LASER-ARC HYBRID WELDING PROCESSES (Review)

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This study deals with the different types of hybrid welding processes in addition to describing the means and situation today regarding the principles and applications of various combinations of laser with welding arc. The processes are analyzed regarding their parameters involved and the type and thickness of the base material. This study looks into the productivity, economy and quality of laser hybrid welding and provides some fundamentals of the set-up of its parameters. The effects of parameters and set-up can be seen in the analysis, thus, the economic feasibility and quality management factors as the basis of analysis can be assessed.

Keywords: *laser-MIG/MAG welding, laser-TIG welding, laser-plasma arc welding, laser-tandem welding, laser-submerged arc welding, hybrid welding process*

The laser-arc hybrid welding process has been investigated since 1978, when Steen and co-workers in the UK published their first paper about TIG augmented laser welding [1]. Nowadays, the lasers used in hybrid welding include the older generation lasers like the CO_2, Nd:YAG and diode laser, and the new disc and fiber laser. The CO_2 laser was the firstly and normally used laser in hybrid welding [2–6]. The Nd:YAG laser was also used in hybrid process for welding of aluminum or materials of high reflectance and steel because of its short wavelength, which guarantees much higher absorption [7]. One reason to use Nd:YAG laser has been the possibility to use optical fiber for beam transportation.

Hybrid welding combines the energy of two different energy sources in a common process zone. Typically the focused laser beam is aimed to 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. Typically this 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 variables grows through coupling the processes. The resultant mutual influence of the processes can have different intensities and characteristics depending on the arc and laser process used and on the process parameters applied [5–9]. 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. It is also possible to use special heads, in which the laser beam is surrounded by electric or plasma arc [9, 10].

With hybrid welding processes the potentials are fundamentally resolved by the appropriate selection of the method set-up and the basic parameter configurations adapted to the demand of material, structure and manufacturing conditions. If the boundary conditions are well chosen, hybrid welding proves to be a really stable, efficient, profitable and flexible technology.

Various studies have revealed that through coupling the processes synergistic effects are achieved and the disadvantages of the individual process can be compensated for, e.g. the typical narrow weld of laser welding leads in some cases to metallurgical and fit-up problems, and the higher heat input of arc welding increases distortion and subsequent rework cost. The advantages mainly come from:

- the gap bridgeability of the process to control the air gap caused by inaccurate groove manufacture and fixturing tolerances;
- the increase penetration and the welding speed above the sum of the single speed, thus, keeping the heat input and thermal distortions to the minimum;
- the increased regularity of the weld bead;
- a significantly wider range of applications adapted to the demands of material, structure and manufacturing conditions;
- the lower investment costs by saving laser power.

Metallurgical property improvements using filler material and diminished porosity due to the promoted escaping of gas out of the enlarged molten pool are also noted especially in the case of partial penetration welds [2, 3, 10–12]. However, in hybrid welding, the arc is stable because the arc cathode spot is located in the thermal action area by the laser radiation, which occurred in the keyhole. Therefore, the results observed with high speed camera show that the plasma generated by the laser was observed to play a vital role in arc stability [13, 14].

Hybrid welding has mainly been introduced in applications, in which plate thicknesses allow single pass welding, and thus also experimental work has been focused on single pass welding. A limiting factor with regard to plate thickness in single pass welding is the power of the laser. Naturally, with high power lasers, it is possible to weld thicknesses of up to 30 mm with

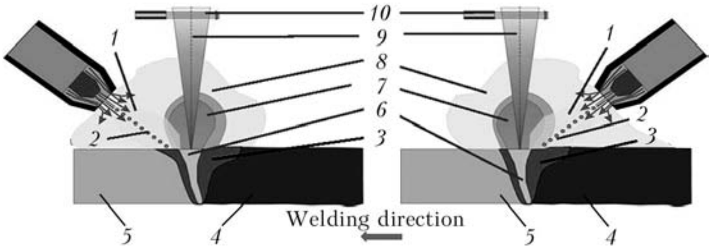

Figure 1. Schematic representation of laser hybrid welding with leading laser and leading arc arrangements: *1* — arc; *2* — filler material; *3* — melt pool; *4* — weld metal; *5* — workpiece; *6* — keyhole; *7* — metal vapour; *8* — shielding gas; *9* — laser; *10* — cross jet

a single pass. But also with medium power lasers, the welding of very thick steel plates is possible by using a gap between the plates to be welded and the multipass welding technique. Hybrid welding gives excellent opportunity to use medium power lasers for thicker sections, like in laser welding with a filler wire. In this case laser does not have to be very powerful, and this means a reduction in the investment cost and still more effective welding can be done. Apart from the square butt preparation, also V- and Y-groove can be used which are partially a result of blanking without any further edge preparation.

