fiber laser (leading) + GMAW 3 mm	571 kJ/m	57,100 kJ/m ²	4.21	 [46]
Low-carbon X8Ni9 steel 14 mm	Square edge, 0 gaps	GMAW (leading) + fiber laser 4 mm	600 kJ/m	42,900 kJ/m ²	1.89	 [39]

Together with heat input and the power ratio, the heat sources' arrangement may affect the shape of the welded section. Assuming a low value of the power ratio and maintaining the same welding parameters, Liu et al. [62] compared the weld cross-sections obtained with the arc- and laser-leading configurations (Table 3).

Table 3. Process configurations' effects on the weld shape and the extension of the arc and laser zones (given the same welding parameters).

Material/ Plate Thickness	Edge Geometry	Setup/ Inter-Distance	Total Linear Heat Input	Total Surface Heat Input	Laser/Arc Power Ratio	Weld Shape/ Reference
High-strength steel 6.6 mm	Single-sided Y, 40° groove angle, 0.8 mm gap	GMAW (leading) + Nd:Yag 3 mm	618 kJ/m	93,636 kJ/m ²	0.44	 [62]
High-strength steel 6.6 mm	Single-sided Y, 40° groove angle, 0.8 mm gap	Nd:Yag (leading) + GMAW 3 mm	618 kJ/m	93,636 kJ/m ²	0.44	 [62]

It is worth noting that the extent of the arc (weld top) and laser (weld root) zones, as well as the shape of the joint, depend on the process's setup. The weld becomes more similar to a wine cup when the laser-leading configuration is adopted.

In any case, the balancing of the process parameters has consequences for the solidification structures and the distribution of alloying elements (Section 4), as the filling action of the electric arc prevails in the upper area, while towards the root the weld is subjected to the deep action of the keyhole.

3.3. Effects of Laser Beam Parameters on Penetration Depth

The laser beam in keyhole mode is generally used to weld substrate layers starting from the bottom of the groove; usually, it works with a spot focus diameter (D_s) of some hundreds of microns. For single-pass LBW of AISI 304 steel plates, it is necessary to have a certain value of the heat input. Assuming the laser power (P) is equal to 10 kW and the beam is focused on the plate's surface ($f_d = 0$), the penetration depth increases as the welding speed decreases, as shown by the curves in Figure 13. These curves are parameterized with the focus diameter (D_s); when it decreases, the power density increases. Consequently, the penetration depth also increases. However, defects, such as underfill, spattering, humping, and porosity, occur.

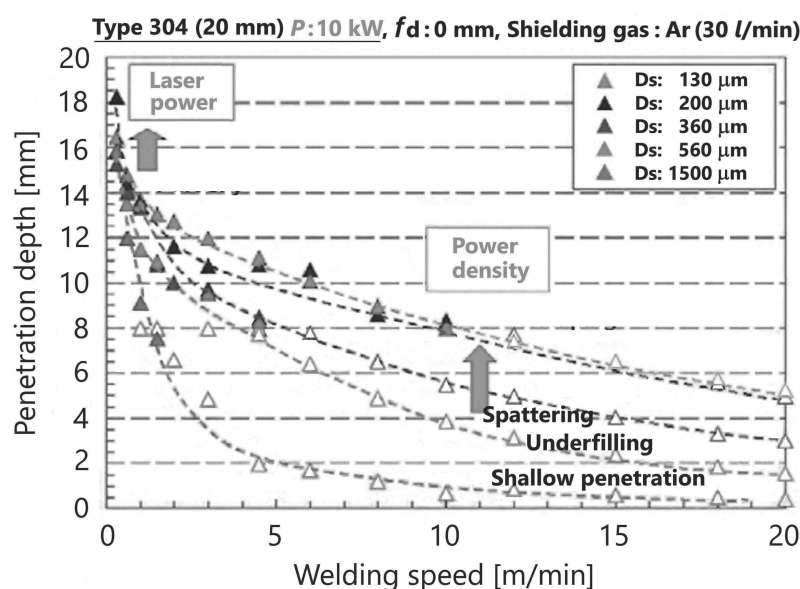


Figure 13. Penetration depth in LBW, according to welding speeds for different values of the laser spot diameter (D_s). Reproduced from [63].

The use of the laser beam is associated with characteristics of efficiency, good repeatability, and reproducibility thanks to the automatic control of the welding parameters. However, Figure 13 shows the variety of parameters involved and their effects on the penetration depth and the possible formation of welding defects, making LBW a complex chemical–physical process. Monitoring and control of quality are therefore key issues in the research and development of LAHW; for a review specifically addressing this field, see the work of Ma et al. [64].

In LAHW, the shape and penetration of the weld bead are governed by the dynamic interactions of laser irradiation with the electric arc, as well as the transfer conditions of the filler metal. In any case, weld penetration increases noticeably as laser power increases, leading to the typical characteristics of hybrid welds, namely, the clearly distinct laser area and the arc area in the cross-section. Figure 14 shows that with the parameters considered in [65] for LAHW of two 10 mm thick AH36 steel plates, weld penetration doubles when laser power triples.

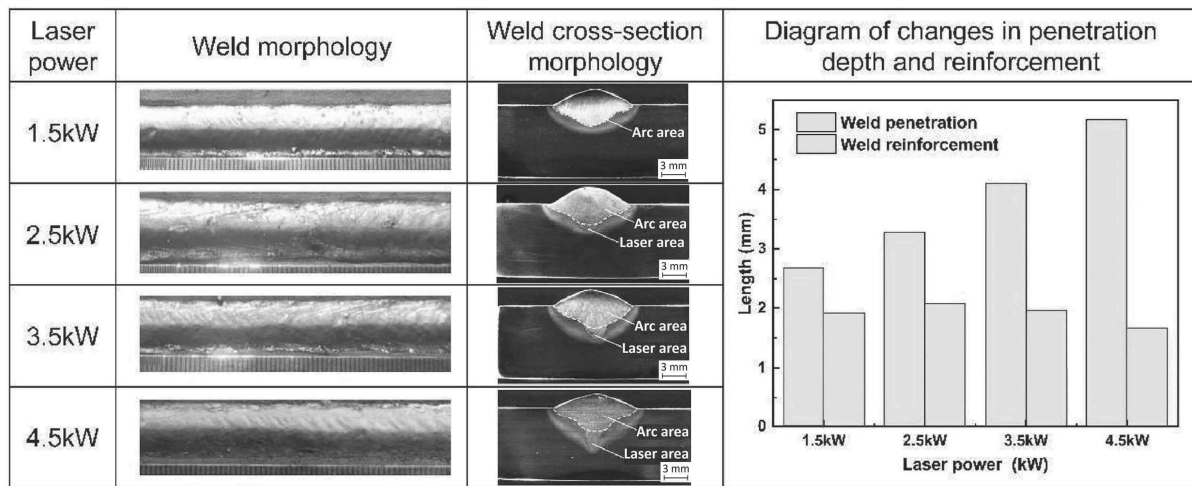


Figure 14. Effects of laser power on weld penetration and morphology of LAHW. Reproduced from [65].

3.4. Combined Effects of Laser Power and Arc Current

By keeping the laser beam power constant, an increase in the arc power results in a greater width of the weld, while its depth undergoes only limited variations (Figure 15a). Vice versa, in the case of a pre-fixed value of the electric arc power, an increase in the laser power determines an increase in the weld depth, while its width undergoes limited variations (Figure 15b).

