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OVERVIEW OF THE EXPLORATION STATUS OF LASER-ARC HYBRID WELDING PROCESSES

P. Kah

Lappeenranta University of Technology, LUT Mechanical PL 20, Lappeenranta 53851, Finland

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Abstract. Metal industries producing thick sections have shown increasing interest in laser–arc hybrid welding processes because of their clear advantages compared with the individual processes of autogenous laser welding and arc welding. One major benefit of laser–arc hybrid welding is that compared to autogenous laser, welding joints with larger gaps can be welded with acceptable quality. The laser-arc hybrid welding process has good potential to extend the field of applications of laser technology, and provide significant improvements in weld quality and process efficiency in manufacturing applications. The objective of this review is to present a set-up for laser–arc hybrid welding processes and introduce a methodical comparison of the chosen parameters. The research describes the principles, means and applications of different types of laser–arc hybrid welding processes.

Based on a review of the current knowledge base, important areas for further research are also identified. The study uses quantitative and qualitative research methods which include in-depth, interpretive analyses of results from a number of research groups. In the interpretive analysis, the emphasis is placed on the relevance and usefulness of the investigative results drawn from other research publications.

The results of this study contribute to research on laser–arc hybrid welding by increasing understanding of how old and new perspectives on laser–arc hybrid welding are evidenced in industry. The research methodology applied permits continued exploration of how laser–arc hybrid welding and its various process factors influence the overall quality of the weld. The study provides a good foundation for future research, creates improved awareness of the laser–arc hybrid welding process, and assists the metal industry in maximizing welding productivity.

1. INTRODUCTION

Laser–arc hybrid welding is a process in which the arc provides energy and molten metal, if filler wire is added, whilst the laser produces characteristics such as deep penetration, arc stability and extension of the root. It is, thus, possible to increase productivity and improve weld quality simultaneously [1,2] in comparison to welds produced with each process independently. This combination of heat sources (Fig. 1) has been receiving considerable attention because it can offer many advantages [3]. These advantages are, for example, deeper penetration, higher welding speeds, wider gap tolerance, better weld bead surface appearance, and reduced welding defects, leading to a smaller amount of porosity. As the heat input of laser – arc hybrid welding (LAHW) is greater than in laser welding, but much smaller than in MAG arc welding, a relatively narrow weld and restricted heat affected zone (HAZ) is obtained, which can minimize distortion [2,4-12]. These potential benefits can, however, only be achieved when the processes are correctly combined.

Laser-arc hybrid welding is not a new technology; the combination of laser light and an electrical arc in an amalgamated welding process dates back to

Corresponding author: P. Kah, e-mail: paul.kah@lut.fi

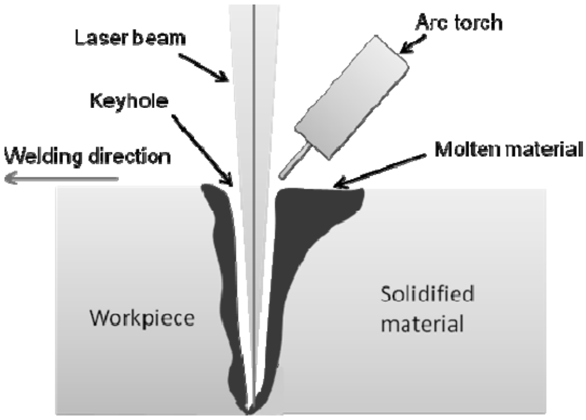


Fig. 1. Schematic representation of the laser-arc hybrid welding process.

the 1970s in the works of Steen and Eboo [2,13], who combined a 2 kW CO_2 laser and a TIG arc for welding and cutting applications. The laser and the arc are quite different welding heat sources but both work under a gaseous shielding atmosphere at an ambient pressure, making it possible to combine these heat sources in a unique welding technique referred to as the *laser–arc hybrid welding process* (LAHW). These early investigations already showed that the combination of a laser beam and an arc within a common process zone is more than a simple combination of the two heat sources. The laser beam creates a vapour capillary, due to its very high energy density of more than 10^6 W/cm², and the so-called keyhole enables a deep penetration welding effect where the beam energy is absorbed throughout the workpiece depth. An electric arc is created between the wire (the anode) and the workpiece (the cathode). The energy flow density of the freely burning arc is slightly more than 10^4 W/cm² in the case of MIG or TIG with wire addition, and this arc melts the filler wire. Droplets are detached and transferred to the workpiece to fill a joint gap, and to create the desired weld shape. TIG augmented laser welding was the first approach to be researched. MIG/MAG was the first commercial application and it is now commonly known as laser hybrid welding [2,5].

Typically the focused laser beam is aimed at a joint perpendicular to the plate surface, whereas the arc torch is tilted to a suitable angle and aimed close to the interaction point of the laser beam and material. This configuration means that the laser beam with its high energy density and the electric arc with high energy efficiency interact at the same time in the same process area (plasma and weld pool) and mutually influence and assist each other. In the hybrid welding process, the number of process variables grows through the coupling of the processes. The resultant mutual influence of the two processes can have different intensities and characteristics depending on the arc and laser process used and on the process parameters applied. A wide variety of hybrid processes exist, depending on the laser source (CO_2, Nd:YAG, diode, fiber or disc laser) and the arc welding process – MIG/MAG, TIG, plasma arc welding (PAW), tandem, submerged arc welding (SAW) – with which it is combined [14]. It is possible to use special heads in which the laser beam is surrounded by an electric or plasma arc [15,16]. With hybrid welding processes the advantages are fundamentally resolved by appropriate selection of the method set-up and adapting the basic parameter configurations to the demands of the material, structure and manufacturing conditions.

The main problem encountered, thus far, in transferring laser–arc hybrid welding from research applications to industrial use has been the high capital cost of the laser equipment. The driving force for research in laser hybrid processing has, therefore, been the perceived need to find ways of reducing the laser power required so that lower power, and thus less expensive, lasers could be used. In this context, it was thought that if the arc was used to preheat the workpiece prior to laser welding, a laser of reasonably low power could be used while still yielding the advantages of laser welding [17]. In addition, preheating of the workpiece facilitates the ability of the CO_2 laser (low absorptivity) to penetrate deeply into the workpiece.

Autogenous laser welding

Autogenous laser welding has gained great popularity as a promising joining technology with its acknowledged advantages of high quality, precision, performance and speed, as well as good flexibility and low deformation or distortion. In addition, it is a valuable process in many industrial applications owing to its suitability for robot technology, reduced man-power needs compared with other welding techniques, full automation, systematization potential and compatibility with production lines [11]. The high-power laser types most commonly used, including the most proven laser systems for hybrid technology development, are CW CO_2 and Nd:YAG lasers, mainly because of their prevalence in laboratory and industrial environments. However, disc, fiber and fiber-delivered high-power diode lasers also meet all the requirements to act as primary heat sources, and it is expected that these laser types will increasingly be applied in future hybrid technology developments. Powers of up to 30 kW for CO_2 lasers, and up to 6 kW for YAG lasers permit high-speed welding. The CO_2 laser was the first laser type adopted and is the most commonly used laser in hybrid welding. The Nd:YAG laser is also used in the hybrid process for welding of aluminum or materials of high reflectance and steel because of its short wavelength, which guarantees much higher absorption. One reason for using Nd:YAG lasers have been the possibility to use optical fibers for beam transportation. Fiber and disc lasers are not only fiber deliverable with equal or higher powers but are much less intimidating for potential hybrid welding users. These lasers are easier to operate and maintain, robust, and relatively low-cost per kW. In spite of the wide application opportunities for lasers in joining, there are certain limitations; namely, the high cost of equipment and maintenance, as well as the demands imposed on joint preparation, welding positions and workpiece thickness. These limitations are encouraging the development of new solutions using different methods [4,7,9,12,18].

The differences between the CO_2 and the Nd:YAG laser in hybrid welding come as a result of their wavelengths. The CO_2 laser is more economical and offers a higher speed than the Nd:YAG laser if the available higher power is utilized. But the laser beam delivering system is more complex for the CO_2 laser than for the Nd:YAG laser, which has a shorter wavelength that can be delivered through an optic fiber. This offers higher absorption especially in the case of welding aluminum.

However, both the CO_2 laser and the lamp-pumped Nd:YAG laser have significant drawbacks. The first one is the relatively low wall plug efficiency at much less than 10%. This means that the systems not only require large amounts of energy to operate but that they also require chiller equipment to extract waste heat [19]. In addition to the required laser power and beam quality, which both determine the achievable penetration depth, one main criterion for the selection of the primary laser beam heat source is the wavelength of the emitted radiation, which can restrict the choice of the usable shielding gas type. For example, welding with a CO_2 laser commonly needs gas mixtures with a high He content or pure He in order to suppress plasma shielding effects, whereas Ar and Ar-based gas mixtures with additions of active gas components such as CO_2 or O_2 can be used for the other high-power laser types. Consequently, hybrid combinations with Nd:YAG, disc, fibre or high-power diode lasers offer more flexibility in influencing the metallurgy of the weld pool and the metal transfer of the arc welding process by allowing greater choice of suitable shielding gases. The specification of each particular process combination usually depends on the specific demands of the welding problem to be solved.

Heat source combinations where the arc acts as the primary heat source are called *laser-augmented* or *laser-supported arc welding processes*. When the two sources are brought together, the laser can stabilize the arc [17,20,21] for the following reasons:

(i) The laser creates a stable hot spot and can lead the arc into the laser keyhole, which provides a very stable anodic or cathodic spot for the arc, confines the arc, and even brings it into the keyhole;

(ii) Laser energy makes the arc ignite more easily; and

(iii) The laser can compress the arc so that it becomes narrower; this is due to the fact that a large amount of ionized particles in the laser plasma enter the arc.