Application fields in laser-arc hybrid welding have been expanding in a variety of workshops and industries (for example, shipbuilding, automotive industry, vessel manufacturing) [9–11, 15, 16], as well as being an extensively studied method for a variety of materials. It is owing to a number of advantages of hybrid welding compared with individual processes.

The distance between the laser beam position and the arc (process distance) is an important parameter of hybrid welding as has been shown in [17]. If the distance is too long, the laser and arc plasmas will be apart from each other resulting in an unstable arc, since the laser plasma and heated material are no longer supporting the generation and maintenance of the arc [18]. According to some researchers, when the separation of the processes is 5 mm or more, the processes are acting independently [18, 19]. Of course this value depends, for example, on the welding speed, laser and arc powers and the material used.

Laser-MIG/MAG welding process. The fundamentals of the coupled process (Figure 1) are nearly the same for both the CO_2- and the solid-state lasers. The laser and arc processes have a common process zone and weld pool. The process can 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 is generating a keyhole within the molten pool to ensure the desired penetration depth. This can be reached at high speed. By combining the laser beam and the MIG/MAG arc, a larger molten pool is formed compared to the laser beam welding process [10].

The microstructure and mechanical properties of the weld metal can be improved by controlling its chemical composition by using proper 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 to use filler material. With regard to those applications, the largest potential of the laser-arc hybrid welding technique is expected to be in the area of using additional filler material and thus the combination of laser-MIG/MAG hybrid welding process which is currently the most preferred laser-arc hybrid welding process [3–10]. This process has been reported to close gaps between 0.6 mm (with 2.7 kW [20]) and 1 mm (with 2.0 [18] and 5.7 kW [15]).

As with any other welding process, also the capabilities of laser-MIG/MAG hybrid welding are essentially determined by the appropriate selection of the system set-up and the basic parameter configuration. In that case, the parameters of laser and MIG/MAG welding can be varied freely in a rather wide range in order to adjust the welding process to the required performance regarding depth, gap bridging, weld shape and metallurgical properties [5].

If we compare the penetration characteristics of laser, MIG/MAG and hybrid welding, it shows that the laser weld has bead concavity, whereas the MIG/MAG-welded seam has extreme weld support and hybrid welding has extreme reinforcement and high weld width with the same penetration depth and the same welding speed as in laser welding. A typical example of such welds can be seen in Figure 2, which somewhat exaggerates the difference, since the welding is performed in bead-on-plate configuration, but still represents the situation.

The penetration depth is mainly determined by the laser beam power and shaping, whereas the weld width is mainly determined by the arc, in particular, by the

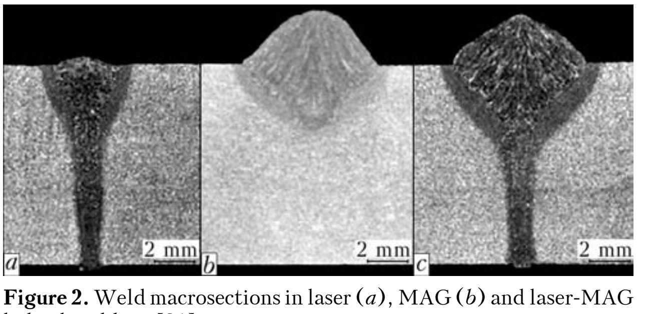

Figure 2. Weld macrosections in laser (*a*), MAG (*b*) and laser-MAG hybrid welding [21]

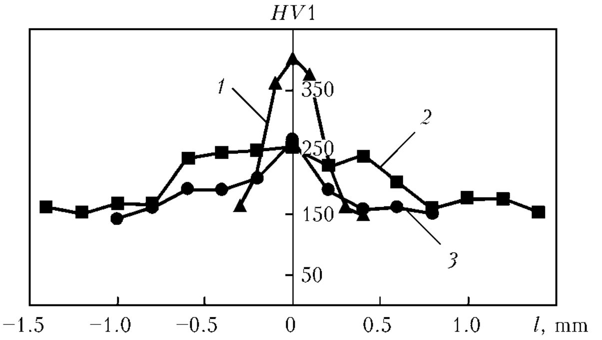

Figure 3. Hardness $HV1$ of weld metals at MIG-laser hybrid welding without gap of 2.13 mm CMn alloy 250 using 2250 W CO_2 laser and 9 kW MIG arc at maximum speed of laser (*1* — 4.4), MIG (*2* — 2.2) and hybrid (*3* — 4.5 m/min) welding [25]: l — distance from weld center, mm

voltage. If there is no air gap, the maximum welding speed achieving full penetration for CO_2 laser-MIG/MAG hybrid welding is lower than for CO_2 laser welding. This is caused by the extra material on top of the workpiece that requires to be penetrated and the fact that the focal point position is diverted from the set-up value. The welding speed can, however, be increased with an increase in the air gap width. Air gaps of up to 1.5 mm in width can be bridged, but at this maximum width the process is quite unstable and produces spatters. The welds produced by hybrid welding have also typically lower hardness in comparison to that in arc welding [22].