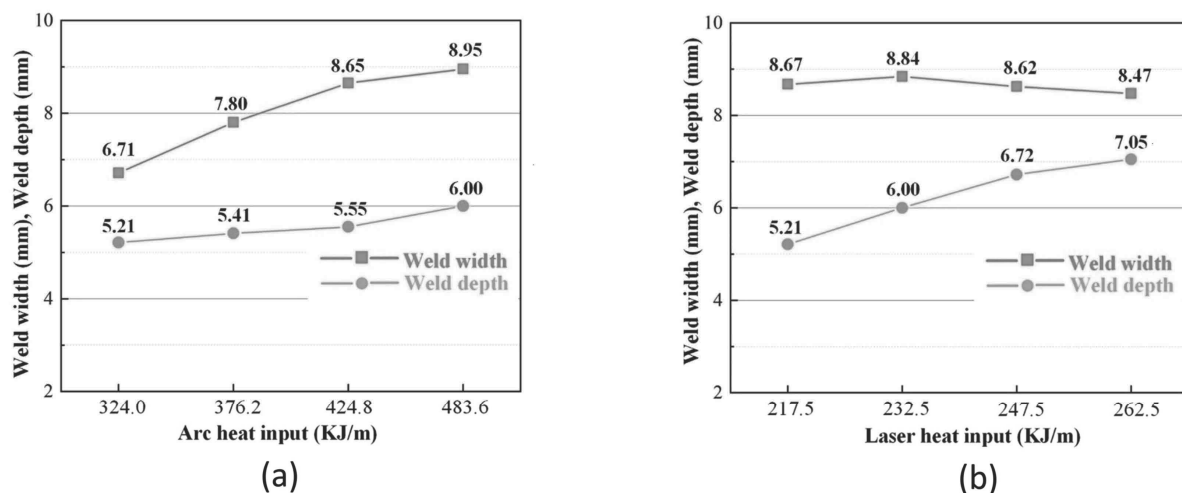


Figure 15. Trend of weld depth and width: (a) effect of the arc heat input for a laser heat input of 232.5 kJ/m; (b) effect of the laser heat input for an arc heat input of 483.6 kJ/m. Reproduced with permission from [66].

3.5. Effects on Pore Formation

Root pore problems can be encountered, particularly in thick steel plates. They can be ascribed to insufficient degasification in deep and narrow laser welds; therefore, to mitigate this phenomenon, the molten pool should be maintained for a longer period. In this regard, coupling the laser beam with submerged arc welding (SAW) could be useful to maintain the molten pool for longer, producing favorable degasification [23].

Some general considerations described by Kim et al. [17] for pore formation in LAHW of aluminum sheets can also be extended to the case of steel. They illustrated how porosity forms when the keyhole becomes unstable and its wall collapses, lowering the weld's quality. When the laser leads, a less deep keyhole and a larger molten pool are formed

compared to when the arc leads. These features allow for a stable convective flow in the pool, promoting degasification and lower pore formation.

Pores form mainly in the lower part of the keyhole when they remain trapped at the solidification end. As the arc current increases, the molten pool enlarges, lowering the chance of keyhole collapse and enabling the pores to reach the top of the molten pool and escape. In this regard, LAHW of medium/low-carbon dissimilar steel plates was carried out in [67], demonstrating that reduced porosity and hence better mechanical strength can be obtained using the arc-leading configuration if the right arc current and laser power are set. The effects of the current on the porosity and tensile strength of the weld are shown in Figure 16a. An increase in the welding current causes a decrease in the porosity percentage, determining, in turn, an increase in tensile strength. Figure 16b shows the laser power's effects. As the laser power increases, porosity first decreases and then increases; consequently, tensile strength first increases and then decreases.

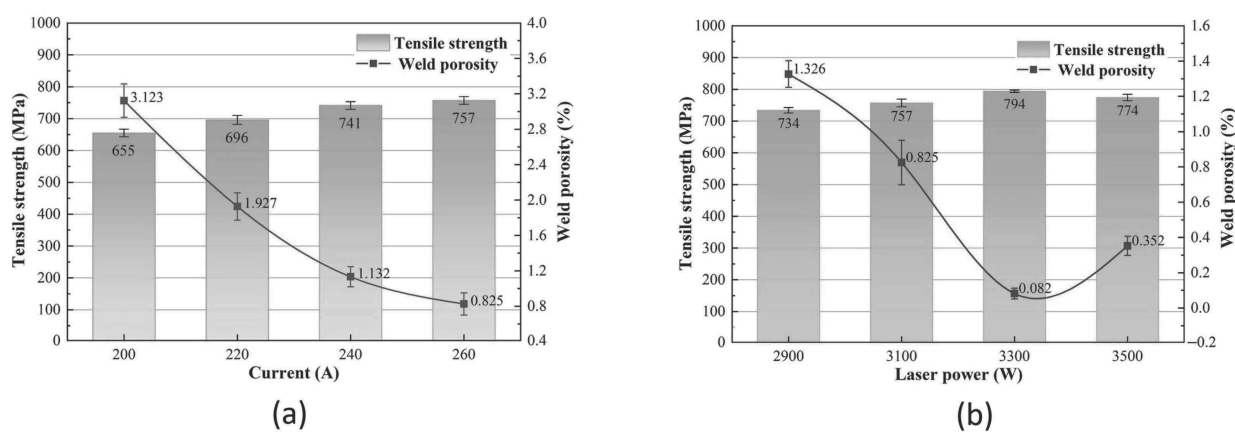


Figure 16. Weld porosity and tensile strength in dissimilar medium/low-carbon steel hybrid welded plates: (a) arc current (with constant laser power equal to 3100 W and welding speed equal to 0.8 m/min); (b) laser power (with constant arc current equal to 260 A, voltage equal to 24.8 V, and welding speed equal to 0.8 m/min). Reproduced with permission from [67].

In [61], the authors butt welded 8 mm thick high-nitrogen steel plates using an arc-leading configuration with the aim of investigating the effects of the inter-distance on weld morphology and porosity. They obtained a pore-free weld with a value of this parameter equal to 6 mm. For further information on issues regarding pore formation in LAHW, see [21].

3.6. Effects of Welding Speed

Keeping the other parameters constant, heat input and penetration depth decrease as welding speed increases. Even with the same heat input, the weld pool's shape and size can be different, as they are closely connected to the welding speed. In particular, there is a change from an elliptical to a teardrop shape when this parameter increases [68].

Concerning penetration depth, the effects of welding speed depend on the process's setup, as shown in Figure 17 for arc-leading (MAG-YAG) and laser-leading (YAG-MAG) configurations. Observing the weld cross-sections, it can be noticed that the arc-leading setup gives rise to deeper penetration. While other parameters are equal, the welds produced using the laser-leading configuration are shallower but wider in the upper part.

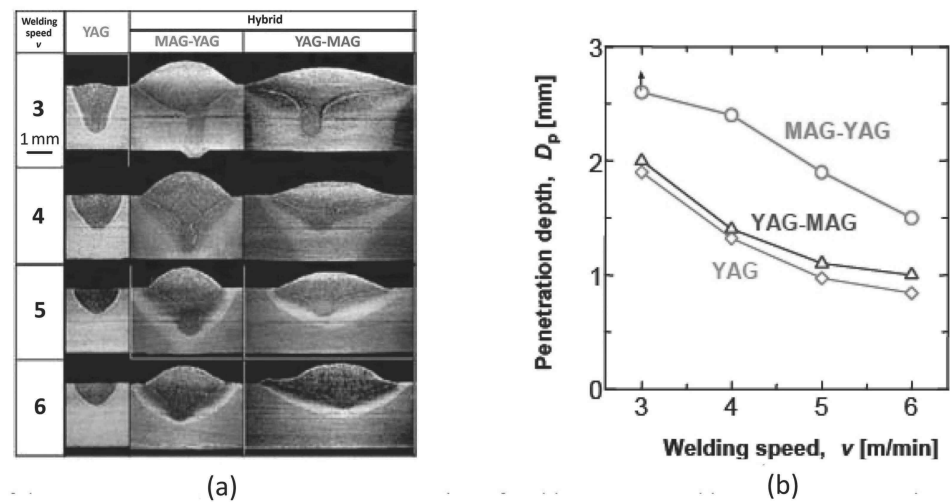


Figure 17. Effects of welding speed and process configuration for arc-leading (MAG-YAG) and laser-leading (YAG-MAG) configurations on 590 MPa high-strength steel plates (laser power 2.6 kW, zero defocusing, current 200 A, shielding gas Ar with 20% CO₂): (a) macrographs of the weld cross-section; (b) penetration depth versus welding speed. Reproduced from [44].