Conventional arc welding processes

Arc welding is the most widely used technology in joining applications because the machines are inexpensive and easy to operate, and the outcomes of the welding processes are successful. Drawbacks include shallow penetration and humping of weld beads in high-speed welding [1,17]. Furthermore, an arc can become unstable and can deviate unpredictably between the workpiece and the electrode tip, resulting in an irregular weld. Under normal circumstances, the arc selects the route between the electrode and the workpiece which has the smallest electrical resistance. For instance, welding of titanium by the MIG process is difficult because the arc cathode is not ‘‘stable’’ and drifts around on the weld bead, producing spatter. Combining as little as 200 W of laser power and a pulsed MIG helps with the weld puddle problem by locking the cathode location, which results in a regular weld bead [22].

Arcs with consumable electrodes, e.g., gas metal arcs, or arcs with non-consumable electrodes, e.g., gas tungsten or plasma tungsten arcs, can be chosen as secondary heat sources for hybrid welding. An arc welding process with increased productivity, like tandem welding and SAW, has also been used as a secondary heat source. The essential criterion for the choice of the electrode type is usually the necessity for filler metal to solve a specific welding problem. If any addition of filler

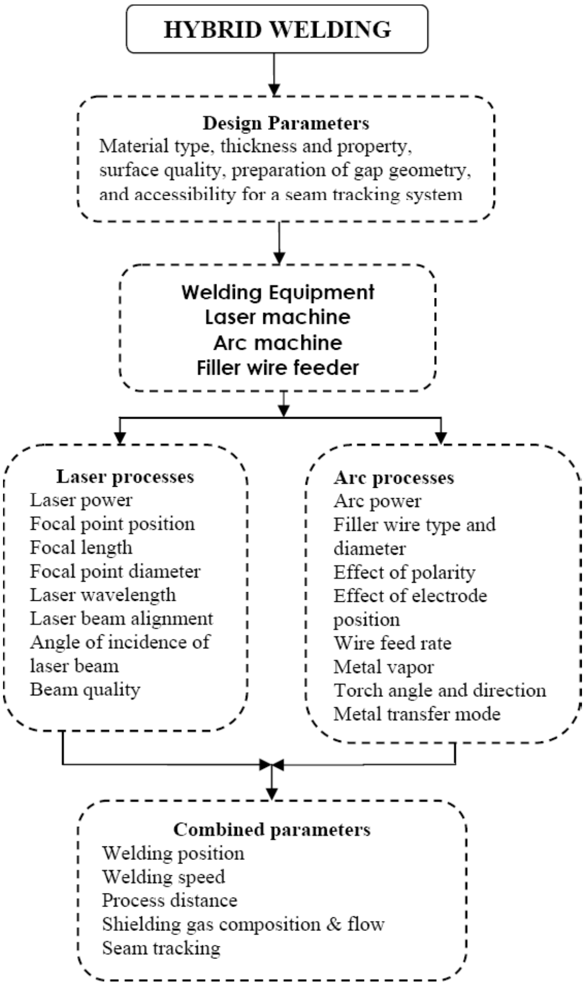


Fig. 2. Flow chart of process parameters in laser–arc hybrid welding.

metal is required, standard or typical procedures with consumable electrodes should be applied, otherwise arcs with non-consumable electrodes are preferred. The specification of each particular process combination usually depends on the specific demands of the welding task. Considering the variety of possible process regimes for each individual process, specification of appropriate processing parameters for laser–arc hybrid techniques has to be regarded as a challenging task. In most of the applications and research discussed below, the laser is the major contributor to the welding action, with the arc providing an assisting or modifying effect, leading to the commonly-used term *arc augmentation*.

In gas metal arc welding, there exist different metal transfers but spray metal transfer because of its high heat input per unit length and ability to reduce spatter, is often the most appropriate metal transfer mode for laser–MIG/MAG hybrid welding. The result is a relatively wider weld bead with good surface finish. Short circuit transfer is not often preferred due to instabilities generated in the molten pool. On the other hand, spray transfer mode is not very suitable for welding of thin metal sheets because it would introduce too much heat [6,23].

Combined effects of hybrid welding

As the two processes are integrated in a single process zone, numerous process parameters must be controlled to ensure good quality welds. The parameters comprise those of the individual processes and those resulting from the combination of the processes. The chart in Fig. 2 shows considerations that have to be taken into account when using a laser–arc hybrid welding process.

The flow chart shows very clearly that, as with any other welding process, the capabilities of laser–arc hybrid welding are essentially determined by appropriate selection of the system set-up and the basic parameter configuration. Manufacture design is the key to the successful performance of laser–arc hybrid welding. Joint access, joint configuration, and part tolerances all play a part in improving the chances for success. The process will benefit more if the product is designed so that the joint and the fit-up are suitable for the process. Too often manufacturers have component designs that have been around for 10 or 20 years and they try to achieve efficiency improvements by just replacing the joining process and keeping the design as it is. This does not necessarily work in the best possible way. Difficulties encountered are, however, not a result of the joining process but of inappropriate component forms; the component was designed to be manufactured with a totally different manufacturing process.

Basic set-up of heat sources

Specification of set-ups for the laser–arc hybrid process involves the choice of at least one primary and one secondary heat source. A variant of set up with a transversely inclined welding torch (Fig. 3) has been applied for welding of plates with different thicknesses, where the combined impact of both heat sources; (i) reduced the edge preparation requirements, (ii) increased the volume of the molten material, (iii) improved the weld appearance with a smooth transition zone between the sheets because the arc was burning preferably to the edge of the thicker plate, and (iv) increased the process efficiency resulting in significantly higher welding speeds compared with the laser welding process alone [6,23-25]. Combinations have involved setups

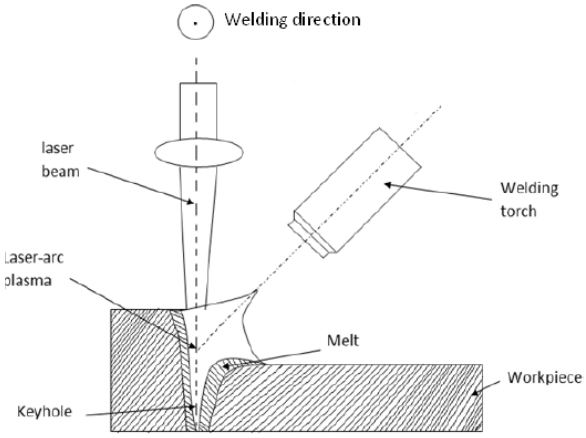


Fig. 3. Schematic diagrams of laser-arc hybrid welding with a transversely inclined welding torch.

with a common process zone (Fig. 1), arrangements where the laser and the arc act separately, as well as setups with more than two sources [26-29]. According to Ishide *et al.* [7], the laser and arc can be arranged in series, as opposed to coaxially, if the welding direction does not need to be varied during the weld. If this is the case, they recommend that the inclination of the arc should be as small as possible – in the range of 15° to 30° relative to the laser axis. However, for any applications involving materials with complicated shapes that require changing the welding direction, it may be desirable to arrange the laser and arc coaxially, which would necessarily require a special weld head.

Besides conventional laser-arc hybrid processes with one laser beam as a primary and one electric arc as a secondary heat source, there have also been some technological developments that make use of two or even more electric arcs. Possible basic configurations already applied are schematically presented in Fig. 4. The first arrangement (a) was realized by [20] using a CO_2 laser as primary heat source and two trailing TIG torches as secondary heat sources. During the process, the first TIG arc (torch 1) was operating at the same side as the laser beam, and the second (torch 2) at the opposite side, with the aim of generating an optimal notch.-free weld seam geometry appropriate for dynamic loading. Compared with the pure laser beam welding process, the fatigue resistance could be increased by approximately 50%.

The second set-up illustrated (Fig. 4) is characterized by two separated arc welding torches acting at the same side as the laser beam. The laser beam and the welding arcs are all aligned along the weld line with the leading arc (torch 1) in a backhand configuration and the trailing arc (torch 2) in a forehand configuration. Such an arrangement, also referred to as a Hydra (Hybrid welding double rapid arc) process, was originally applied by [31], who combined a CO_2 laser welding process with GMAW processes. Compared with the conventional laser-arc hybrid process with only one arc as a secondary heat source, the deposition rate of the filler material could be increased substantially, leading to higher welding speeds and a reduced thermal load. Alternative configurations of the Hydra process comprise variants where the arcs are arranged parallel to the weld line, either in a leading or trailing position relative to the laser beam axis. The inclination angles can be varied so that both backhand and forehand configurations can be realized. The best results for gap bridging ability have been achieved with two leading arcs [32].

The third variant shown (Fig. 4) was realized by [33] and is the application of two consumable electrodes (each with its own power source). Multiple electrodes are commonly used to improve welding productivity by increasing the deposition rate of the filler material. In combination with the conventional

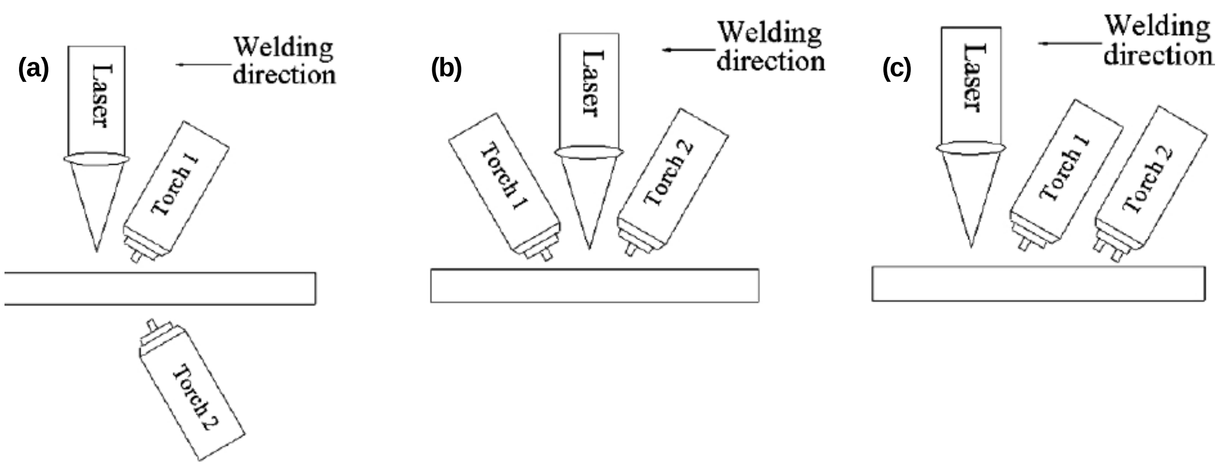


Fig. 4. Configurations using two or more electric arcs.