According to an experiment carried out to investigate the stability of the condition of a hybrid CO_2 laser-MIG/MAG process by analyzing the influence of several process parameters, it was shown that the optimum process distance depends on the metal transfer mode in shielded-gas metal arc welding. The base metal transfer mode is important in order to achieve a stable and repeatable process. It has been reported in many papers that arc parameters giving the pulsed/spray arc should be preferred to the short/globular arc [10, 23]. Nd:YAG laser radiation, due to a lower interaction with the arc plasma, allows a closer approach to the arc than CO_2 laser radiation. The focal point should, in most cases, be set below the workpiece surface to maximize penetration [9]. Normally, the smallest possible arc inclination is desired. Angles in the range of 15 to 30° relative to the laser axis work with technically acceptable effort.

Lui et al. [24] studied the process parameters of laser-MAG hybrid welding of HSLA-590 steel using a 2.4 kW CO_2 laser with MAG welding. They found that the arc-leading hybrid bead was not as smooth as the laser-leading bead. Considering the bead appearance, the laser-leading process is better than the arc-leading hybrid process. It was also examined that the hybrid weld metal had a higher toughness than the laser weld metal even at higher welding speed.

Hardness measurements in MIG-laser hybrid welding were made on butt welds with a zero gap and the maximum possible welding speeds resulting in sound welds. Figure 3 shows that the maximum values are HV1 400, 258 and 268 for the laser, MIG and hybrid processes, respectively. This corresponds to 2.5, 1.7 and 1.75 times the base material values, respectively. Despite the higher value in the center of the hybrid weld as compared to the MIG weld, the hardness values of the hybrid weld are generally $HV1$ 20–50 lower than those of the MIG weld. This also results in a 40 % reduction of the size of the HAZ, from 8.6 to 5.2 mm^2, measured with the aid of digital image processing. The bainite is completely avoided in MIG-laser hybrid welding where acicular ferrite is formed in the HAZ. This also explains the considerable reduction in the hardness of the weld metal [25].

The effect of the gap distance in butt welding can be visualized by plotting the maximum welding speed to the ability to bridge gaps (Figure 4). The laser welding process displays a clear drop in the welding speed at a gap wider than 0.1 mm. For the MIG welding, no change is evident at variable gap distances. For the hybrid welding, only a small decrease in the maximum welding speed is observed at increasing gaps. With a gap size of 0.6 mm, a reduction in speed of only 22 % (from 4.5 to 3.5 m/min) is seen [25].

Different joint configurations, materials and material thickness have been investigated in hybrid welding by different research groups. Figure 5 shows excellent misalignment tolerances reported in [15] on

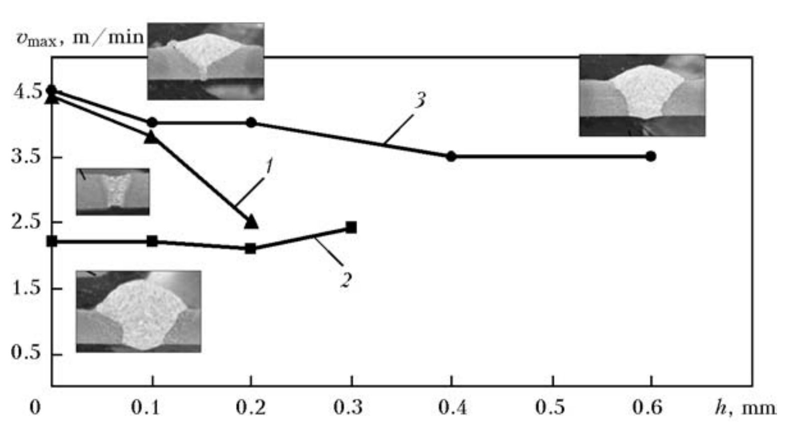

Figure 4. Effect of gap width h on maximum speed v_{max} of laser (*1*), MIG (*2*) and hybrid (*3*) welding of 2.13 mm CMn alloy 250 using 2250 W CO_2 laser and 9 kW MIG arc [25]