3.7. Effects of Filler Transfer Conditions

LAHW is carried out with high welding speeds; consequently, the wire feed rate must also be set at high values. For this reason, a high current is necessary to maintain the arc length at equilibrium; hence, the torch should be water-cooled to avoid overheating.

During welding, the filler metal passes from the electrode wire to the melt pool essentially via short circuit, globular, or spray transfer mode [45]. With low voltage, electrical short circuits occasionally occur between the molten pool and the tip wire, while a higher voltage produces a longer arc in which no short circuit is created and the filler is transferred as a spray of molten metal from the wire to the melt pool [69].

By using a low wire feed rate together with high voltage, the globular transfer mode is activated, and large droplets form at the wire's tip. This transfer mode, accompanied by large spatters, is unstable. Therefore, it is advisable to operate in the stable spray transfer condition by setting, in addition to the high voltage, a high wire feed speed, which in turn depends linearly on the current (Figure 18).

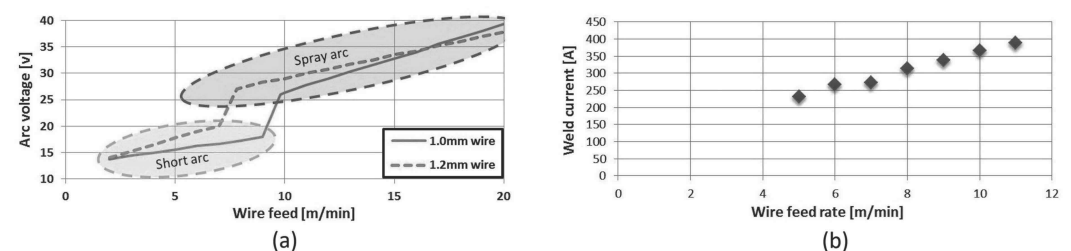


Figure 18. Arc welding parameters: (a) ranges of short arc and spray arc; (b) correlation between wire feed rate and current. Reproduced from [69].

It should be noted that the laser beam affects the distribution of droplets from the filler wire, which becomes scattered and enlarged. In addition, when the laser power exceeds a specific value, some droplets may escape from the weld pool as spatter. The spray transfer mode is also better at reducing spatter under high laser power [70].

3.8. Effects of Shielding Gas

The choice of shielding gas composition is crucial for welding, particularly in hybrid processes, as the laser plasma affects the droplet transfer mode. Researchers have

ascertained that the best welds in terms of geometric characteristics, microstructures, and mechanical behavior are obtained using mixtures of gas containing percentages of CO_2 . However, it was observed that concentrations of CO_2 beyond certain limits can be negative for the transfer mode, which in turn affects process stability and weld morphology. In this regard, Zhang et al. [71] carried out research on the effects of shielding gas composition in LAHW of HSLA steel. They observed that the use of pure Ar makes the process unstable, with a lot of spatters on the metal's surface, while stability improves when Ar is mixed with 5–20% CO_2 . Percentages of CO_2 equal to 18 or 20% in Ar were used also in other work, such as [25,44,65].

3.9. Effects of Edge Geometry and Gap

In the case of traditional arc welding, workpiece preparation of very thick plates requires deep grooves with double V geometry to be filled with multiple passes, while for the hybrid technology one or two passes and edges' preparation with Y geometry can be sufficient. In a recent article, Clemens et al. [72], in coupling SAW and LBW, carried out the butt welding of grade S355 structural steel with the edge preparation illustrated in Figure 19.

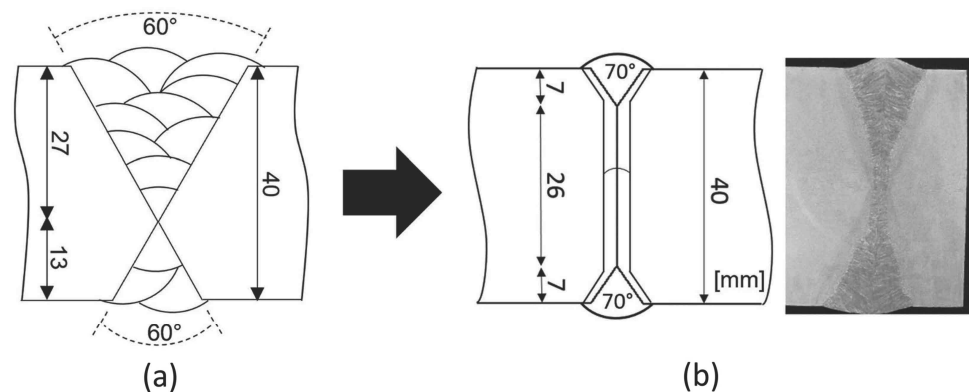


Figure 19. Comparison of edge preparation: (a) traditional arc welding; (b) LAHW with layer counter layer procedure. Reproduced from [72].

When plates are not excessively thick, workpiece preparation is limited to square edges and gaps of some tenths of a millimeter. Turichin et al. [73] investigated the gap's influence on bead geometry. By carrying out LAHW trials on high-strength, low-alloy steel plates with thickness equal to 7 mm, they found that the weld's width decreased on the upper surface of the plates as the gap's width increased from 0 up to 0.3 mm. Meanwhile, a further increase of the gap caused an increase in the width at mid-depth and at the root of the weld. Therefore, the wire alloy elements' penetration increased, and the weld's geometry changed from "cup-shaped" to "vase-shaped" (Figure 20).

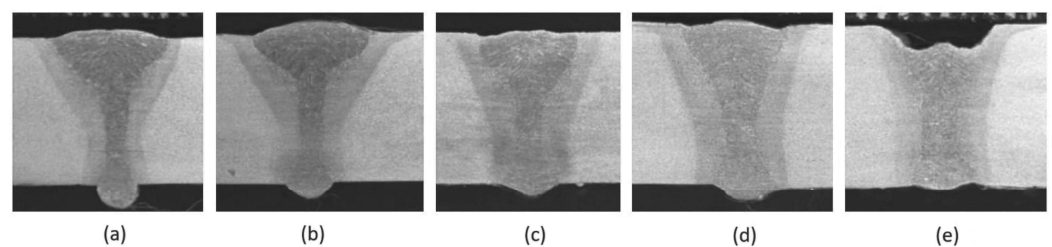


Figure 20. Cross-sections of welds (thickness equal to 7 mm) obtained for some values of the gap's width: (a) 0 mm; (b) 0.3 mm; (c) 0.6 mm; (d) 0.9 mm; (e) 1.2 mm. Reproduced from [73].

At low welding speeds, gravity drop-out is an obvious problem of single-pass welding in a flat position. The possibility of avoiding drop-out and sagging was explored in [74]

using electromagnetic support of the weld pool based on the generation of Lorentz forces inside of it. Structural steel plates (thickness of 25 mm) were chamfered with square grooves and placed flat on the magnetic support. With this setup, gap full penetration, without gravity drop-out and notches, was achieved by performing single-pass LAHW at a low welding speed. Furthermore, the misalignment of edges was also considered, successfully bridging a gap up to 2 mm (Figure 21).

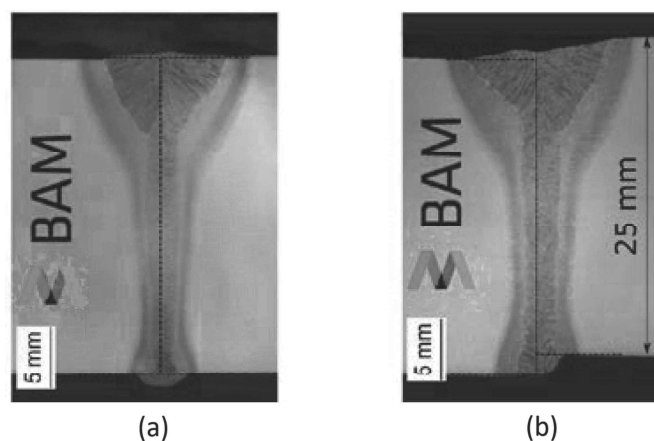


Figure 21. Cross-sections of welds between 25 mm thick structural steel plates: (a) without gap and edges offset; (b) with 2 mm gap between edges. Reproduced from [74].