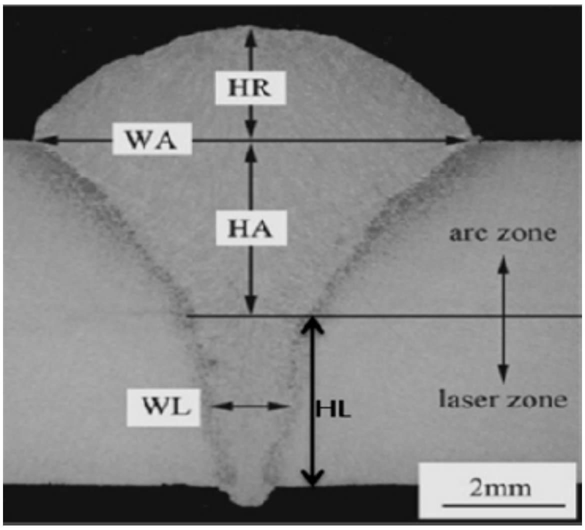


Fig. 5. Weld macrostructure and shape of laser–arc hybrid welding, replotted from [20].

hybrid laser-arc process (laser beam and torch 1) the cooling rates of the weld can be systematically controlled by varying the distance between the hybrid and the tandem-arc process. Development has been carried out using the laser and arc source directed onto the same side of the workpiece and also on opposite sides. The former arrangement is preferred in most industrial applications because the design of an integrated and compact welding head is more straightforward.

Weld shape of laser–arc hybrid welding

The shape of the laser–arc hybrid weld resembles a wine glass and can be divided into two parts, as shown in Fig. 5; the upper wide part is the arc zone and the narrow part below is the laser zone. This weld shape characteristic shows that the energy distributions of the laser and arc in the molten pool are different during laser–MIG/MAG hybrid welding. The arc energy mainly acts on the upper part to shape the wide arc zone, and the laser energy enters the bottom part of the workpiece through the keyhole and is the principal factor producing the laser zone with obvious deep penetration welding characteristics [34].

It is clear that the dimensions of the arc zone and the laser zone can be changed by the laser–arc energy ratio affecting the energy distribution in the molten pool of hybrid welding. In other words, a decrease in the energy ratio of the laser arc (ERLA) can reduce the difference in width and height between the two zones and change the wine-cup shape of the hybrid weld. In MIG/MAG welding, the higher the arc current, the bigger the arc pressure and the impinging force of the melted droplet on the molten pool. So, a higher arc current with higher arc force can drive more melted metal towards the weld root, which means that more heat enters the bottom part of the weld to increase the penetration of arc zone HA and more substrate at the laser zone is melted to increase the width of the laser zone WL. On the other hand, this phenomenon can also reduce the accumulation of the heating effect of the arc energy in the arc zone, which decreases the width of arc zone WA. As a consequence, the dimension difference between the laser zone and arc zone reduces with decreasing ERLA [20,35]. When hybrid welding has a high ratio of laser power, the process is more like laser welding and may obtain a harder microstructure, such as martensite or bainite, and fine grain in the weld. When hybrid welding has a low ratio of laser power, the process is more like arc welding and only attains coarse grain and pearlite with relatively low hardness [36].

The increase in arc power mainly depends on the increase in the wire feeding rate and the voltage of the arc; an increase in the volume of molten metal leads to an increase in the weld fill height (if the joint dimensions remain constant). The weld widths depend on the arc power but their ratios differ. With increasing arc power, the increased augmentation of the weld width is lower than that of the weld fill height, because the area heated by the MIG/MAG arc cannot enlarge directly proportional to the arc power.

The laser energy has some influence on the weld fill and reinforcement-to-width ratio of the hybrid weld, which varies with the laser power, laser–arc distance and location of the laser focus, the arc power and welding speed [37]. The ratio between the depth of the laser zone and that of the arc zone can vary considerably, depending on the laser power, edge preparation, the welding process, welding parameters and type of material. The weld shape in hybrid welding also depends on welding factors such as the gap condition, leading heat source, motion of the molten metal in the gap and preheating effects [38].

2. TYPES OF LASER-ARC HYBRID WELDING PROCESSES

Laser-MIG/MAG welding process

The fundamentals of the coupled process (Fig. 1) are nearly the same for both CO_2- and solid-state lasers. The laser and arc processes have a common process zone and weld pool. The process can

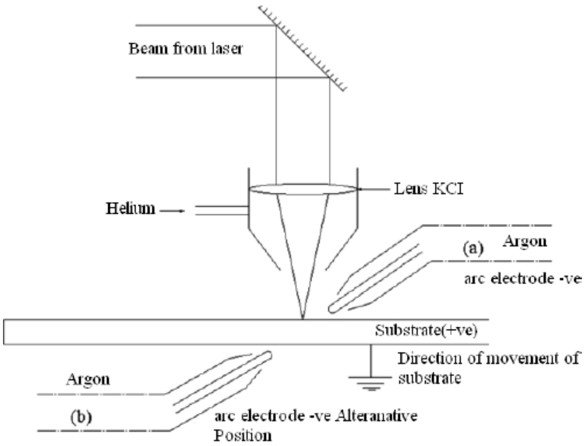


Fig. 6. Laser–arc welding system which first appeared in 1979, replotted from [2].

be controlled in such a way that the MIG/MAG welding part provides the appropriate amount of molten filler material to bridge the gap or fill the groove, while the laser generates a keyhole within the molten pool to ensure the desired penetration depth. By combining the laser beam and the MIG/MAG arc, a larger molten pool is formed compared to the laser beam welding process, permitting welds to be made in joints with greater fit-up problems and gaps than can be normally welded by autogenous laser welding.

The microstructure and mechanical properties of the weld metal can be improved by controlling its chemical composition using an appropriate filler material. In this case, the wire feeding elements should distribute homogeneously all over the weld metal to attain a homogeneous microstructure. It is not easy, however, to attain homogeneous distribution in narrow and deep penetration hybrid welds. The hot crack affinity of extrusion compound alloys is another reason for the use of filler material. With regard to such applications, the greatest potential of the laser-arc hybrid welding technique is expected to be in the area of additional filler material and thus the laser-MIG/MAG hybrid welding process, which is currently the most preferred laser-arc hybrid welding process [39-43].By using the MIG/MAG process (continuous or pulsed arc) as the arc process in laser hybrid welding, the gap bridging ability can be increased as the addition of filler metal is more controlled and its volume can be higher than cold wire feed used together with plasma and the TIG arc [17,44].

Laser-TIG welding process

When a TIG arc is operated simultaneously with a laser beam, a heat condition is established in which, it is theorized, laser absorption is improved. The

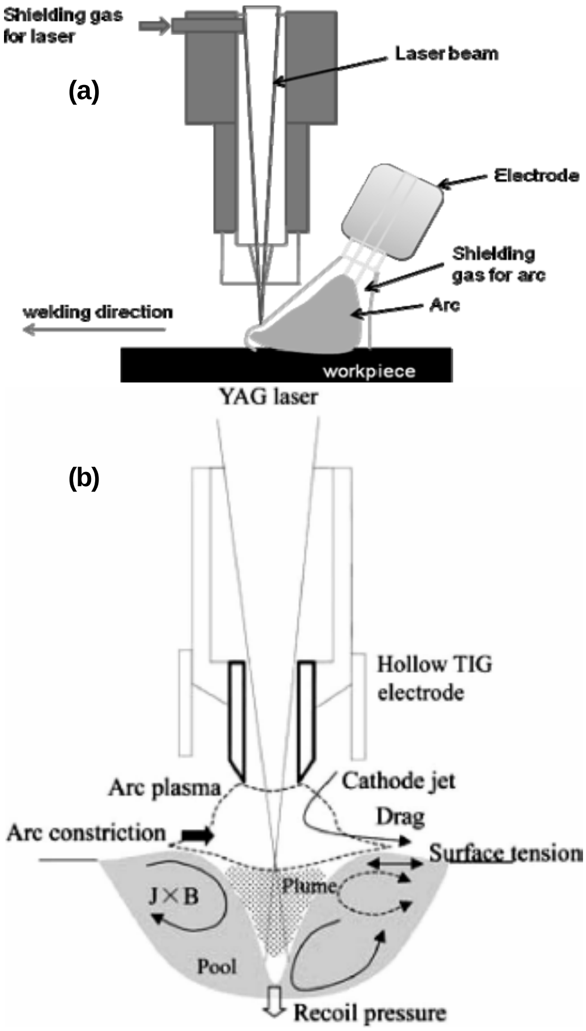


Fig. 7. Schematic illustrations: a) Sketch of laser–arc hybrid welding, Ar shielding gas was supplied to the laser and TIG arc [46]; b) Coaxial hybrid process with hollow TIG and laser, replotted from [48].

absorption of the laser energy into the base material is enhanced in this heated region [40]. Laser-TIG hybrid welding has proven to be a promising technique to weld very thin austenitic stainless steel sheets (0.4-0.8 mm) in a butt joint configuration [44]. The molten pool generated by the laser stabilizes the TIG arc allowing welding speeds as high as 15 m/min with the laser trailing. In order to avoid thermal distortions and excess fusion, the TIG welding current has to be minimized and the use of additional shielding gas is necessary [44].

