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The influence of parameters on penetration, speed and bridging in laser hybrid welding

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1. Introduction

The hybrid welding process (Fig. 1) combines the laser beam and the conventional arc such that both heat sources are incident in a single weld pool [1]. The process has received a great deal of attention in recent years as a high speed, high efficiency, high quality welding process which compensates for the weaknesses of individual welding processes. The process was first developed by Steen and Eboo using a 2 kW CO_2 laser and gas tungsten arc welding (GTAW), and it produced some interesting results. The laser was found to stabilize the voltage and current of an unstable arc, reduce the arc column resistance and increase the depth-to-width ratio of the resulting weld morphology [1]. As laser technology developed, higher-power welding lasers were more readily available, and the process has gained interest in industrial applications and in research.

Various laser–arc hybrid welding processes exist, depending on the combination of the specific types and power levels of the laser sources (CO_2, Nd:YAG, fiber and disc laser) and the arc sources (GMAW, GTAW, PAW, tandem, submerged), as has been previously assessed [2]. Usually the name of the process begins with the name of the process introducing the higher power in the joint process; i.e. in the GTAW/YAG laser hybrid process the power of GTAW is higher than that of the YAG laser. Many studies have been conducted concerning the potential and advantages of the process combination [1-18]. The potential has most often been to increase the weld penetration and to improve the bridging ability and the weld speed compared to the individual processes of laser and arc welding.

Many researchers have concentrated on the influence of either the geometric parameters, such as the process distance and the laser beam focal position [5-7, 19], or the energy parameters, such as arc voltage, arc current and laser power [8-10], an increase in the penetration depth [11, 12], the accuracy of the weld butt joint surface and improved misalignment tolerance [9], increased welding speed, porosity reduction and weld stability [13, 17].

The parameters are usually not specified well enough to allow one to reproduce exactly the conditions for a particular operation. The user must optimize the parameters for a particular processing operation experimentally in order to obtain the best results. These results depend on the ratio of the power between the two energy sources and also the design parameters of the system. The main parameters significantly influencing the process result in this study can be grouped into design parameters (material thickness and gap geometry), combined process parameters (welding speed, process distance) and material parameters (type of material).

In this description analysis, the effects of various welding parameters, such as the laser power, the arc current, the welding speed, the distance from the beam optical axis to the electrode wire target point (subsequently called *process distance*) and the focal point position, on weld penetration, the increase of welding speed and the gap bridging ability will be investigated. There are different reports concerning the optimum positioning regarding these parameters. This paper analyses various other papers and takes into consideration the parameters that influence the penetration depth, welding speed and gap bridging capabilities.

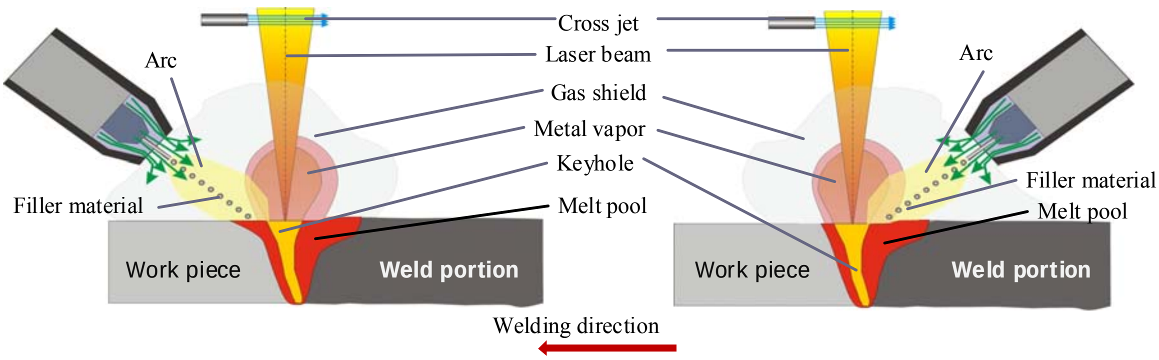

Fig. 1 Schematic representation of laser hybrid welding with leading laser and leading arc arrangements

2. Results of the effect of the variables

There are many process variables associated with laser–arc hybrid welding, and it is important to understand how they affect the welding process. In laser-arc hybrid welding, the arc power controls the weld width and root opening bridging ability, and the laser power controls the penetration [1, 12, 13]. The laser-arc hybrid welding process has an increased melting efficiency, as measured by the weld cross-sectional areas, over the sum of the individual processes [3, 4].