3.10. Hybrid Process Modeling

The wide variety of process parameters of LAHW, the ways in which they can be combined, and their effects, which have been previously discussed, highlight the difficulty of identifying rational correlations in order to support the optimization of the parameters' settings according to the requirements of a specific application.

Excluding purely experimental approaches, the correlation between process parameters and their effects on the welded joint for predictive and optimization purposes requires modeling of the complex multi-physics phenomena underlying the interaction between the electric arc and the laser beam. Advanced modeling specifically developed for these purposes must take into account a wide range of aspects that are essential for an effective interpretation of laser–arc interactions and the hybrid welding process's conditions. Uncoupled models of heat transfer assume that the laser and the arc can be treated as independent heat sources.

This type of simplified approach, without accounting for changes in arc and laser power density distributions due to mutual interactions, has been used to describe various aspects of transport phenomena developed in the weld pool [75]. Gaussian surface or volume flux terms are often used to represent heat sources [76]. The thermal distributions of the arc, the laser, and their hybrid system can be described through Goldak double ellipsoid volumetric terms [77]. The effects of phase transformations on resultant welds have been addressed by taking account of fluid flow in the weld pool and latent heat due to phase changes [78]. Further advanced thermo-metallurgical numerical models have been developed specifically for the hybrid laser–arc welding process to predict phase formations and the melt pool's dimensions and their implications for the mechanical properties of the welded joint [79].

For detailed overviews of the modeling of the complex phenomena that arise in LAHW processes, the contributions by Rao [80] and Richardson [81] can be referred to. The application potential of numerical modeling approaches for LAHW simulation have been specifically reviewed by Wang et al. [82], taking into account heat source selection laws,

flow and temperature fields, stress distributions, and the influence of laser–arc interaction on weld defects and properties.

3.11. Final Remarks on Parameters' Settings and Process Control

A variety of parameter combinations was adopted in the reviewed articles. Some representative sets are shown in Table 4, ordered according to increasing plate thickness; the laser beam power varies from 3.75 to 14 kW, the current is between 95 and 300 A, and voltage is around 23–30 V, while the welding speed remains in the range of 0.6–1.3 m/min. In most cases, the plates have square edges and zero gaps, and the shielding gas is inert or a mixture with CO₂. Notes on the main results are briefly indicated together with the respective references in the last column. It can be observed that total powers greater than 10 kW are used for welding steel plates with thicknesses of 10 mm and more.

Table 4. Welding parameters for single-pass LAHW.

Material/ Plate Thickness and Edge Preparation	Setup/ Inter-Distance	Beam Power	Arc Current and Voltage/Arc Power	Welding Speed	Wire Feeding Rate	Shielding Gas	Note/ Reference
S960QL steel 5 and 7 mm Butt plates with square edges, 0 gaps	GMAW (leading) + disk laser 2 mm	3.75 kW	274–290 A 27 V 7.4–7.8 kW	1.3 m/min	8.5 m/min	Ar + 18% CO ₂	Good bridgeability of plates with different thicknesses [25]
HSLA steel 10 mm Bead on plate experiments	GMAW (leading) + fiber laser 3 mm	6 kW	236 A 29 V 6.84 kW	1.2 m/min	8 m/min	Ar + 20% CO ₂	Gas mixture for best droplet transfer mode [71]
AISI 316L stainless steel 10 mm Butt plates with I grooves	Fiber laser (leading) + GMAW 3 mm	10 kW	95 A 25 V 2.4 kW	1.3 m/min	5 m/min	Ar + 2%CO ₂ + 30% He + 0.03% NO	Best setup for alloy mixing [46]
AISI 316L stainless steel 10 mm Butt plates with I grooves	GMAW (leading) + fiber laser 3 mm	10 kW	95 A 25 V 2.4 kW	1.3 m/min	5 m/min	Ar + 2%CO ₂ + 30% He + 0.03% NO	Low mixing at the bottom [46]
High-Mn steel 15 mm Butt plates with I grooves	GMAW (leading) + fiber laser 8 mm	14 kW	300 A *	1.02 m/min	*	Pure Ar	Best welding parameters for full penetration [19]

* Data not available.

Various methods have been developed and applied with the aim of predicting and attaining the required properties of the joint and improving weld quality through optimal setting of process parameters in laser–arc hybrid systems. These approaches include the use of Design of Experiment (DoE) techniques to manage the wide set of variables involved under statistically optimal conditions [83], combined with multi-objective optimization approaches [84], regression analysis models [85], response surface methodology (RSM) [86], and numerical simulation [87], and they have evolved by using advanced computational systems based on neural networks, fuzzy logic, and optimization algorithms, e.g., for prediction and optimization of welded joint strength [88,89] or the weld's profile [90].

Advanced digital techniques also find an elective field of application in facing the significant technological challenges of welding quality monitoring. The potential of numerical simulation for monitoring and controlling laser–arc hybrid welding processes has been investigated [64]. Advanced soft-computing tools have been applied to real-time defect monitoring, as in the case of convolutional neural networks used to improve defect detection and parameter optimization in laser–MIG hybrid welding [91] or enhance defect monitoring in high-power laser–MAG hybrid process [92].

The integration of visual analysis techniques, numerical simulation, and AI techniques, such as machine learning and digital twins, appears to be very promising in overcoming

this challenge, as highlighted by Tessema and Bismor [93] with their comprehensive review of quality control and monitoring in hybrid welding. A further brief review of AI-supported quality control systems for laser–arc hybrid processes has been outlined by Klimpel [94].

4. Weld Solidification Issues

The typical cross-section of hybrid welds is characterized by a wide upper zone and a deep and narrow one, which form in different proportions depending on the experimental setup and the process parameters (Tables 2 and 3).

The formation of these zones is attributable to the electric arc and the laser beam [39], even if such a clear distinction can be assumed only for the convenience of discussion. Effectively, the laser energy is absorbed along the entire thickness, while the action of the arc mainly affects the upper zone, giving rise to a large width [23].

In this regard, Figure 22 shows two different types of cross-sections obtained with arc-leading and laser-leading configurations, respectively, using the welding parameters shown in Table 3. First of all, it can be noted that the weld produced by the arc-leading arrangement is quite triangular and the laser zone is very short, while for the laser-leading configuration the arc zone is wider but reduced in height. These morphologies affect the alloying elements' distribution and therefore the microstructure, as will be discussed in the following.

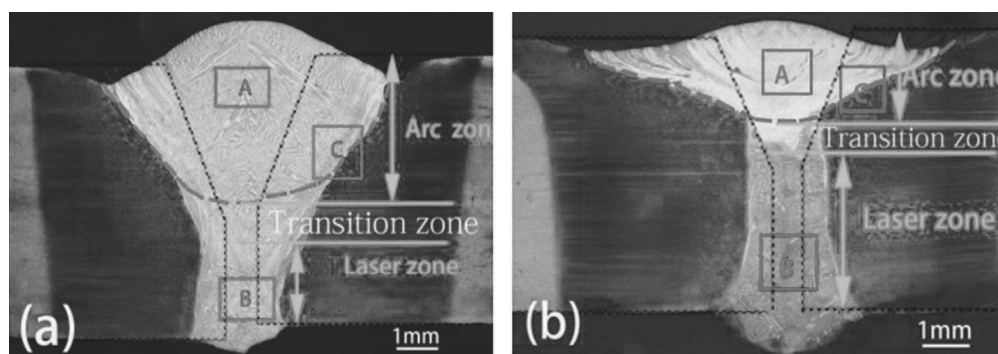


Figure 22. Cross-sections of high-strength, low-alloy steel plates welded with different setups (A = arc zone, B = laser zone, C = fusion line zone): (a) arc-leading; (b) laser-leading. Reproduced with permission from [62].