A schematic diagram of the TIG arc augmented laser welding system, which first appeared in 1979, is shown in Fig. 6. The arc torch was mounted either above or below the substrate. The tungsten electrode was always kept negative while the working piece was positive. When the laser and TIG on opposite sides of the workpiece, a 300% increase in speed was obtained. With the laser and arc on the same side of the workpiece a 100% increase in speed at the same arc current was achieved on 0.8 mm thick titanium and on 2 mm thick mild steel [2,13]. Furthermore, with the laser and arc on the same side of the workpiece, it was also observed that the undercutting, typical of high welding speeds, was absent. Mazumder [45] reported that the resulting welds had many of the characteristics of an autogenous laser weld, but tended to have a wider fusion zone at the top, due to the influence of the broader arc, and a wider HAZ.

Different laser–TIG hybrid configurations exist, as shown in Fig. 7. Fig. 7 is a sketch of laser–arc hybrid welding with Argon shielding gas supplied for the laser and TIG arc. Laser–arc hybrid welding differs from coaxial hybrid welding in that the effect of the current on the hybrid arc and weld penetration is consistent. However, the maximum penetration achieved with coaxial hybrid welding is 20% deeper than in the case of laser–arc hybrid welding with similar heat input, as reported by Chen *et al*. [46]. Moreover, the critical current of the transition of the welding mechanisms, i.e. droplet to spray mode, is much higher in coaxial hybrid welding than in laser–arc hybrid welding. The reason is probably that while the laser traverses the whole arc in laser–arc hybrid welding, especially at a high current, the energy absorption or defocusing of the laser by the TIG arc is more severe, which reduces the energy density of the heat source acting on the workpiece, especially in the case of a CO_2 laser and TIG arc. In coaxial hybrid welding, on the other hand, the distribution of current density create an opening of the arc centre by the hollow tungsten electrode, and the focus point of the laser is likewise rather small. Furthermore, YAG laser–TIG hybrid welding can obtain deeper penetration compared with CO_2 laser–TIG hybrid welding at the same laser power [46].

One example of a combined welding method with a coaxial laser and arc is the configuration developed by Ishide *et al*. [47]. This avoids the aiming problems and size requirements of the TIG or MIG torch as the laser beams are focused immediately below the arc (Fig. 7). Since the beam quality of the laser is impaired in this method, it is not suitable for deep penetration welding of thick plates. If, as in Fig. 7, a coaxial structure is utilized in which the laser beam is passed along the hollow cathode TIG central axis, it is possible to use a laser beam of high quality to form a deep keyhole. Additionally, since the plasma flow is reduced and the outward convection currents are inhibited by the hollow cathode, it is anticipated that an inward convection current will be formed in the molten pool by a small inward drive (for example, by the electromagnetic force j × *B*, generated in the arc current channel concentration due to the metal vaporization of the laser plume) and there is a possibility of a dramatically increased penetration. The effects of these actions are listed below [48]:

i) Since the current concentration is moderated at the cathode tip and the plasma flow is reduced, the drive force of outward-directed convection flow in the molten pool is reduced, making inward convection flow more readily induced.

(ii) Since the arc pressure is reduced due to the reduction in the plasma flow, it is possible to slow down humping bead formation by increasing the current and speed of the welding process.

(iii) The arc pressure can be regulated by the inner gas type and flow, and the penetration shape of the molten pool can thus be optimized.

(iv) By directing a high beam quality laser onto the centre of the molten pool from directly above, the arc anode region is constricted, and inward-directed convection currents are induced by electric current concentration.

The TIG process can be operated either with or without filler metal addition. Utilization of the TIG process together with a CO_2 or Nd:YAG laser welding process finds use mainly in thin sheet applications. It has been reported that the TIG arc cannot transfer a lot of filler metal to the process (if filler wire is used) because part of the heat of the arc is used to melt the filler wire [44].

Laser-PAW process

In a process for laser-plasma hybrid welding, the laser beam and the plasma jet are brought together in the process region close to the workpiece, as in Fig. 8. In operation, the plasma torch is positioned at an angle of approximately 45° to the laser beam. A free microwave- induced plasma jet is generated in a high-frequency microwave source and guided in a hollow waveguide. The process gas is introduced into the microwave transparent tube through the gas inlet opening and plasma is generated by an electrode-free ignition of the process gas [48,49]. The main arc initiation is via a low amperage pilot arc formed between the tip of the electrode and the nozzle. When the pilot arc is switched on, it produces sufficient heat to ionize the air gap between the nozzle and the workpiece. An additional advantage from the tungsten electrode is that the electrode is placed behind the nozzle that provides the characteristic jetting effect of the plasma gas. Stable arc operations are maintained for relatively

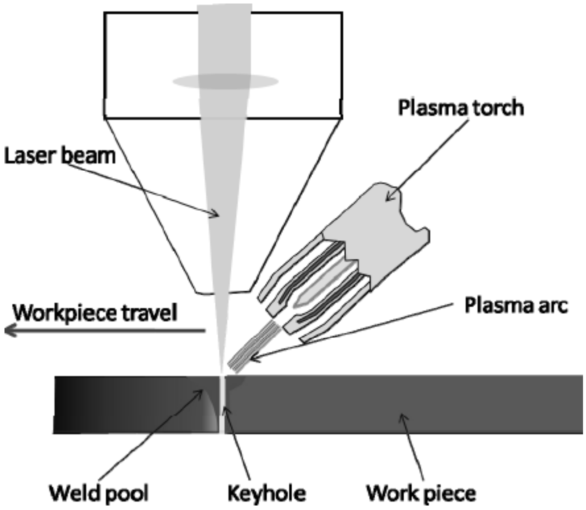


Fig. 8. Experimental arrangement of plasma arc augmented laser welding system.

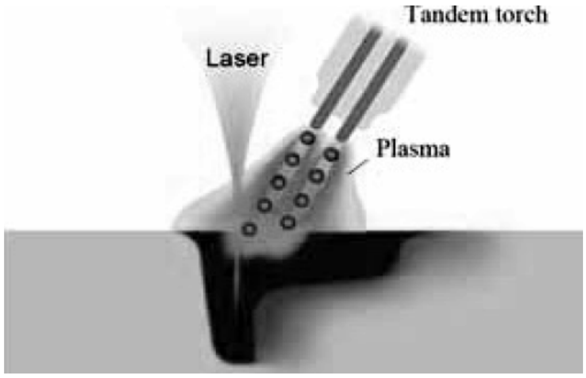


Fig. 9. Illustration of laser–tandem arc hybrid welding.

long periods without deteriorating the electrode since the tip of the electrode is not exposed to impurities [49].

Plasma arc welding can be used together with the laser beam process in such a way that the laser beam is surrounded by a concentric plasma arc. The heat of the plasma arc introduces heat treatment which reduces the cooling rate and decreases the weld hardness and the development of residual stress states. It is therefore possible to tailor the microstructure of the weld and HAZ to the application at hand [17,49,50].

Laser-tandem welding process

The process principle of laser tandem-MIG hybrid welding is outlined in Fig. 9 [43]. The laser beam is set at approximately 90° to the workpiece and is used for welding the root. Both of the other trailing arcs have a pushing tilt angle and are used to increase the ability to bridge root openings and increase throat thickness. The process uses three different power outputs, thus the outputs can be set depending on the desired welding result. The welded joint geometry, the preferred joint overfills and the welding speed can be selected by means of a suitable power output. Reported mostly by Staufer [52], the key advantage of combining the processes in this manner is the fact that as the filler metal melts off, it generates an arc pressure which does not act on the workpiece but is distributed across separate arc roots. In the laser tandem-MIG hybrid process, control of the laser power, the power of the arc and the arc lengths is possible separately, which results, it is claimed, in better drop detachment, more stable arcs and fewer spatters. Moreover, when using this process it is also possible to use laser-MIG/MAG hybrid welding with a single arc [51].

In hybrid welding, the arc torch has to be oriented with a flatter angle than in conventional arc welding because the laser beam may impinge the gas nozzle if the arc torch is too close to the laser beam. Consequently, in most hybrid welding heads, the torch makes a 30° angle to the perpendicular position, which is not normally the case in conventional arc welding. Since the arc process in hybrid welding influences the shape of the upper side of the weld seam, arc stability must be taken into careful consideration.

Laser-SAW hybrid welding process

The laser-MIG/MAG hybrid welding process encounters problems in some applications with regard to pores at the root of the sheet when plate of more than 12 mm thick is welded with partial penetration. This has been attributed to insufficient degasification in deep and narrow laser welds. To mitigate this phenomenon, the molten pool has to be maintained for a longer period [52] and for this reason experiments have been done with maintaining the molten pool using the laser-SAW hybrid process, thus creating more favorable degasification possibilities. Here both processes are moved as close as possible (13-15 mm) into one process zone [53].

Coupling the two processes, laser beam welding and the SAW process, in one process zone proved to be a problem, since the flux was found to fall into the keyhole of the laser beam and the laser radiation was absorbed by the flux and not by the component. Consequently, a device impeding this «falling forward» of the flux has been designed and built. One starting point is a separating plate (patented by RWTH, Aachen University) which is mounted

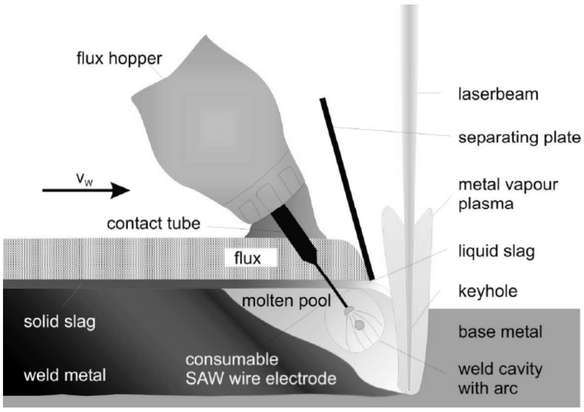


Fig. 10. Schematic representation of laser-submerged arc hybrid welding, replotted from [54].

between the laser beam and the flux feeder (Fig. 10).