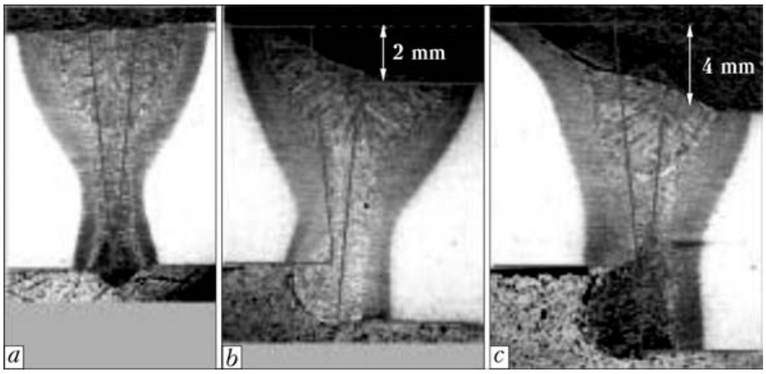

Figure 5. Macrosections of the pipeline steel X52 welded joints 10 mm thick at speed of hybrid welding of 1.0 (*a*) and 0.8 (*b, c*) m/min [15]

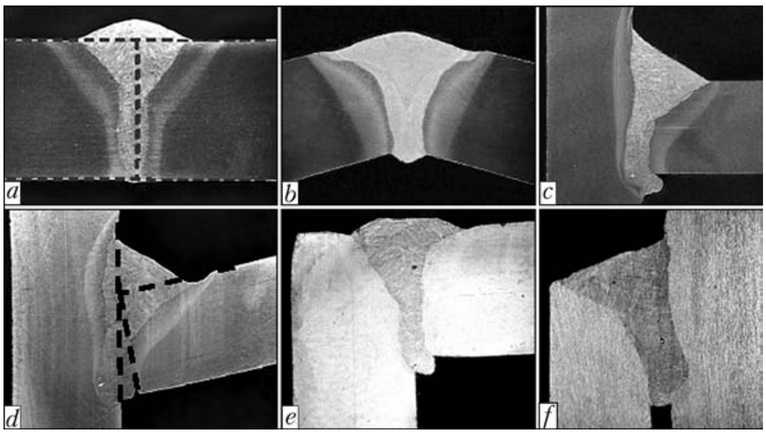

Figure 6. Macrosections of the different configuration hybrid-welded joints for 6–8 mm heavy section steel (*a–e*) and 2 mm thin sheet steel (*f*) [26]

hybrid welding of 10 mm pipeline steel X52 with 10° single V-groove and 1 mm root face, using CO_2 laser of 10.5 kW, MIG pulse arc, filler wire G3Si1 of diameter 1.2 mm and assist gas argon–helium mixture at wire feed rate of 5.2 m/min. Hybrid welding is superior to the laser welding in respect of this joint preparation fault.

Hybrid welding has also shown a very good weld bead reinforcement junction to the base material of different joint configurations (Figure 6) [26]. According to the description, a 3 kW Nd:YAG laser using a 0.6 mm fiber or a 6 kW CO_2 laser were used. The welds were crack- and pore-free welds of sufficient strength, and produced at very high speeds.

A study was recently conducted in Fraunhofer-Institut fuer Lasertechnik (ILT) [3] 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 shown 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 downhand and side position. It was noticed in the same experiment that thicknesses ranging up to 25 mm can be welded (Figure 7) without any hot cracks, and if they exist, with only few small pores. V- or Y-groove preparation in the range of 4–8° full angle and suitable welding speed mutually with the right energy input per unit length are the vital points to be considered.

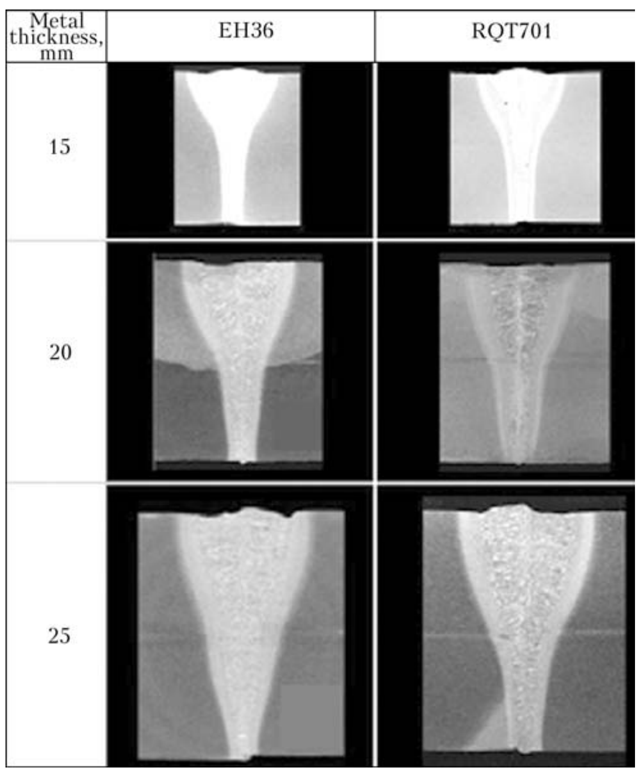

Figure 7. Cross-sections of optimized hybrid welds used for mechanical and technological tests [3]

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 with 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 and 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 [13, 16, 17, 27].