4.1. Solidification Modes

In general, the microstructure in the weld's bottom, mainly due to the laser's action, consists of fine bainite and martensite laths, while in the upper zone, coarse grains are present [20].

It is well-known that solidification structures depend on the characteristic parameters of the molten pool, such as the growth rate of the solid/liquid interface (R) and the temperature gradient (G) in the liquid metal [95]. The first parameter can be evaluated thanks to the welding speed (v) and the angle (α) between the welding direction and the normal to the isothermal surface delimiting the molten pool (Figure 23), which is $R = v \cdot \cos \alpha$ [96].

In the weld's centerline, along the direction of welding ($\alpha = 0$), the growth rate (R) assumes its maximum value, while along the fusion boundary the growth rate reaches smaller values. On the contrary, the temperature gradient in liquid metal (G) is relatively high near the fusion boundary, as the molten pool is in contact with the relatively cold solid metal, while it reaches a minimum value at the centerline.

The G and R values change in opposite ways along the solid/liquid interface; therefore, the G/R ratio can be considered as a useful parameter to characterize the solidification mode, which varies from planar–columnar near the fusion line to eventual equiaxed

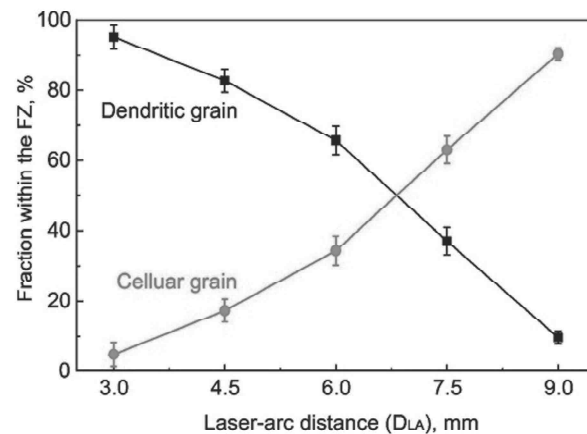


Figure 25. Effect of the laser–arc inter-distance on solidification modes. Reproduced with permission from [98].

In the weld cross-section of Figure 22a, obtained with the arc-leading configuration and a power ratio equal to 0.44, the solidification structure of the arc zone consists of columnar dendrites growing perpendicularly from the fusion line towards the molten pool center and becoming finer in the laser zone. Using the laser-leading configuration (Figure 22b), the laser zone prevails, and the structure is also dendritic but even finer.

Li et al. [99] obtained similar results using the arc-leading configuration to weld two plates of high-nitrogen steel (thickness equal to 8 mm) with a power ratio equal to about 0.4. The weld cross-section is typically characterized by a wide upper zone and an underlaying area, where the effects of the arc and the laser, respectively, prevail (Figure 26).

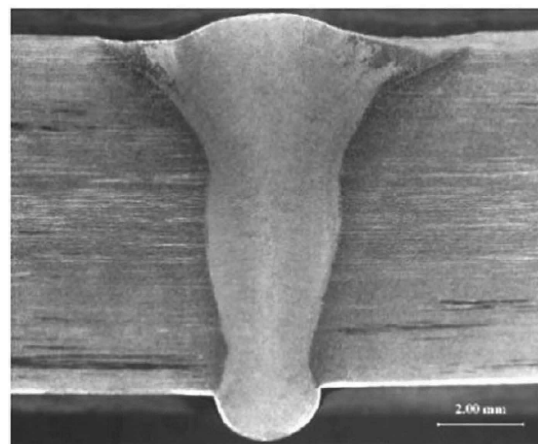


Figure 26. Cross-section of the joint between high-nitrogen steel plates obtained with LAHW (arc-leading configuration). Reproduced with permission from [99].

Results of metallographic observations are given in Figure 27. In the molten zone, grains nucleate on welding pool walls and grow up in the direction of fast heat dissipation, following the typical epitaxial solidification mode. The grains grow most rapidly along the direction perpendicular to the liquid/solid interface, assuming a columnar dendritic morphology, with secondary arms forming at high undercooling. In the weld's centerline, the microstructure consists of equiaxed grains and a small number of columnar dendrites; here, temperature gradients are low, and grains, which are not affected by rapid solidification, grow in the equiaxed mode [99].

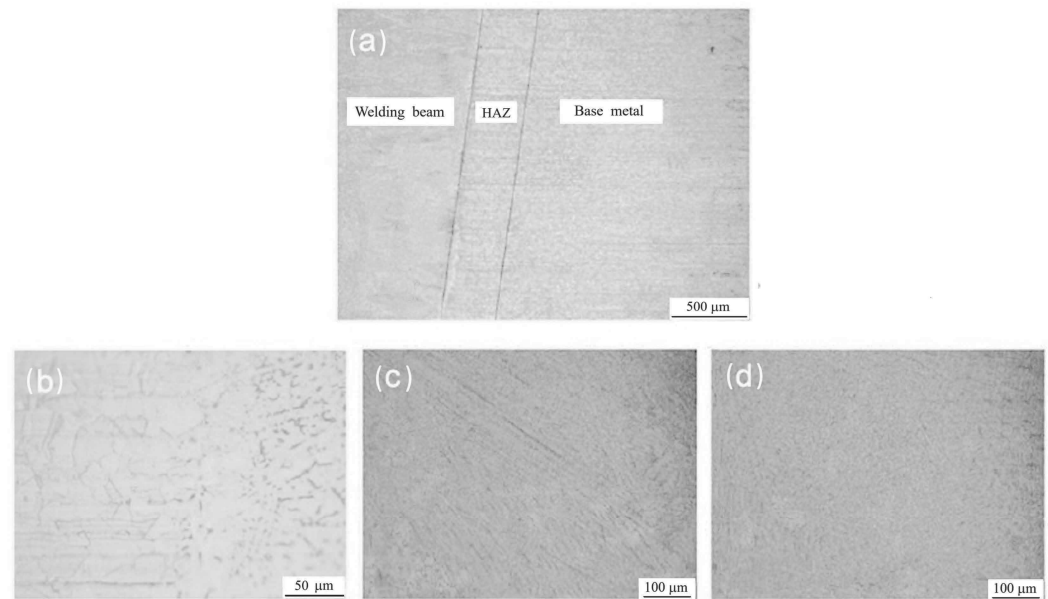


Figure 27. Microstructure of the joint between high-nitrogen steel plates obtained with LAHW (arc-leading configuration): (a) low magnification view; (b) details of the FZ; (c) dendrites' alignment near the fusion line; (d) weld's centerline zone. Reproduced with permission from [99].

4.2. Weld Composition

In [39], the authors welded two 14.5 mm thick ferritic plates using the laser-leading configuration with different parameters and filler wires (power ratio in the range of 1.6–2.0). Under these process conditions, the extension of the laser zone along the thickness prevails (see, for comparison, the cross-sections in Figures 22, 26 and 28).