Thus, these parameters are based on the type and thickness of the base metal, the welding processes, and the output power of the sources, the joint geometry and the tolerance. It should be pointed out that in the following the tests have been carried out both with bead-on-plate welding and in a butt joint. These results are not fully comparable due to different joint conditions, which mean in practice that there is no gap or air gap in the joint. Due to this, the filler material added is fed into the top of the plate since there is no space for filler material in the joint. Typically, the arc parameters used lead to a wire feed rate of some meters per minute, introducing filler material several cubic millimeters per minute. In a joint, this volume of material partly flows down, bridging the gap and forming the root pass. Since this is not the case with bead-on–plate, the effect can be seen in cross-sections of welds as a strong widening of the weld on top and typically as a formation of a rather high weld bead. In the worst case, the filler material disturbs the process by flowing into the keyhole and making it collapse. Similarly, the results gained with full penetration are not comparable with the ones reaching the same penetration depth in a thicker material without full penetration. The full penetration changes the behavior of the keyhole and requires changes to parameters. In the case of full penetration, the acceptable weld also requires the optimization of parameters to ensure root quality. Since the quality criteria are different, this leads to different parameters ensuring acceptable weld quality.

2.1. Penetration depth

The laser–arc hybrid welding process does not only require a high laser power but also a high beam quality to be able to achieve the so-called deep-penetration effect by the formation of the keyhole. One of the reasons for a deeper penetration as well as an increase in the welding speed of the laser–arc hybrid welding process compared to pure laser welding is the higher amount of energy delivered to the workpiece. High penetration welds and at high travel speeds can be made, typically a 1 mm penetration for every kW of laser power at 1 m/min. Another reason may be the better absorption of laser energy when heat is accessed from the second arc heat source. For lower welding speeds, full penetration is achieved, enabling the excess laser power to be transmitted through the keyhole, thus influencing the heat input in the weld, which also influences the melt flow. There is a minimum welding speed below which the keyhole is no longer stable since the pressure of the metal vapour is no longer able to keep the keyhole open against gravity. The deepest penetration for the given conditions is achieved at speeds just above this minimum. A small air gap can improve the penetration and increase the welding speed compared to welding without an air gap [18-22].

There are quite many researchers who think that the penetration in the laser–arc hybrid welding process does not depend on the arc current but on the laser power in CO_2 laser–GMA hybrid welding and Nd:YAG laser–GTA hybrid welding [6-11,23]. This is due to the fact that quite many of these studies have used a relatively low laser power. Fig. 2[11] shows cross-sectional photos of a Type 304 stainless steel weld at various laser powers. In the experiment, a GTAW electrode of 3.2 mm in diameter was used. The welding was performed in the Direct Current Electrode Negative (DCEN) mode. Welding conditions, such as the laser power, arc current and welding speed, were changed in order to evaluate the weldability and the penetration depth. The main welding conditions are the laser power P_L (on the plate) 1.7 kW (cw), the focal point position *fd* 0 mm, the welding speed *V* of 8 or 10 mm/s, the arc current *I* 100 A, the electrode height *h* 2 mm, the process distance *d* 2 mm, the angle of the electrode α 55°, and the Argon shielding gas at the flow rate *Rg* 5.0 or 6.7 x 10–4 m^3/s. The effect of the laser power on penetration was investigated by welding with the YAG laser alone or the YAG laser combined with GTA in the range of 0.6~1.7 kW. Both in the YAG laser and in the GTAW–YAG process, the penetration became deep as the laser power increased. Even though the arc increased considerably, the penetration made in the GTAW–YAG process was only 0.5 mm deeper than that in the YAG process with each power. It was found that the increase in the laser power was more effective than that in the arc current in order to obtain a deeply penetrated weld bead [11]. The figures, however, show that the width of the weld bead is increased with the arc power (Fig. 2).