The choice of process gas (shielding gas) parameters is an important factor in hybrid welding. With Nd:YAG lasers the selection of process gas can be determined according to the arc stability demands and bead shielding properties; for MIG/MAG welding also droplet detachment and spatter-free metal transfer have to be considered. In this case argon will constitute the dominant portion of the gas used. Small additions of oxygen promote droplet detachment and reduce spatter. Mixtures of helium lead to higher arc voltage and the corresponding power increase results in wider welds, but also destabilize the arc. Nevertheless, using CO_2 lasers, a helium mixture is often used to avoid plasma shielding. Fortunately, the presence of the laser beam enables acceptable arc stability even with a significant helium portion [27].

Within the automotive industry, Volkswagen and Audi are two particularly well-known examples of companies convinced by the benefits of hybrid laser-MIG welding. In the shipbuilding industries the technique is slowly gaining a firmly established acceptance for a wall thickness of 15 mm [6, 9, 15, 28].

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 that laser absorption is improved. The absorption of the laser energy into the base material is enhanced in this heated region [5]. This combination creates a moving common melt pool along the weld pass. A typical schematic diagram of laser-TIG welding is presented in Figure 8.

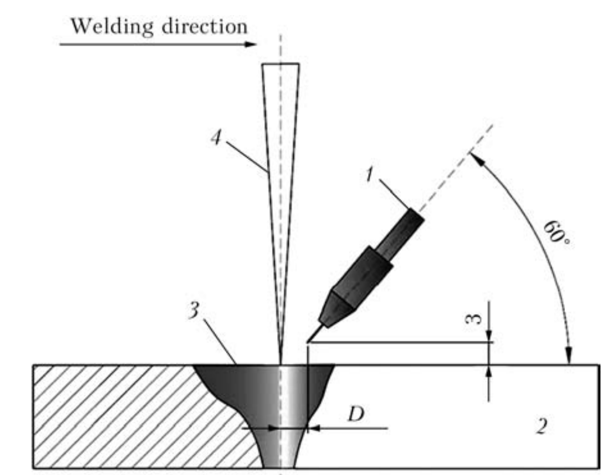

Figure 8. Schematic set-up of hybrid CO_2 laser-TIG welding [29]: *1* — TIG welding torch; *2* — workpiece; *3* — weld pool; *4* — laser beam; *D* — laser–arc distance

Steen and Eboo [1] conducted their experiments with CO_2 laser and TIG arc. It was found that combining a TIG arc with the laser meant serious advantages to the process: firstly, the arc root remained stable in the hot spot generated by the laser so that the arc, even of low current, can be performed with high welding speed without instability, and, secondly, the arc root is narrowed in the combined process which appears to avoid some of the undercutting normally associated with high speed arc welding especially of aluminum alloys. The absorptivity of the weld metal increases with an increase in temperature in the case of a 10,600 nm wavelength [1, 15, 30]. It is also reported that both the CO_2 laser and the TIG welding processes greatly depend on the shielding gas and its protecting method used [6].

Lui and Zhao [31] have studied the welded joint of magnesium alloy and steel by using different joining techniques. They found that due to the high energy intensity and the fast stir action in the molten pool, it is possible to weld magnesium alloy and steel by laser-TIG hybrid welding, which is almost impossible with conventional fusion welding processes, with the following parameters: laser power of 400 W, welding speed v = 15 mm/s), TIG welding current I = 80 A, process distance of 1 mm, laser focus position of 1 mm, diameter of the tungsten electrode of 3.2 mm, angle between the electrode from the workpiece and welding direction of 50°, and the argon flow rate of 0.5 l/s. Moreover, the laser pulse frequency was 39 Hz.

One of the defects of laser welding is porosity due to the high power density and deep penetration especially in the case of partial penetration. A great challenge is to avoid or decrease the number of weld pores when welding aluminum. The set-backs are porosity due to the evaporation of alloying elements such as magnesium. Cracks can also appear if the welding parameters are not suitable [6, 14]. However, porosity formation in weld metal depends on the TIG welding current and the composition of the shielding gas in laser-TIG hybrid welding.