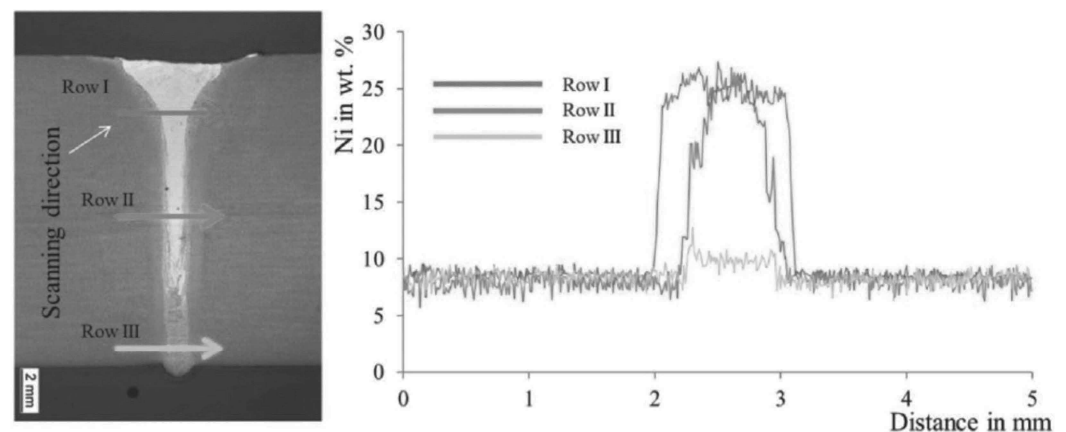


Figure 28. Cross-sections of ferritic steel plates butt welded using the arc-leading setup and Ni concentration profiles. Reproduced from [39].

The upper zone of the weld in Figure 28, where the arc's action prevails, shows an austenitic microstructure due to the alloying effect of the Ni-based filler wire, but the Ni concentration profile becomes narrow and decreases near the roots. Finally, the weld root is characterized by an austenitic microstructure with some traces of ferrite [39].

Effectively, the distribution of the alloy elements of the filler wire throughout the weld's thickness is of concern, as they tend to have low transportation ability towards the root. In the root area, the fraction of the transported filler metal is substantially lower compared to the upper part of weld, with detrimental effects on mechanical properties, as demonstrated in [100]. The authors butt welded two HSLA steel plates (thickness equal to 40 mm) using the trailing arc position. To assess filler penetration along the weld's

thickness, the distribution of non-metallic inclusions, supplied by the metal-cored filler wire, was monitored by inspecting the longitudinal macro-sections in addition to the usual cross-sections. The observations showed that in the root, the filling element amount is only half of that found in the upper zone of the weld. At low welding speeds (<1.0 m/min), the filler metal's transportation to the root zone can be improved by increasing the air gap, whereas higher welding speeds cause weld pool instability and reduce the filler metal's transportation efficiency.

5. Laser–Arc Welding of Clad Steel

Due to its many advantages, LAHW is currently used for joining clad steel plates. These are composite structures consisting of an inexpensive carbon steel substrate with a superimposed layer of stainless steel or other alloys containing strategic elements [101]. Clad steel plates are produced by hot rolling [102,103] or using other technologies [104,105] to achieve specific properties. The current methods allow for a secure interface between the two metals, providing a viable and cost-effective alternative to the use of expensive alloys. Due to diffusion in hot-rolled clad plates, a decarburized zone consisting of coarse ferritic grains (with the absence of pearlite) and a carburized layer form on carbon steel and austenitic stainless steel sides, respectively [106].

Details regarding the interface between the carbon steel substrate and the stainless steel cladding layer in hot-rolled plates are shown in Figure 29. According to the effects of diffusion, the following zones can be observed across the interface [107]: far from the interface, unaffected carbon steel consisting of ferrite and pearlite aligned along the rolling bands (Zone 1); a decarburized layer near the interface, mainly composed of ferrite (Zone 2); a carburized austenitic layer characterized by Cr-carbide precipitation at the grain boundary (Zone 3); and, far from the interface, an unaffected austenitic steel microstructure (Zone 4).

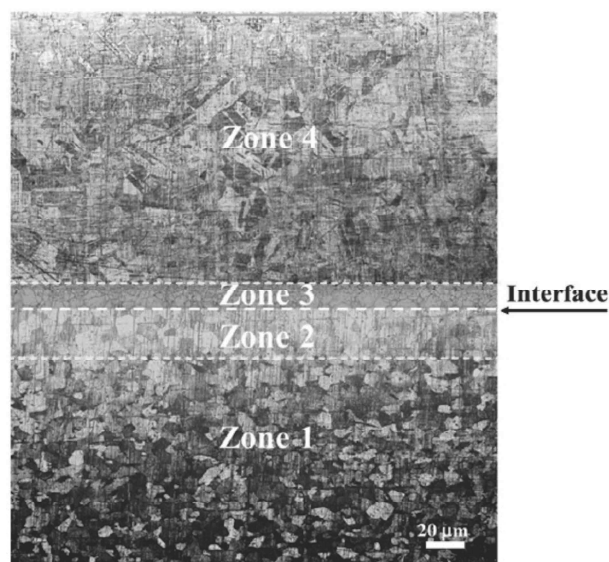


Figure 29. Micrograph taken through the interface of carbon steel/stainless steel in hot-rolled plates. Reproduced with permission from [107].

Welding technology is deemed indispensable for clad steel, as bolting involves the risk of exposing the substrate to corrosion. The usual arc welding standard for clad steel follows a sequence of multiple passes with the use of specific fillers (see, for a review, [108]). In this regard, Ban et al. [109] reported a comprehensive study addressing the metallurgical and mechanical characterization of the welds between two plates of Q355 structural steel (10 mm thick) clad with a layer of AISI 316 stainless steel (2 mm thick). All butt welding trials were carried out using GTAW with pure Ar as the shielding gas. The effects due

to the use of only the ER316L filler were compared with those due to the use of different fillers, such as ER50-6 and ER316L, for the structural steel level and the austenitic steel level. The results of mechanical tests showed that by using different fillers, the specification requirements can be met, achieving excellent mechanical properties.

However, even when using different filler wires with the most suitable compositions in the various passes, the heating cycles involve dilution phenomena that can potentially affect the composition and metallurgical features of FZ and HAZ [110,111]. Furthermore, the traditional welding methods, consisting of multi-passes of the electric arc, reduce the overall process efficiency. Therefore, the possibility of limiting the number of passes by using high-penetration LBW was also investigated. In [112], the authors butt welded two 2205/X65 clad plates, 4 mm thick, using a fiber laser apparatus in a single pass. They obtained full-penetration welds without any defects; however, the FZ showed a non-uniform composition and a hard martensitic microstructure at the carbon steel level. Another possibility is single-pass LBW by interposing consumable inserts between the clad plates. However, this does not allow for adequate differentiation of the weld's composition at the level of the cladding layer from that at the level of the base metal [113].

To overcome these shortcomings, LAHW appears to be a good solution for joining clad steel plates in a single pass. In [114], 9 mm thick clad plates were butt welded with the arc-leading setup using a filler wire made of ER310 austenitic stainless steel, highlighting that the corrosion resistance of the weld is more greatly influenced by the laser power than by the speed of the filler wire.

In [98], the authors, using a fiber laser apparatus coupled to a trailing arc torch, welded two carbon steel plates clad with a thin AISI 304 layer (overall thickness of 5 mm) in a single pass. The authors also investigated the effects of laser–arc inter-distance values in the range of 3–9 mm, as they observed that the stability of the welding process was compromised when the laser–arc distance fell outside of the optimal range of 1 mm to 9 mm. The welding trials in [98] were performed by butt positioning the plates with the cladding surface facing the two heat sources (Figure 30).

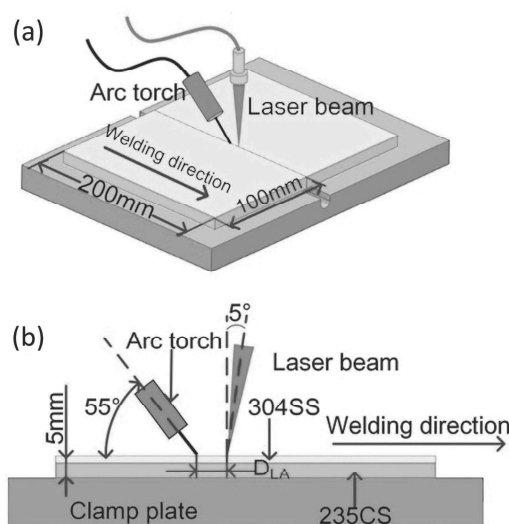


Figure 30. Setup of the hybrid LBW-GMAW process with a leading arc: (a) overview; (b) parameter settings of the hybrid process. Reproduced with permission from [98].