In previous investigations, the spatial distance of both processes and the separation of the weld into two regions namely, the laser-welded and SA-welded region, have been found to be critical. The distance must be chosen to be short enough to ensure that the smallest possible quantity of flux falls forward and large enough that the slag running ahead of the process does not block the sheet. The inclination angle of the separating plate is also most important. If the inclination angle is too large, the separating plate may be captured by the laser beam, and if it is too small, the arc might burn between the separating plate and the filler wire, an area which has not shown any mixing of the weld material. The synergy effect of the increased welding speed of the SAW process is considered just the result of preheating from the welding process [54].

The combination of laser welding and submerged arc welding is a completely new process and suitable for the production of welded joints containing Y welds. A particularly advantageous feature of the laser-SAW process is the reduced risk of plasma shielding. It is easier to couple the shorter wavelength of the solid-state laser into the material to be processed. The flexibility of the equipment also improves with a shorter wavelength, since the complicated beam guidance via mirror optics can be dispensed with and the laser beam can be guided via optical fiber into the processing optics. The laser-SAW hybrid process improves degassing by covering the molten metal with the slag and has good gap bridging ability, giving increased welding possibilities compared to laser welding thick plate by permitting the use of different diameters of wire. The application of suitable wire/flux combinations is expected to increase the potential of the process and open up new fields for the laser technology [53]. Welding speeds of up

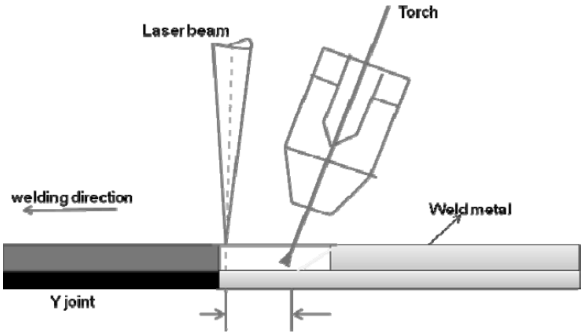


Fig. 11. Combination of laser and arc processes, replotted from [17].

to 5 m/min can be achieved by the use of appropriate welding fluxes and optimum parameters with ac phase displacement in the wires [55].

Tandem technique

Another possibility for hybrid welding with two energy sources is to use a tandem technique in which each energy source acts independently but makes a joint weld pool (Fig. 11). The greatest effect is achieved if the laser beam is used to produce the root pass, and arc welding with a consumable electrode is used for filling the passes. The arc process to be used for filling the passes depends on the type of material and thickness of the workpiece. The MIG or TIG process with an additional hot or cold wire should be used when welding nonferrous metals and high alloy steels [5].

Hybrid and extra shielding gas nozzle

Laser GMAW welding was the subject of study in the 1980s and various authors reported the advantages of the synergistic action of the welding arc and the laser beam. Fig. 12 shows a device for welding with a MIG arc combined with a laser and an additional shielding gas nozzle. This configuration is most commonly used with a CO_2 laser. Developments in this field have continued in recent years with similar set-ups and the literature reports not only general findings but also some practical applications [55-58].

Laser arc hybrid plus tandem arc process

Laser MIG/MAG hybrid plus tandem arc process has been developed. The process works by combining a tandem arc with a laser–arc hybrid welding process. Fig. 13 shows a schematic diagram of the laser–arc hybrid plus tandem welding process. The laser–MAG hybrid plus tandem welding head shown

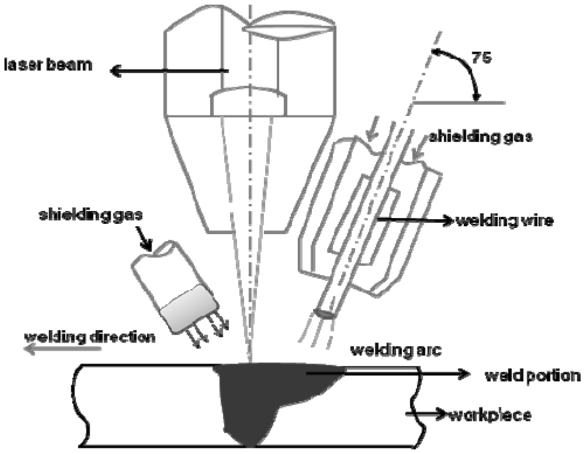


Fig. 12. Schematic representation of laser welding apparatus, replotted from [5].

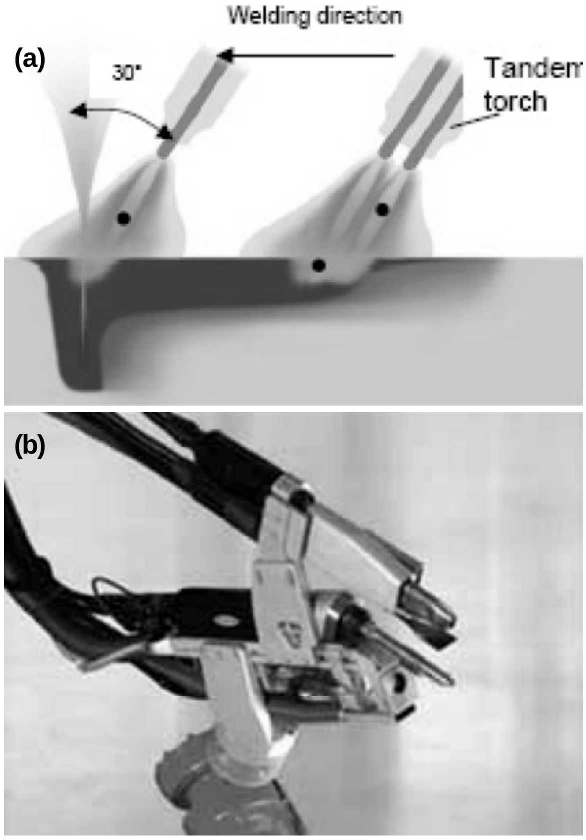


Fig. 13. Schematic outlines: a) laser hybrid welding process with three arcs (laser–arc hybrid + tandem), b) laser–arc hybrid + tandem welding head, replotted from [60].

in Fig. 13 was developed by Fronius International GmbH.

An important aspect of the use of laser–arc hybrid welding in general and laser–arc hybrid + tandem in particular is to ensure that the configuration used has positive effects on the weld metal metallurgical properties. For this reason, the laser beam is inclined at a tilt angle of ~ 5° leading. Precisely adjusted to the laser, the first (single wire) arc is positioned at an inclination of ~ 30° and followed by the MIG/MAG tandem torch. The spatial distance between both the single and tandem wire depends on the objectives to be achieved. As the MIG/MAG is intended to be enhanced, the tandem wire process needs to be spaced further apart from the laser–arc hybrid process. One of the major advantages of operating the processes in this way is improved weld bead control obtained by a beneficial energy distribution across the weld pool area. The above-mentioned hybrid tandem welding is particularly suitable for the welding of metals with high thermal conductivity, such as aluminium and copper [12].

In the search to be able to join thicker plates and obtain deeper weld penetration, much attention has recently been paid to laser–MIG hybrid welding [15,59]. Deployment of the first industrial laser–MIG hybrid system at the factory of an oil tank manufacturer by Fraunhofer ILT in 2000 triggered widespread interest in the welding industry and various hybrid systems have been installed in the automotive, shipbuilding and tube production industries [17]. All the examples described so far have the arc and laser both consisting of two independent welding heads. Coaxial combined welding heads have been investigated but they have only been realized in laser–TIG or laser plasma arc hybrid welding, which makes them applicable to 3D joints and to situations demanding a more compact welding head [60].

Normally, the smallest possible arc inclination is desired, that is, angles in the range of 15° to 30° relative to the laser axis. Because of the difference in the wavelength, Nd:YAG laser radiation allows a closer approach to the arc than CO_2 laser radiation as much less radiation is absorbed by the arc plasma. Nevertheless, with the standard approach of combining a discrete arc torch in an off-axis configuration with a laser-focusing head, there are certain limitations with the possible position and orientation of the arc. In order to prevent the torch nozzle from interfering with the laser beam, it has to be positioned at a sufficient distance and at a suitable inclination. Another problem with this off-axis configuration approach is that it promotes entrainment of air into the weld by the venturi effect. To address these problems, Fraunhofer ILT has designed a welding head where the laser beam and arc are surrounded by a common water-cooled nozzle device with an integrated contact tube.