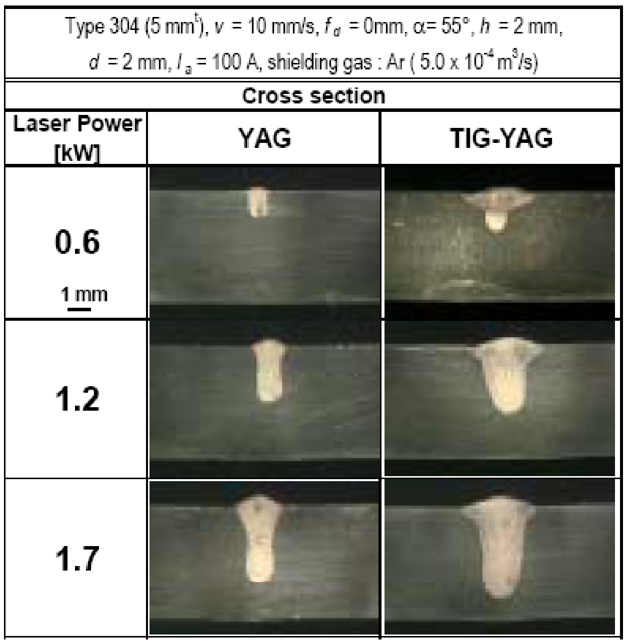

Fig. 2 Cross-sections of Type 304 stainless steel subjected to a YAG laser only and GTAW arc–YAG laser hybrid welding with various laser powers [11]

In the same study [11], it was found that the optimum distance for a deeper penetration existed and was different for GTA–YAG and YAG-GTA (Fig. 3). Therefore, the reason for the deeper penetration in the shorter process distance can be explained by considering the natural concentration of the arc due to free electrons generated by the laser beam, the reduction in laser reflection due to the molten pool generated and the small heat conduction losses of laser energy in reaching a melting point. On the other hand, in the YAG–GTA welding process, the penetration depth in the case of distance d = 5 to 9 mm is shallower than that of YAG laser welding alone. It is conjectured that the keyhole closed or the direction of the liquid flows changed [11].

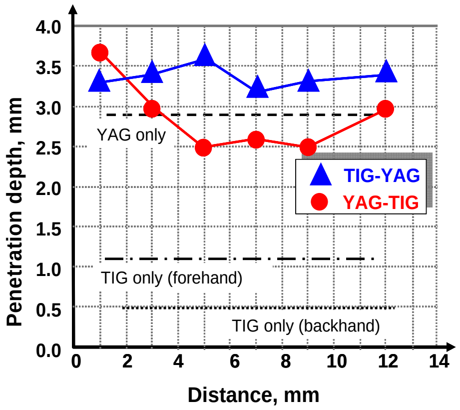

Fig. 3 Effect of process distance on the penetration depth with YAG laser–GTA hybrid welding [11]

The process distance in the YAG laser–GMA hybrid welding of the aluminium alloy A5052 of 2, 3 or 4 mm in thickness on penetration is different due to the variables chosen in the experiment [21]. The deepest penetration and the largest melted area were obtained at the process distance of 1 to 3 mm depending upon the GMAW current of 60 to 240A. In order to investigate this, the molten pool behaviour and wire droplet transfer during laser hybrid welding at various distances were observed with a high-speed video camera. At 0 mm, the droplets from the wire were reported to become irregular in shape. This was attributed to the interaction due to laser-shooting, and thus laser-absorbed energy in the molten pool was shielded. On the other hand, at 4 mm or longer, the molten pools appear to be separately produced with the laser beam and the GMA. Consequently, the process distance of approximately 2 mm might exert the greatest effect on the formation of deeper penetration. The penetration depth increased with a decreasing process distance, but it again became almost equivalent to that of single YAG laser welding at the process distance of 0 and 10 mm, as shown in Fig. 4 [24]. The angle of 30° of the electrode from the laser beam axis was adopted in the experiments, and the GMAW wire was A5356 of 1.2 mm in diameter. In this study, the Nd:YAG laser maximum power P = 4 kW and the GMAW maximum current 350A in the DCEP (Direct Current Electrode Polarity) pulsed arc mode were used. According to the report, the YAG laser beam absorption within argon plasma and resulting plasma shielding are expected to be negligible [24].

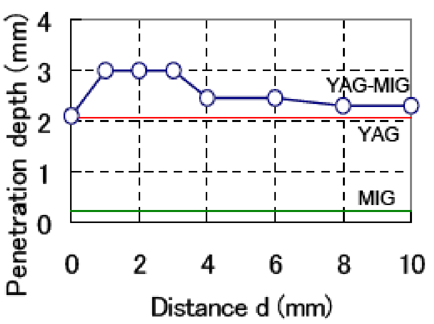

Fig. 4 The effect of process distance on penetration [24]

Other research groups have also estimated when the laser beam and arc processes still act together and when the process is the most efficient. The results of a test [22] carried out on low carbon steel S355 of a thickness of 6 mm with a 6 kW CO_2 laser and Esab Aristo 2000 arc welding equipment proved to be interesting. The shielding gas used in the experiments was a mixture consisting of 50% He + 45% Ar + 5% CO_2, and it was introduced into the process via a GMAW torch. The GMAW process was in the pulsed mode. It was concluded that the maximum distance between the processes can be approximately 4 mm in order to establish a laser-arc hybrid welding process. A deeper penetration reached with a leading torch can be explained by the fact that the arc is already melting the workpiece surface, and when the laser beam reaches the location of the molten material at an elevated temperature, it is able to start penetrating the metal on an already warm surface. The leading torch also ensures better weld quality.