Gou et al. [115] tested the tandem configuration to join two 2205/X65 clad plates (thickness of 3 mm) with the ferritic steel facing the heat sources (Figure 31), obtaining good results through an optimal choice of welding parameters. In their experiments, the trailing arc followed the laser beam at a distance of 15 or 20 mm, giving rise to a reheating effect and lowering the cooling rate. Thermal power and laser–arc inter-distance

are key parameters, as they affect grain size and the content of alloy elements in ferrite and austenite. Thermal cycling curves showed that the weld bead was heated to the ferrite-to-austenite transformation range (1250–800 °C), promoting increased nucleation and growth of austenite in the 2205 duplex steel side.

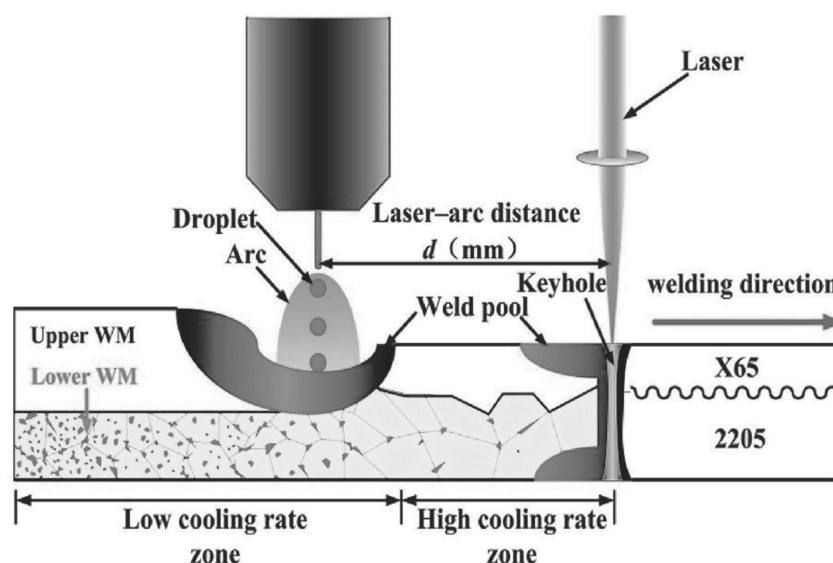


Figure 31. Setup of the tandem LBW-GMAW process with a leading laser. Reproduced with permission from [115].

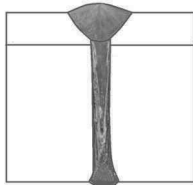
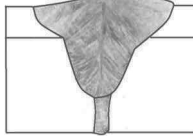
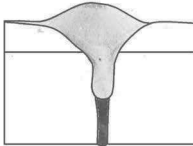
Recently, some authors have highlighted that LAHW allows for joining thick clad steel plates [116,117]. They have also demonstrated the benefit of distinguishing arc and laser zones to concentrate the filling action of the electric arc in the cladding layer. Effectively, the non-uniform distribution of the filler along the thickness of the joint can be useful in clad plates. In this way, the joint composition at the cladding layer and the base metal levels can be differentiated.

The effects of linear and surface heat input as well as power ratio values considered in [116,117] are compared in Table 5. The balance between the areas where the influence of the laser or the arc predominates is crucial to maintain the composition of the cladding layer in the welds.

In [116], an arc-leading setup with an inter-distance equal to 3 mm was used to weld two mild carbon steel plates clad with AISI 304 austenitic steel (total thickness of 13 mm) in a single pass. The authors used a high power ratio (equal to 9.9) and low heat input, obtaining a very narrow weld with an arc zone limited to the austenitic layer (3 mm thick), while the remaining narrow laser zone extended to the entire carbon steel substrate (10 mm thick). In particular, the authors addressed their experimental work to investigating the effect of the wire feeding rate, showing how values too high or too low make the clad layer a weak zone.

In [117], the presence of two separate zones was ascertained in the case of welding austenitic clad steel plates (total thickness 9 mm) with the laser-leading tandem configuration by comparing the effects of two inter-distances, 8 and 55 mm. In the first case, a power ratio lower than one and high heat input led to an extended upper zone and a short, narrow tail in the weld root zone. In the second case, an inter-distance equal to 55 mm generated the conditions for the tandem mode, in which the heat sources acted separately without synergistic effects. For this reason, despite the higher thermal input, the area affected by the electric arc was smaller than in the first case.

Table 5. Effects of heat input and laser/arc power ratio on the weld shape and width of clad steel plates.

Materials/ Total Plate Thickness	Edge Geometry	Setup/ Inter-Distance	Total Linear Heat Input	Total Surface Heat Input	Laser–Arc Power Ratio	Weld Shape/ Reference
AISI 304 (clad)/ Q235 (base) 13 mm	Square edge, 0 gaps	GMAW (leading) + fiber laser 3 mm	449 kJ/m	34,538 kJ/m ²	9.9	 [116]
Low-carbon X8Ni9 steel 9 mm	Square edge, 0 gaps	CO ₂ laser (leading) + GMAW 8 mm	835 kJ/m	92,778 kJ/m ²	0.43	 [117]
Low-carbon X8Ni9 steel 9 mm	Square edge, 0 gaps	CO ₂ laser (leading) + GMAW 55 mm (tandem)	1150 kJ/m	127,778 kJ/m ²	0.28	 [117]

A theoretical–experimental model of the thermal field simulation [118], based on the phenomenological laws of heat conduction, was used in [117] for analyzing the interaction between the thermal fields generated by the two sources. As demonstrated in Figure 32, the melt pools resulting from the leading laser beam (in red on the right side of the graphs) and the trailing electric arc (in red on the left) exhibit a lack of overlap. In the specific case considered, the 8 mm inter-distance represents a value slightly higher than the threshold above which the overlapping of the fusion zones is lost. Effectively, by increasing the inter-distance (tandem mode), the melt pool areas are completely separated and smaller due to the lack of synergy between the heat sources.

Concerning solidification, Cao et al. [116] highlighted the effects of high values of the power ratio. At the clad layer level, the electric arc's action prevails; therefore, the welds are wide, with an austenitic microstructure favored by the introduction of alloying elements. Conversely, along the substrate, the welds are solidified under the laser beam's action, assuming a narrow shape characterized by martensite laths. The respective compositions were determined by the authors through EDS measurements.

Based on calculations of the equivalent composition and the Cr_{eq}/Ni_{eq} ratio, the solidification mode can be ascertained with the Fe–Cr–Ni pseudo-binary phase diagram [119], the Shaeffler diagram [120], or the WRC 1992 diagram [121]. This finding is crucial, as the austenitic microstructure becomes less susceptible to hot cracking when solidifying as ferrite, which subsequently transforms into austenite (FA mode [96]) with a retained content of primary ferrite of approximately 5% [122]. In this case, a beneficial effect of preventing hydrogen embrittlement can also be achieved [123].

Solidification cracking is a common welding defect (mostly in high-sulfur steels, austenitic steels, and aluminum alloys) dependent on material composition and welding parameters. A critical value of the wire feeding rate beyond which the solidification mode changes from austenite–ferrite (AF) to ferrite–austenite (FA) was determined in [116].

Research has demonstrated the possibility of minimizing the occurrence of solidification cracking by choosing the right welding parameters. In this regard, see the articles by

Coniglio and Cross, who reported the experimental case studies present in the literature on the effects of welding speed and weld metal characteristics, as well as crack formation during solidification [68], discussing the different methods for testing [124] and modeling [125] such effects.