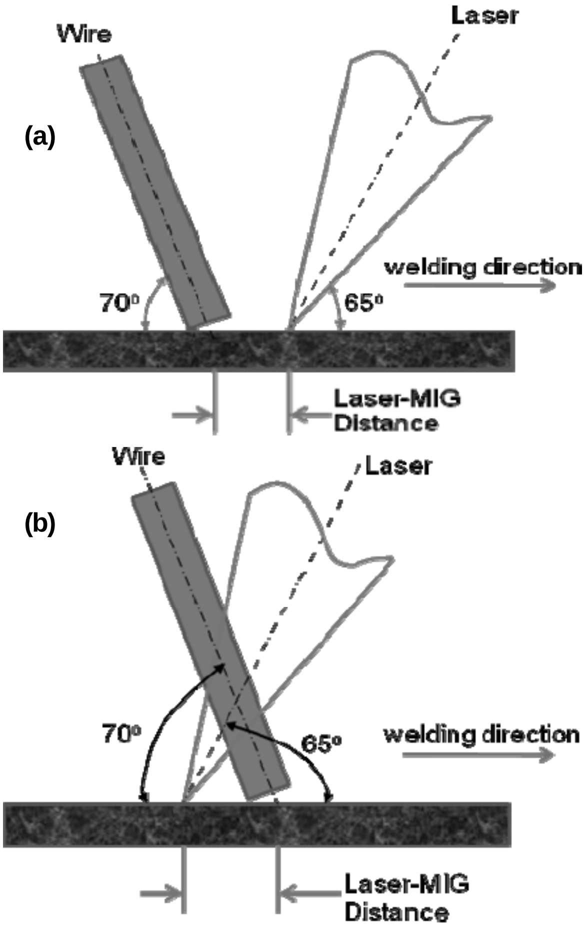


Fig. 14. Schematic set-ups of laser beam and wire: a) laser separated from wire, b) laser crossed with wire, replotted from [65].

Laser and wire

The effect of the set-up conditions of a laser beam and wire and the laser beam parameters on wire melting phenomena and gap tolerance in butt joints have been investigated by different authors[61-63].The studies include hybrid welding with either a CW YAG laser (wavelength 1064 nm) or fiber laser (wavelength 1520–1610 nm). For a fiber laser combined with a pulsed MIG arc for welding an aluminum alloy, it was reported by Wang et al. [63] that in order to obtain a deeper penetration, the laser beam should be separated from the wire by a process distance at which there is no direct interaction between the laser beam and the droplet during its transfer (Fig. 14). On the other hand, in order to join a wider gap, for example, for a butt joint, it was found better for the laser beam to be set to cross with the wire (Fig. 14) for more than 2 mm so that the laser beam could directly irradiate the wire surface to melt it. As a result, the arc current could be decreased so that the molten pool size formed by MIG is increased efficiently and the gap tolerance increased. From the viewpoint of laser absorption by the wire or the molten droplet, according to the approach reported by Wang et al. [63], about 10% of the laser energy is absorbed in the wire during hybrid welding when the laser beam is directly irradiated on the wire surface.

3. MAIN CONSIDERATIONS AND BENEFICIAL SECTORS

Certain competitive factors must be considered before installation of a laser–arc hybrid welding system. The industry in which the company competes must be assessed from the outset, because the dynamics of the industry drive all the other factors. LAHW is ideal for conditions where machined components, expensive fixtures and tooling are not practical. It works best with long, continuous welds and high-duty cycles (longer operational time). It is very suited for shipbuilding, if the shipbuilders improve fixturing and tolerances, and transportation vehicle industries, and industries manufacturing steel structures, where it can be used for a wide variety of applications.

Hybrid welding markets will mostly be in industries where conventional arc welding is currently used. The cost of implementing LAHW varies widely and depends on many factors, such as the volume of production, the laser power required, the number and complexity of tooling and fixtures for the application, and the level of automation needed. When deciding whether or not to invest in a hybrid welding system, the productivity and other benefits of the process have to be well understood. Fortunately, as with most technology, the costs of these machines are likely to drop over time as LAHW gains popularity and usage. Furthermore, because LAHW uses high energy density and thus low total energy use, users may make considerable savings on energy costs.

Currently, LAHW is not very appropriate for customized built-to-order jobs or orders involving many small, complex parts with small features and tight areas, or complex 3D welding, even though this could change as technological research advances. Before considering implementation of LAHW in a factory environment, it has to be ensured that upstream processes can deliver parts that are consistently of the quality necessary for automatic welding. LAHW allows manufacturers to rethink their approach to designing and manufacturing steel structures in ways that will reduce both the amount of material and energy consumption, and achieve

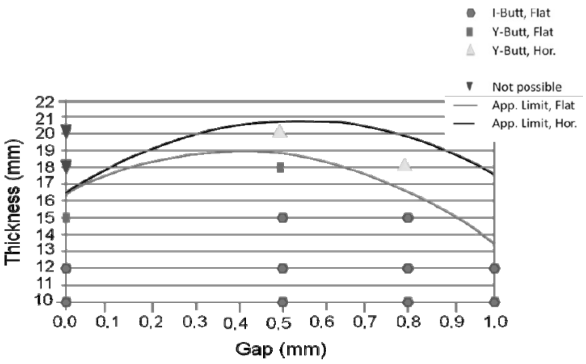


Fig. 15. Observed thickness limits for equipment used at FORCE Technology, replotted from [75].

higher levels of automated fabrication and assembly.

Further obstacles to overcome prior to greater utilization of the process are the physical limitations. The first limitation is the maximum thickness that can be welded such that a free-formed root bead can still be produced. The limit today is between 12 mm and 15 mm for a power level 10-12 kW, depending on the laser used. Higher power lasers having potential for deeper penetration up to 25-30 mm are not able to reach this penetration due to root quality problems.

Any material that can be welded with a conventional laser or arc process can be welded using hybrid welding technology. To date, successful development programs have been carried out for applications with steel, aluminum, copper and titanium. The hybrid approach used is governed by the material thickness and the requirements of the individual application. Laser–TIG and laser–PAW tend to be used more often for thinner sheet metal applications (< 3 mm) while laser–MIG/MAG, is generally used for welding thicker sections (≥3 mm), although it has been used in automotive sheet metal applications.

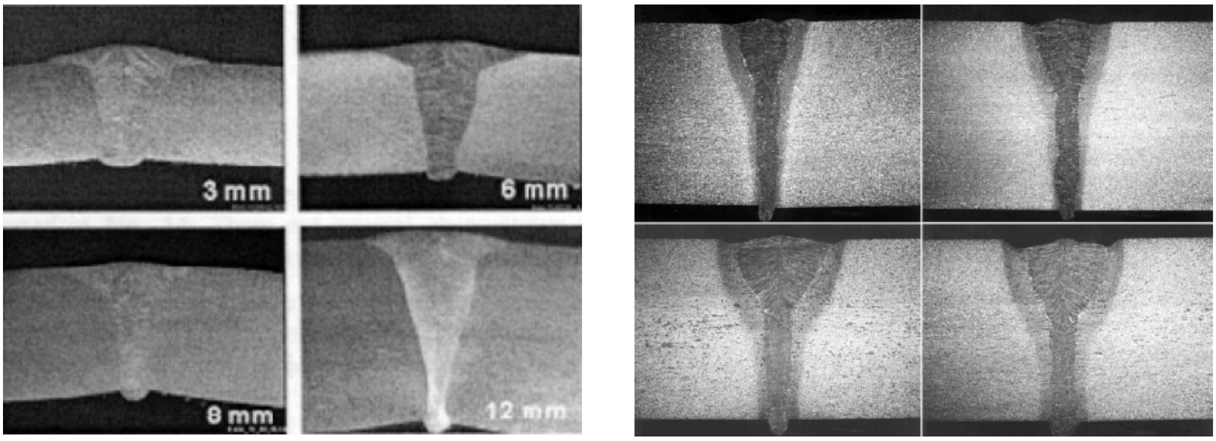
4. APPLICATIONS

As a result of its apparent advantages, laser–arc hybrid welding technology has become more attractive in recent years and has excellent industrial application prospects in many fields, such as the aerospace, automotive, off-road vehicle, shipbuilding, oil and pressure vessel industries. Research on improving the weldability of materials by this process, mainly involving laser–TIG, laser–MIG and laser–PAW hybrid welding, has achieved some success, but studies of the effects of the welding parameters on the microstructure of the weld and the mechanical performance of the process are still few. Interest in its application in industrial production continues to increase [37,64-66]. Volkswagen and Audi are two well known examples of companies that have adopted the laser-arc hybrid process in their production lines [64,69]. Many others have followed suit or are currently evaluating the process, such as companies in the vessel fabrication, pipe welding (orbital up to 6 mm wall thickness), and the aerospace and energy sectors.

Laser–arc hybrid welding is a relatively tolerant process, as far as welding parameters and their selection are concerned. With ordinary steels, which are easy to weld with conventional or laser welding methods, hybrid laser welding has no major problems. Mechanical properties can be maintained in the acceptable range in most cases. The most challenging materials are high or ultra-high strength steels, where attention needs to be paid to welding conditions and welding parameters. Hybrid welding is a potential process for steels and aluminium alloys for most applications [68]. Productivity is improved through increased welding speed. For sheet material it is possible to get a 40% enhancement of the welding speed compared to conventional autogenous laser welding.

An air gap in the joint is advantageous for laser hybrid welding because its presence appears to increase the maximum penetration. In the case of welding of plates with a greater than 4 mm thickness, the maximum bridgeable air gap width is smaller than with thinner plates [69]. When a 0.4 mm air gap was created in an 8 mm thick butt joint of mild steel, the maximum welding speed was increased by 12.5% compared with a joint without an air gap. If the plates are shear-cut, and the groove has a minor V shape, it is possible to increase the welding speed by approximately 60% with CO_2 laser–MAG hybrid welding [62,70,71].

Hybrid welding has mainly been introduced in applications in which plate thicknesses allow single pass welding. A limiting factor with regard to plate thickness in single pass welding is the power of the laser. With high power lasers, it is, of course, possible to weld thicknesses of up to 30 mm with a single pass, but by using a gap between the plates to be welded and a multipass welding technique, welding of very thick steel plates is also possible with medium power lasers. Hybrid welding affords opportunities to use medium power lasers for thicker sections, like in laser welding, through utilization of a filler wire. In such operations the laser does not have to be very powerful, which means a reduction in the investment cost, and yet effective welding can still be done. As well as square butt preparation,



(a) (b)

Fig. 16. a) CO_2 laser–MAG hybrid welding of stainless steel tubes and weld cross-sections[9], b) cross-section of hybrid MAG–laser weld in S355 15 mm structural steel with initial gaps i) 0.0 mm initial gap; ii) 0.5 mm initial gap; iii) 0.8 mm initial gap; iv) 1.0 mm initial gap, replotted from [75].

also V- and Y-groove can be used, which is partially a result of blanking without further edge preparation.