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. The molten pool generated by laser stabilizes the TIG arc allowing welding speeds as high as 15 m/min with the laser trailing. The combination of both the laser and TIG arc is able to produce full-penetrated welds with enough width to absorb small cut edge defects or misalignments between the two sheets. In order to avoid thermal distortions and excess fusion,

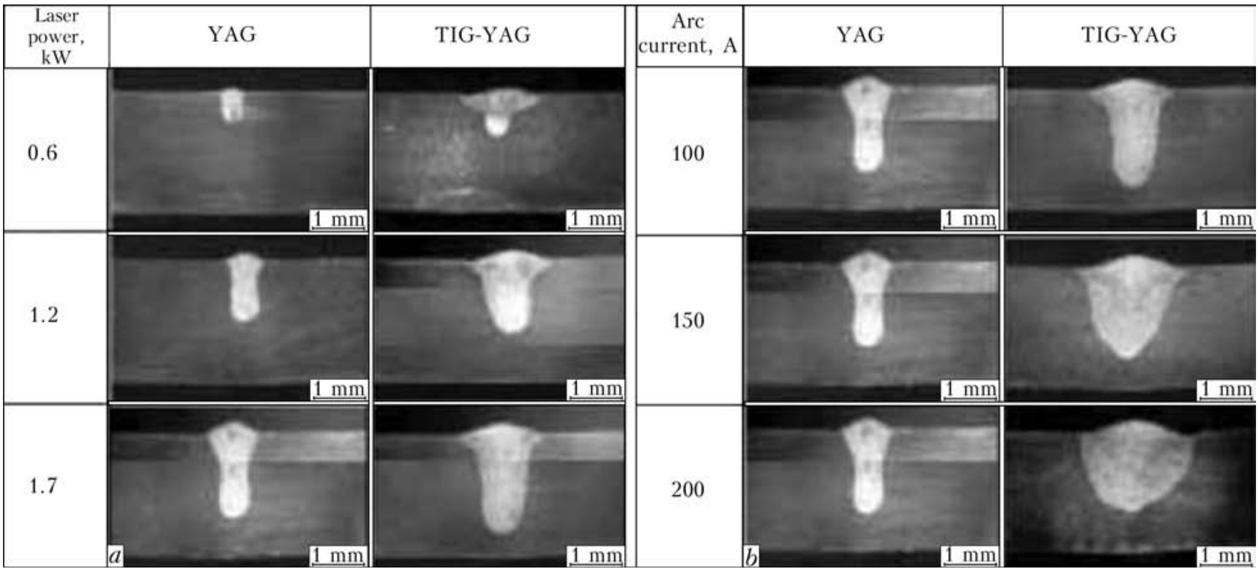

Figure 9. Cross-sections of 304 type stainless steel 5 mm thick in YAG laser and hybrid laser-TIG welding at various laser power (*a*) and arc current (*b*) [12]: *a*, *b* — v = 10 mm/s, α = 55°, h = 2 mm, d = 2 mm, I_a = 100 A, Ar as shielding gas ($5\cdot10^{-4}$ m^3/s); *b* — P = 1.7 kW

the TIG welding current has to be minimized and the use of additional shielding gas is necessary [32].

It is also noted by other researchers that the penetration in the hybrid welding process does not depend on the arc current but on the laser power in CO_2 laser-MAG hybrid welding and Nd:YAG laser-TIG hybrid welding [26, 33]. Figure 9, *a* shows the cross-section of the 304 type stainless steel welds subjected to YAG laser and YAG laser-TIG hybrid welding at various laser powers. In all of the welds, the penetration of hybrid welds was deeper than that of YAG laser welds when the TIG welding current was kept at a constant value. However, in the cases of different TIG welding currents and constant laser power, the penetration remained the same, but the weld width grew with the increase of TIG welding power as shown in Figure 9, *b* [12].

Laser-PAW process. In a process for laser-plasma hybrid welding to weld workpieces, the laser beam and the plasma jet are brought together in the process region close to the workpiece (Figure 10) [34]. 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 [34–36]. 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 without deteriorating the electrode for relatively long periods since the tip of the electrode is not exposed to impurities [35].

By using a hybrid laser-plasma welding process, the arc heat source is introduced which can be used as a heat treatment tool to increase cooling rates after welding. In this way the presence of a brittle microstructure, which is susceptible to failure during service, can be reduced. In addition, by using hybrid laser-plasma welding as an integrated welding and heat treatment system, the production time can be significantly reduced [35].

The process offers significant advantages when used for laser-plasma welding including a stiff, high-temperature, columnar arc with good directional properties which permit greater tolerance compared with laser welding to disparity and comparable poor fit-up conditions. Furthermore, for a relatively small capital increase this process offers commercial advantages and potential for multiple applications of lasers in the manufacturing industry. At present, there are only a