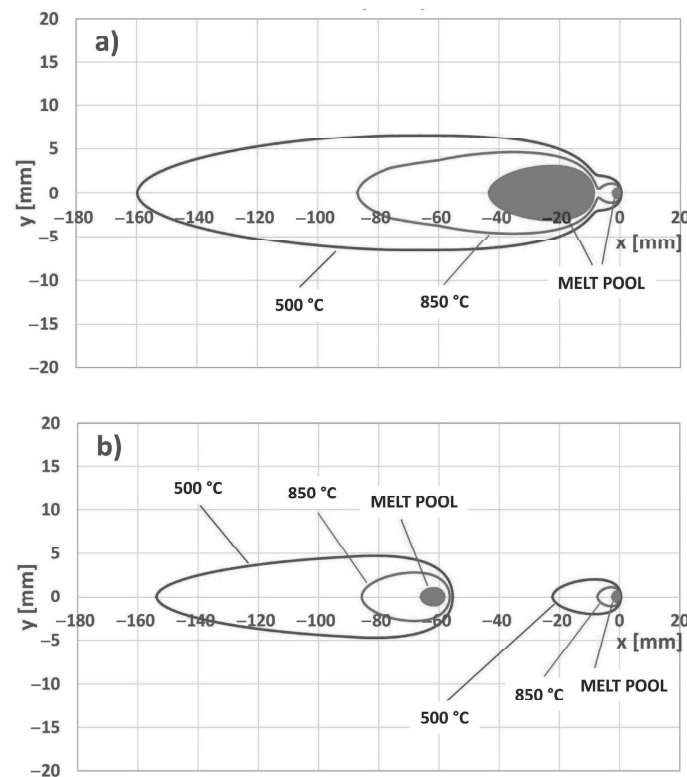


Figure 32. Simulated thermal fields on butt-welded clad steel plates, considering two different values of the inter-distance: (a) 8 mm (almost overlapping melt pools); (b) 55 mm (tandem mode). Reproduced from [117].

6. Conclusions and Future Developments

Hybrid welding processes have seen increasing development over the last decade to meet the demand coming from industry for a viable alternative to the traditional welding methods. The present review of the scientific literature on LAHW, mainly covering the last ten years (Figure 33), has specifically aimed to highlight the effects of laser–arc system configuration and process parameters on weld penetration and morphology while also considering consequences for solidification modes and weld composition along the thickness, which have important implications, particularly in clad steel welding. It has shown how LAHW combines laser and arc processes, overcoming their characteristic disadvantages and preserving their specific advantages. The need for an appropriate working configuration and an accurate selection of process parameters to meet the specific design requirements has been highlighted. In particular, it has been analyzed how the electric arc and the laser beam setup, as well as the welding parameters' settings, can determine the synergistic action of the heat sources, influencing the final characteristics of the welded joints.

As a general criterion for evaluating the shape and size of a joint, the values of linear and surface heat input and the power ratio were considered, with the first two parameters being the determining factor for achieving full penetration, while the third one affects the weld shape. Even considering the general criteria discussed in Section 3, the adoption of a set of process parameters remains an experimental choice addressed on a case-by-case basis by the various authors. Effectively, due to the interconnection of their effects, setting

welding parameters is a very complex challenge for which only case-specific solutions are available. From this perspective, some significant cases have been selected in Tables 2–5.

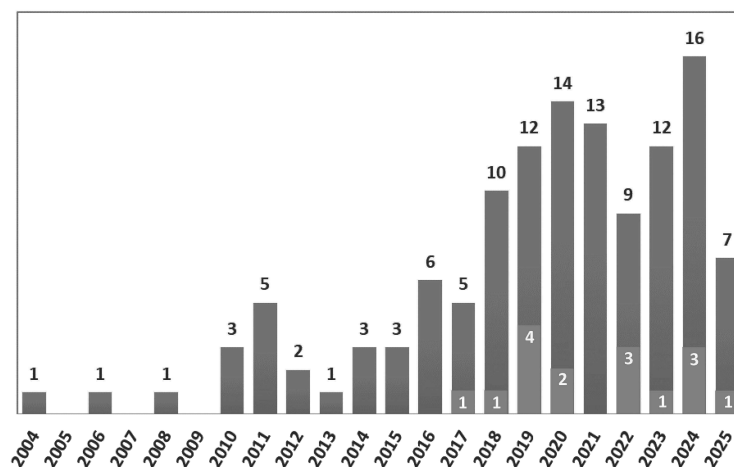


Figure 33. Temporal distribution of the articles examined in the current review (red bars indicate articles that specifically deal with application to clad steels).

From this overview, it emerges that many issues are worthy of attention from researchers.

- From a technological point of view, the development of integrated laser–arc heads at low costs is desirable to allow for greater diffusion of this welding method.
- Technological improvements could also have a beneficial effect on the environmental efficiency of the process, which, although promising based on the results of the first studies, deserves further investigation considering the ever-increasing importance of sustainability nowadays in the field of high-intensity manufacturing processes, such as welding.
- From the state of the art analyzed, a common approach emerges in analyzing the effect of sources' interaction on the final joint, which is primarily based on experimental investigations and sometimes strengthened by numerical simulations. An in-depth study of the complex combination of multiphysical phenomena involved in sources' interactions is needed to outline the principles underlying their effects and predict weld joint properties.
- Among the thermophysical phenomena that contribute in a particularly complex way to hybrid technologies, further research should be addressed to studying the coupled effects between laser–arc hybrid plasma and the molten pool, which are crucial for the generation of welding defects, such as porosity, undercuts, humps, and spatters, all closely connected to the set of welding parameters.
- In more general terms, a key issue to consider is the most effective method to approach the evaluation of the thermal fields to foresee the effects of the hybrid process modes. Such a procedure would enable metallurgical and mechanical predictions, also in relation to the generation of residual stresses.
- Due to the complexity of the phenomena during solidification, weld metallurgy requires targeted investigations. In this regard, some issues not thoroughly studied, such as filler and base materials' composition, as well as melt pool shape and the cooling rate due to the welding conditions, are crucial and deserve to be further explored. An example is the welding of austenitic clad plates. In this case, some authors have demonstrated the advantage of distinguishing the arc and laser zones in order to concentrate the filling action of the electric arc in the cladding layer, differentiating the microstructure of the joint (austenitic at the cladding level, where the filling action prevails) from the ferritic one of the base steel.

- The wide variety of process parameters in LAHW and the ways in which they can be combined make the identification of rational correlations among them and their effects on joint properties a very complex challenge that requires further effort to outline effective supports for the optimization of parameter settings according to the requirements of each specific application. Investigations on quantitative correlations between the main parameters and their effects could make it possible to define ranges of reference values that are significant and reliable as a guide for practitioners in industrial applications.
- Lastly, the new frontiers of artificial intelligence, machine learning, and digital modeling open up wide possibilities in the evolution of welding technologies towards more intelligent and adaptive processes. It is reasonable to imagine that the integration of established welding technologies and advanced digital tools can contribute to the development of more proactive and efficient approaches to welding process setting. In this way, hybrid welding could be improved for specific applications and its potential use extended to a wide range of industrial fields.

Author Contributions: Conceptualization, G.C., F.G., S.M., C.S., A.S., and M.E.T.; methodology, G.C., F.G., S.M., C.S., A.S., and M.E.T.; investigation, G.C., F.G., S.M., C.S., A.S., and M.E.T.; data curation, G.C., F.G., S.M., C.S., A.S., and M.E.T.; writing—original draft preparation, G.C., F.G., S.M., C.S., A.S., and M.E.T.; writing—review and editing, G.C., F.G., S.M., C.S., A.S., and M.E.T.; visualization, G.C., F.G., S.M., C.S., A.S., and M.E.T.; supervision, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partly funded by the University of Catania, Italy, within the plan “PIANO di inCentivi per la Ricerca di Ateneo 2024/2026”, action line 1 “Progetti di ricerca collaborativa”, project “INTERMETA—INTERazione tra campi TERMici e leghe METAlliche nei processi per fusione: Simulazione e analisi parametrica”, Department of Civil Engineering and Architecture.

Data Availability Statement: No new data were created; therefore, data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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