HYBLAS, a European project, studied process methods for laser-MAG hybrid welding of thick steels with yield strengths of up to 690 MPA. The project partners carried out extensive investigations using CO_2 lasers of up to 20 kW power level and Nd:YAG lasers up to 7.2 kW with the aim of expanding the capability of the techniques regarding thickness (25 mm in one pass), bridgeable gaps (over 1.5 mm), hot crack prevention and fatigue properties [72]. Using double MAG–laser hybrid welding to define the upper process limit, high strength structural steel of 30 mm thickness was laser hybrid welded with a single pass from both sides simultaneously with two MAG power sources developed by Fraunhofer ILT. One MAG source was placed on the opposite side of the steel. This is obviously a viable technique when manufacturing conditions permit. Fig. 15 presents the observed thickness limits for equipment used at FORCE Technology (a Rofin Sinar SR 170 17 kW CO_2 laser combined with a Fronius TPS330 arc welding power source) [72].

Compared to results from the literature for multi-kW CO_2 laser hybrid welds of 20 mm thick plates, it could be demonstrated that the welding speed achievable with a fiber laser can be 50% to 200% higher due to the more favorable wavelength and better absorption. One even bigger advantage is the potential to weld in a flat welding position with 20 mm penetration, which is not possible with the CO_2 laser hybrid process [69].

A popular application of laser hybrid welding is the welding of containers, tanks and tubes. Fig. 16a shows an application of the hybrid welding of single-pass longitudinal joints of AISI304/304L stainless steel tubes [9]. The wall thicknesses in the application vary between 2.4 and 14.4 mm. The CO_2 laser–MAG (pulsed) hybrid welding process creates a smooth and regular bead with a sound root. The welding speed achieved is 10 times higher than a conventional welding process, even though joint manufacturing is in both cases carried out as shear cut edge preparation [9]. The cross-section of a hybrid MAG–laser weld in S355 15 mm structural steel with various initial gaps is shown in Fig. 16b [75]. In most instances, hybrid welding offers 10 to 40% improvement in productivity compared to autogenous laser welding. Further improvements of up to 49% are possible with a higher power laser or pre-machined fittings.

Metalwork in shipbuilding often suffers from a lot of deformations caused by thermal cutting and/or heat input from welding. The deformations need to be straightened to achieve flat sections. Although methods are available to reduce distortions caused by heat input, nevertheless, distortions are more or less unavoidable. One way of reducing distortion is by decreasing the heat input through the use of lower heat input processes for cutting and welding. For this reason, laser welding and more recently laser-arc hybrid welding are receiving greater attention in European commercial shipyards. MEYER in Germany, STX Finland in Finland, FINCANTIERI in Italy and Odense steel shipyard in Denmark are examples of shipyards using laser processing. In particular, cruise and passenger ships are well suited for this application as the steel work is dominated by the large number of deck structures needed, which typically are made in 5–8 mm plate

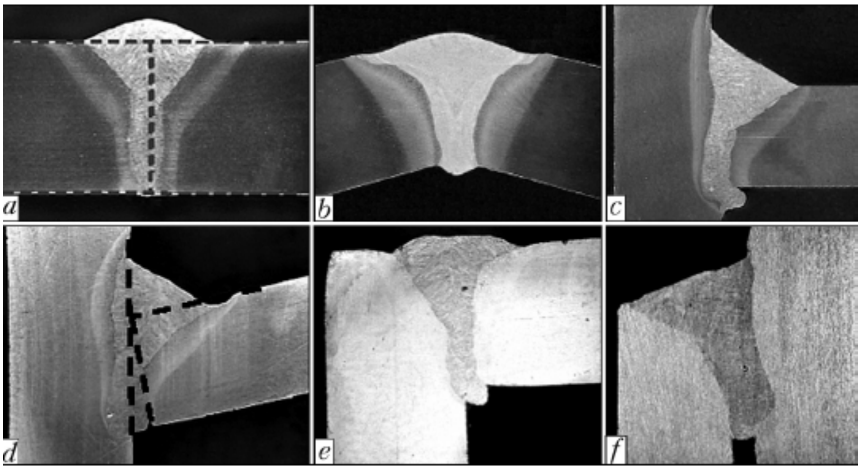


Fig. 17. Macrosections of the different configuration hybrid-welded joints for 6—8 mm heavy section steel (*a*—*e*) and 2 mm thin sheet steel (*f*), replotted from [82].

thickness. Laser–MIG/MAG hybrid welding allows for the possibility of further modifying the weld bead shape, eliminating undercut, increasing gap bridgeability and reducing the propensity for cracking and porosity compared to autogenous laser welding [5,37,73,74]. It is reported by Kristensen [75] that "the major motivation in shipbuilding is reduced distortion as it is estimated that between 20 and 30 percent of the man-hours used in shipbuilding is due to reworking caused by welding distortion".

Laser-arc hybrid welding has been used widely in the welding of steel, aluminium and other alloys. This is, however, not unproblematic; there is a serious problem of energy waste in the process of welding magnesium alloys because of the low photoelectric transformation efficiency of the laser [64], considerable reflection of laser energy in the welding of some non-ferrous metals [76], and the absorption and defocusing effects of the laser beam when it penetrates the arc plasma [77]. In studies of magnesium alloys, it was found that when a low-power laser beam is coupled with a TIG arc, the weld penetrations of hybrid welding can double that of the penetration of TIG welding alone, and the weld joint shows good mechanical properties. Therefore, low-power laser–arc hybrid welding technology in which the laser power used is less than 400 W has been proposed for welding of magnesium alloys [78].

Different joint configurations, materials and material thickness in hybrid welding have been investigated by a number of research groups. Hybrid welding has also shown a very good weld bead reinforcement junction to the base material of different joint configurations (Fig. 17) [79]. According to the description in [79], when a 3 kW Nd:YAG laser using a 0.6 mm fibre or a 6 kW CO_2 laser was used, the welds were crack- and pore-free welds of sufficient strength, and produced at very high speeds.

A study was recently conducted in the Fraunhofer-Institut fuer Lasertechnik (ILT)[39] looking to expand the previous state of the art of laser-MAG hybrid welding of high strength structural steels. The majority of the welds were carried out with an incorporated nozzle for hybrid welding fabricated by ILT. The results showed that the laser beam power and the welding speed have to be regulated to the plate thickness and the gap width for butt joints in the down hand and side position. It was noticed in the same experiment that thicknesses up to 25 mm can be welded (Fig. 18) without any hot cracks, and if they exist at all, with only few small pores. V- or Y-groove preparation in the range of 4 - 8° full angle and a suitable welding speed compatible with the right energy input per unit length are the vital points to be considered.

New materials have been adopted and new power sources have been developed in laser and hybrid welding processes of boilers. Tight wall panels for boilers are constructed based on welding the two sides of a pipe made with flat connections. In the study by Well [80], it was reported that welding of tight wall panels was performed based on the hybrid technique with a fibre laser, using the MAG method, in an active gas shroud 82% Ar + 18% CO_2 and with a leading laser beam inclination of 58° in the opposite welding direction for pipes (S235JRG2 20 × 5 mm) and flat workpieces arranged for welding in the horizontal rolled position (I position). Compared to laser welding, laser–arc hybrid welding can provide a more desirable geometric shape of the weld, that is, better width-to-penetration depth pro-

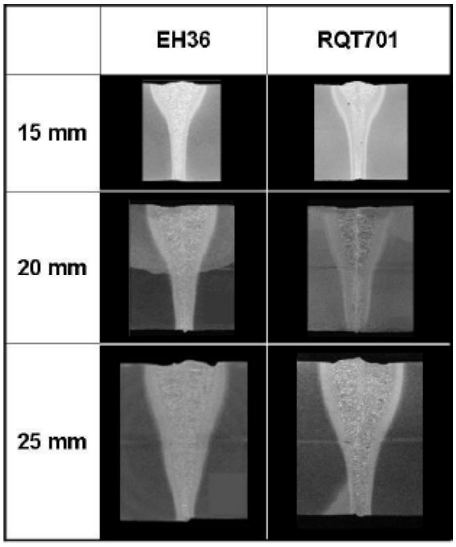


Fig. 18. Cross-sections of optimized hybrid welds used for mechanical and technological tests, replotted from [83].

portions (b/h). The most advantageous property of tight wall panel joints, that is, the geometric shape and b/h ratio of the weld, was about four times more efficient with laser-arc hybrid welding compared to currently obtained efficiencies for tight wall welding with an electrode. Pipe-flat butt joints are possible in the welding position using laser–MAG hybrid welding [81].

Laser–MAG hybrid welding technology is not currently in use in the power industry. While improvements in lasers and the significant decrease in their price have improved their application advantages, amendments to currently used standards and technical guidelines are, however, necessary in order to implement this technology in the manufacture of pressure elements for the power industry [81].

5. MAIN CONSIDERATIONS AND BENEFICIAL SECTORS

Certain competitive factors must be considered before installation of a laser–arc hybrid welding system. The industry in which the company competes must be assessed from the outset, because the dynamics of the industry drive all the other factors. LAHW is ideal for conditions where machined components, expensive fixtures and tooling are not practical. It works best with long, continuous welds and high-duty cycles (longer operational time). It is very suited for shipbuilding, if the shipbuilders improve fixturing and tolerances, and transportation vehicle industries, and industries manufacturing steel structures, where it can be used for a wide variety of applications.