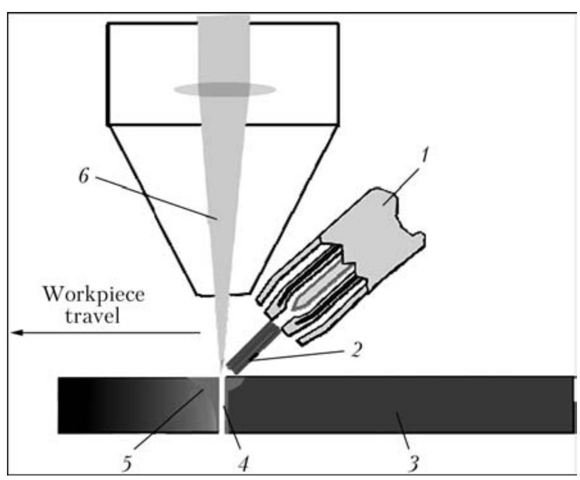

Figure 10. Experimental arrangement of plasma arc augmented laser welding system: *1* — plasma torch; *2* — plasma arc; *3* — workpiece; *4* — keyhole; *5* — weld pool; *6* — laser beam

few hybrid laser-plasma systems installed in industrial applications but this will most likely change in the future due to the great potential of the process. In order to stimulate the use of hybrid laser-plasma systems, a thorough scientific understanding of the process and investigation of its industrial feasibility are required [34].

Early tests on the laser-augmented PAW process [34] were carried out using a 400 W CO_2 laser and a 50 A arc current. In the experiment a wide variety of different materials were tested which included mild steel, stainless steel, titanium and aluminum in various thicknesses from 0.6 to 2.0 mm. It was noted that the combined process can suppress humping in high speed welding with thin sheets. In plasma arc-laser welding, a higher tolerance to beam–gap misalignment (0.15–0.5 mm at 2 m/min and 50 A) has been noted.

It was reported [37] that the laser-assisted PAW process eliminates hot cracking in the fusion zone for aluminum alloys 6061 and 6111 when using a continuous power arc instead of the pulsed arc. Fusion zone dimensions for both stainless steel and aluminum were found to be wider than laser welds. It was also noticed that the laser-plasma welds did not appear as shiny as with pulsed Nd:YAG laser welding. The laser-plasma hybrid welding process was also experienced to be a very stable process, a phenomenon that has earlier been described for laser-GMA welding.

Laser tandem-MIG welding process. The laser tandem-MIG process is combinations of laser welding and the arc processes with only one molten zone. The process principle of laser tandem-MIG hybrid welding is outlined in Figure 11 [9]. 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 for increasing 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 what welding result is desired. The welded joint geometry, the preferred joints overfill, and the welding speed can be selected by means of suitable power output for the tandem process. Also, by regulating the welding speed, focal point diameter and laser power, the depth of the root can be adjusted in the course of bevel preparation. Moreover, two different filler metals with various compositions can be used to attain the desired metallurgical properties [9].

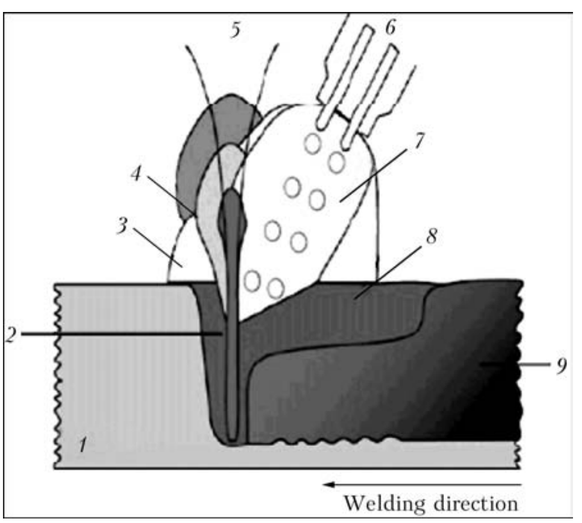

Figure 11. Schematic sketch of laser tandem-arc welding [9]: *1* — workpiece; *2* — keyhole; *3* — shielding gas cloud; *4* — laser-induced plasma; *5* — laser beam; *6* — electrode; *7* — arc; *8* — weld bead; *9* — molten pool

By selecting favorable process parameters the weld metal properties such as geometry and structural constitution can be purposefully influenced. The arc welding processes increase the gap bridging ability by the amount of the filler material added. It also determines the weld width and thus decreases the requirements of weld preparations. Process efficiency can be considerably increased by the interactions of the processes.

Reported mostly by Staufer [9, 38], the vital advantage of combining 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 the control of the laser power, the power of the arc and the arc lengths is possible separately which is claimed to result in better drop detachment, more stable arcs and fewer spatters. Moreover, with this process it is also possible to use laser-MIG/MAG hybrid welding with a single arc. The laser tandem hybrid process has been investigated by Staufer [38] for a structural steel pipe, which complies with the standard EN 10149-2 for a pipe with a wall thickness of 8 mm and an inner diameter of 500 mm. It was reported that by using a Y-groove preparation, a full penetration weld can be achieved.