Hybrid welding markets will mostly be in industries where conventional arc welding is currently used. The cost of implementing LAHW varies widely and depends on many factors, such as the volume of production, the laser power required, the number and complexity of tooling and fixtures for the application, and the level of automation needed. When deciding whether or not to invest in a hybrid welding system, the productivity and other benefits of the process have to be well understood. Fortunately, as with most technology, the costs of these machines are likely to drop over time as LAHW gains popularity and usage. Furthermore, because LAHW uses high energy density and thus low total energy use, users may make considerable savings on energy costs.

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Further obstacles to overcome prior to greater utilization of the process are the physical limitations. The first limitation is the maximum thickness that can be welded such that a free-formed root bead can still be produced. The limit today is between 12 mm and 15 mm for a power level 10-12 kW, depending on the laser used. Higher power lasers having potential for deeper penetration up to 25-30 mm are not able to reach this penetration due to root quality problems.

Any material that can be welded with a conventional laser or arc process can be welded using hybrid welding technology. To date, successful development programs have been carried out for applications with steel, aluminium, copper and titanium. The hybrid approach used is governed by the material thickness and the requirements of the individual application. Laser–TIG and laser–PAW tend to be used more often for thinner sheet metal applications (< 3 mm) while laser–MIG/MAG, is generally used for welding thicker sections ($\geq$3 mm), although it has been used in automotive sheet metal applications.

6. SUGGESTIONS FOR FURTHER STUDY

Laser–arc hybrid welding involves numerous process parameters and, therefore, raises numerous topics of study. Key issues include laser power, joint type and materials. The wide and growing range of laser sources currently available opens a wide area of study. High beam quality, shorter wavelength (absorptivity is higher for steel) and more easily controllable power levels certainly have a great effect on process behavior. Arc equipment from different manufacturers is different as regards its capabilities, characteristics and metal transfer modes. One interesting starting point for further study would be issues pertaining to the temperature distribution in the arc and the thermal cycle in the workpiece when both energy sources are in operation.

A common limitation with much of the research which effects comparison of different parameters and results is that very many experiments have been performed for bead-on-plate and butt joint welding without an air gap. The results from these tests may differ from results for welding a real joint with a specific joint preparation and, in practice, always with a small air gap.

One of the main factors affecting the widespread implementation of laser–arc hybrid welding is the significant initial capital investment required to purchase the laser system. Despite this significant cost barrier, hybrid welding is being applied across a number of different fields, including shipbuilding, automotive welding, pipelines and railcar industries, primarily in Europe and Asia. Its potential expanded application in the joining of important alloys, including stainless steels, advanced high strength steels, titanium and aluminum alloys, will require considerable research, rigorous characterization and systematic cost analysis. The above-mentioned alloys often require different filler and base metal combinations, which will have to be determined for various hybrid welding conditions in order to obtain optimum weld properties. Significant research also needs to be done to understand the correlation between welding conditions and the resulting weldment structure and properties for each alloy. Providing a detailed characterization of the structure and properties for each alloy remains a major task.

Although hybrid welding has enjoyed growing acceptance in recent years, many important questions about its underlying scientific principles remain unanswered. For example, although laser–arc interactions have been examined and increased arc stability and bending of the arc towards the laser-generated keyhole noted, the origin of the synergistic interaction that occurs between the arc and laser-generated plasmas for various welding conditions is not well understood. Spectroscopic investigations of the optical emissions may provide a better understanding of the laser–arc interactions from the spatial and temporal distributions of electron temperatures and densities in the plasma for various welding conditions. A better understanding of the origins of keyhole stability under the conditions of hybrid welding through experimental and theoretical research would also be useful since collapse of the keyhole is believed to play an important role in porosity formation in laser welds. Computational modeling of the heat transfer and fluid flow will enable understanding of the weld pool geometry and cooling rates both within the weld pool and the HAZ. In addition, computed cooling rates at all locations within the weldment can be helpful in understanding the evolution of weld microstructures. Cooling rate data can also be used to help to avoid cracking, brittle phase formation and thermal distortion. Better sensing and process control of the hybrid welding process would also be helpful in expanding its applications.

The addition of shielding gas and/or process gas is another process parameter which has to be tested as further work in the field of laser-submerged arc hybrid welding. If efficient solid-state lasers, e.g. fiber lasers, can be used, the shielding gas could be dispensed with and a compressed air jet could be used. Cleaning of the weld surface would be reduced in this way and the method would become even more economically viable

7. CONCLUSIONS AND SUMMARY

A number of simultaneously occurring physical processes have been identified as contributing to the unique properties obtained during hybrid welding. However, physical understanding of these interactions is still evolving. This review critically analyzed recent advances in the fundamental understanding of hybrid welding processes with emphasis on the physical interaction between the arc and laser and the effect of the combined arc–laser heat source on the welding process. Important areas for further research were also identified.

It has been acknowledged in this study that the different laser–arc hybrid welding processes, the relative set-up of the process distance, the parameter set-up, and the shielding gas play a very important role in the performance and resulting weld quality. The use of laser–arc hybrid welding processes for welding of metals offer advantages that the rate of welding, reduced post-weld re-working costs are gain.

In recent years, many variants of the laser-arc process have been developed and fundamentally investigated, demonstrating their considerable potential for robust and efficient solutions for practical welding problems. Industrial applications of the hybrid welding technique have been realized in the automotive and the shipbuilding sector. Other industrial branches that already make use of hybrid laser-arc heat sources include pipe-line and offshore installations, the aerospace and aviation industry, the power-generation industry and the off-road and heavy vehicles sector. Owing to the reported improvements in productivity, efficiency and quality, it can be expected that hybrid welding methods will be increasingly adopted for future industrial welding application as an alternative to conventional welding methods.

Laser-arc hybrid welding is designed to overcome problems commonly encountered during either laser or arc welding, such as cracking, brittle phase formation and porosity. When placed in close contact with each other, the two heat sources interact to produce a single high intensity energy source. This synergistic interaction of the two heat sources has been proven to alleviate problems commonly encountered in each welding process individually. It allows increased gap tolerances, compared to laser welding, while retaining the high weld speed and penetration necessary for efficient welding of thicker workpieces.

As a result of the considerable extension of the field of industrial applications and the efficiency of the combined process, it is possible to reduce investment costs, manufacturing time and fabrication costs, and increase productivity compared to autogenous laser welding. In most instances, hybrid welding offers 10 to 40% improvement in productivity compared to autogenous laser welding. Improvement of productivity can be increased with a higher power laser and machined fitting.

From the present research it might be concluded that the combination of the laser beam and electric arc is ideal for fusion welding of thick workpieces, materials with high heat conductivity, and specially shaped structures and welded joints. However, some inherent limitations and deficiencies should be taken into consideration, such as the sensitivity of the process to the set-up of various variables and the cost of the equipment. Based on the literature, known expertise in the welding arc and its properties, and knowledge of the laser beam, it can nevertheless be stated that the combination of both heat sources eliminates some of the deficiencies of each individual heat source, such as low efficiency of energy transfer to the weld.

Further obstacles to be overcome prior to greater utilization of the hybrid welding process are the physical limitations of the process. The first limitation is the maximum thickness that can be welded such that the ability to produce a free-formed root bead will still be retained. The limit is between 12 mm and 15 mm for a power level of 10-12 kW, depending on the laser type used. Higher power lasers having potential to achieve deeper penetration up to 25-30 mm are not able to effectively reach this penetration due to root quality problems. Secondly, the hybrid process allows greater fit-up variation than normally possible for autogenous laser welding of thinner material; as the thickness increases, the limitation of the hybrid welding process will require industries to improve their fit-up tolerances over what is currently achieved for the arc process. The cost for this expansion will have to be factored against the profits of the hybrid welding process.

The geometrical arrangement of the chosen heat sources plays a most important role for the capability and efficiency of the hybrid process, and has a significant effect on the properties of the generated joints. Distinguishing between techniques with common and separated operation points is important. Realizing a common operation point means that the arc root and the laser beam spot centre are directed into the same location on the material being welded. It is not possible to give general recommendations for optimal basic setups in hybrid laser-arc welding because there are many specific factors that must be taken into account. The most proven arrangements combine the laser beam and the electric arc within a common process zone leading to a single process plasma and a common weld pool.

It is clear from the development that has taken place over the years that laser and laser–arc hybrid welding have applications within shipbuilding, the pipeline and aircraft industries, and land transportation. Compared with CO_2 laser–TIG arc hybrid welding, solid state laser (e.g. Nd:YAG laser, fiber laser and disc laser) + MIG/MAG arc hybrid welding will have wider applications in the future because of the flexibility, automatisation and robotisation of the process. The early involvement of regulatory bodies and classification societies in this development has helped facilitate introduction of the technology.

However, this technology is experiencing only slow growth in today's industries. Some reasons for this slow acceptance are the high cost of initial investments and the complexity of the process, resulting from the large number of parameters involved. Set-up of the processing parameters requires a high degree of skill and accuracy, and these imperatives, added to an incomplete knowledge of the process, are limiting factors for industrial applications.

The "hybrid age" may have been slow in coming but has accelerated in the last few years. This acceleration has been motivated by enhancement in lasers, especially high brightness lasers. These new lasers have allowed for easier integration into systems and lower ownership costs, which have positively impacted on the process. In addition, as new standards become available, there is a potential for the technology to be accepted and implemented. The promotion of hybrid welding processes by one of the world's largest arc welding and laser companies (Lincoln Electric Corporation and IPG Photonics) for the development of laser-arc hybrid welding systems also suggests a positive shift in how industries view the process. Manufacturers who embrace this technology stand to make significant gains over their competitors.

Hybrid welding requires an appropriate selection of the system set-up and basic parameter configurations. If these boundary conditions are well chosen, the hybrid process proves to be a really stable, efficient and flexible technology. However, if they are not properly set, there will be defects in the weld; 20 mm thick it is now considered as the state of the art to weld joints with gaps in the range of 0 to 1 mm in a flat position and using an I-, V- or Y-edge preparation with high strength structural steel.

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