Laser-SAW process. The laser-MIG/MAG hybrid welding process met problems in some applications with regard to pores at the root of the sheet when more than 12 mm thick plate is welded with partial penetration. This was attributed to the insufficient degasification possibility of deep and narrow laser welds. To prevent this, the molten pool has to be maintained for a longer period [39]. This was the reason for experimenting with maintaining the molten pool for a longer time by using the laser-SAW hybrid process and thus creating more favorable degasification possibilities. Here both processes are moved as close as possible (13–15 mm) into one process zone [28].

The coupling of the processes, both the laser beam welding and the SAW process in one process zone proved to be a problem, since the flux had been falling into the keyhole of the laser beam and the laser radiation had been absorbed by the flux and not by the component. For that reason, a device which impeded this «falling forward» of the flux had been designed and built. One starting point is the separating plate (patented by RWTH, Aachen University), which is mounted between the laser beam and the flux feeder (Figure 12).

As far as previous investigations are concerned, the spatial distance of both processes and the separation of the weld into two regions, namely, the laser-welded and SA-welded region, has been noticeable. The distance must be chosen to be short enough to ensure that the smallest possible quantities of the flux are falling forward and large enough that the slag running ahead of the process does not jam to 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. Those areas have not shown any mixing of the weld material. It has just been the preheating, brought in the laser beam welding process which resulted in the synergy effect of increasing the welding speed of the SAW process [21, 40].

So, it is established that hybrid laser-SAW is the most attractive variation of laser-arc hybrid welding. The industry shows interest in hybrid laser-SAW and a possible practical application. This will be further increased through the use of less expensive, more robust and more flexible laser power sources. Further development of this process and a wider field of application are to be expected from the use of solid-state lasers. Particularly advantageous 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 would also improve 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 [28].

For achieving better degasification and a weld, if it has a pore quantity which is as low as possible, or a pore-free weld, the solution may lie in the expansion or stabilization of the vapour capillary. One possibility for this would be welding and testing with adapted oscillating optics.

The addition of shielding gas/or process gas is another process parameter, which has to be tested for further work in this field. 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, for cleaning of the weld surface would be reduced this way and the method would become even more economically viable [28].

Laser-SAW hybrid process improved degassing through the covering of the molten metal by the slag, good gap bridging ability, increased welding possibilities compared to laser welding thick plate by using different diameters of wire. Large potential expected through application of suitable wire/flux combinations, new fields of application of the laser technology [28].

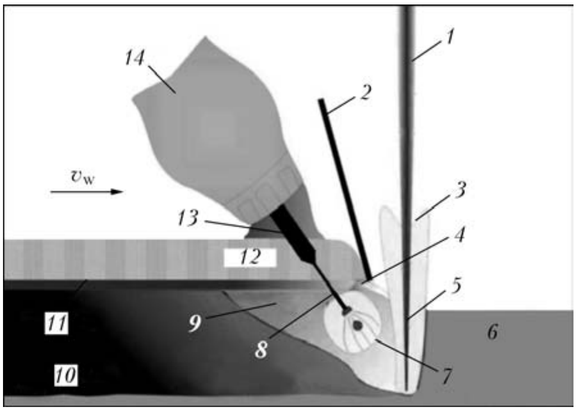

Figure 12. Schematic representation of laser-submerged arc hybrid welding [28]: *1* — laser beam; *2* — separation plate; *3* — metal vapour plasma; *4* — liquid slag; *5* — keyhole; *6* — base metal; *7* — weld cavity with arc; *8* — consumable electrode wire; *9* — molten pool; *10* — weld metal; *11* — solid slag; *12* — flux; *13* — contact tube; *14* — flux hopper

CONCLUSIONS

From the study to assess the different types of laser-arc hybrid welding, it came out that the process is involved in a growing number of industrial applications due to the economic and technical advantages of this technology. Some important superior features, compared to laser welding, are listed below:

• this disruptive technology has the potential to dramatically change construction methods, accepted production paradigms and business economics. 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, hybrid process proves to be a really stable, efficient and flexible technology. Thus, if they are not properly set, there will be defects in the weld;

• productivity is improved through an increased welding speed. For sheet material it is possible to get a 40 % enhancement of the speed compared to conventional laser welding;

• when using hybrid welding, the investment cost for the laser power source is significantly less and the electrical efficiency is much higher;

• with 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. Thus, laser-MIG/MAG hybrid welding has the capability of single-pass full penetration and is confirmed for an increased thickness range;

• another practical consideration in introducing the hybrid process in industrial applications is the ability to produce quality welds in the face of a changing joint gap for welding thicker sections by allowing achievable edge preparation;

• in an industrial application, it is conceivable that the gap would vary throughout the weld, and it is desirable to develop a single set of processing conditions to accommodate this condition, so that expensive sensor feedback and real-time parameter adjustment is not required;

• nevertheless, this technology is recognizing only a slow growth in today's industries. Some explanations for this slow acceptance are the high investment costs and the complexity of the process due to its large number of parameters. The 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 the limiting factors for its wider industrial application.

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