Kutsuna and Chen [25] have suggested that the distance should be equal to or below 2 mm when the CO_2 laser power is 2 kW and the GMAW current 200 A to achieve the maximum penetration. They pointed out that the optimal distance is dependent upon many things, such as the laser power, the GMAW torch angle, the arc size (arc parameters such as like voltage, current and pulsing are of importance) and the molten pool size. They noticed that the arc becomes unstable if the distance is too long because the laser and arc plasmas are apart from each other. It was also noticed that if the processes are aimed at the same point, the filler wire end is also melted by the laser beam. Minami *et al.* [26] have suggested that if the processes are headed to the same spot, the penetration will decrease because the laser beam is absorbed by the laser and arc plasmas and the metal from the filler wire blocks the penetration of the laser beam. A similar result has also been presented by Ishide *et al.* [27] in the case of GMAW–Nd:YAG hybrid welding: the greater the process distance, the smaller the penetration depth is and the higher the weld reinforcement. Campana *et al.* [28] have also reported that in the welding of AISI 304 stainless steel, the mutual distance between the sources plays an important role since it can be noted that for distances between 2 and 4 mm the maximum penetration depths can be achieved, whereas when the laser beam is more than 6 mm away from the arc, the penetration depth decreases since the synergy between the processes is missing. Decreasing the laser-arc separation dramatically increased the penetration of the welds. There is also a corresponding decrease in width as the laser-arc separation is decreased. It is clear that reducing the laser-arc separation is advantageous because it promotes higher penetration in the uniform fusion zone welds and reduces the size of the laser only region in the two-part fusion zone welds [29, 30]. When the distance between the sources is equal to 0 mm, the repeatability of the results is greatly compromised. This is probably due to the weld pool turbulence caused by the filler metal droplets impacting the keyhole generated by the laser beam, causing instability in the whole process with a dispersion of results.

It was reported by Hayashi *et al.* [31] that the penetration depth of the weld beads produced in a flat position was greater in laser–arc hybrid welding of a thick steel plate with a process distance of 0 mm, as shown in Fig. 5 [31] (welding speed of 17 mm/s, CO_2 laser of 30 kW, GMAW arc current 500 A and GMAW arc voltage 47 V). These tests also showed that in the laser–arc hybrid welding of thick steel plates of 25 mm in thickness with a square groove, a deeper penetration is obtained in the horizontal position than in the flat position.

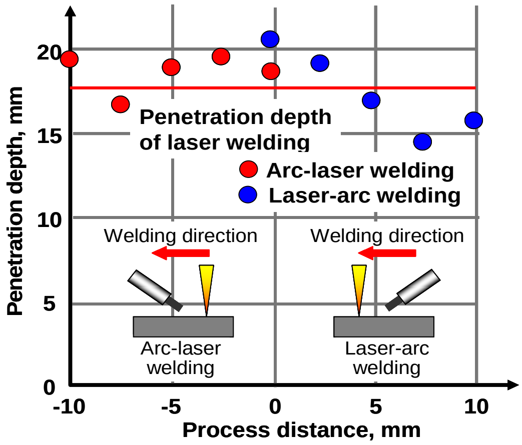

Fig. 5 The effect of process distance on penetration depths in a flat position [31]

A smaller process distance allowed a complete mixing of the filler material throughout the fusion zone, which provided consistent weld quality and improved gap tolerance. However, the smaller distance increased the complex interaction between the laser beam and the GMAW, which made it difficult to identify the parameters that could provide full penetration without backside blow-through [32]. According to some studies, when the separation of the processes is 5 mm or more, the processes act independently. Of course this value depends, for example, on the welding speed, laser and arc powers and the material used.

Another study compared the penetration and bead width in the laser leading and GMA leading hybrid welding processes (Fig. 6) [33]. The experiment was carried out with bead-on-plate welding with a 2.4 kW CO_2 laser and a 3000 A DC GMA welding machine of HSLA-590 steel, and it showed results with high power laser. It was concluded that the arc leading hybrid welding process is more acceptable in terms of penetration compared to laser leading.

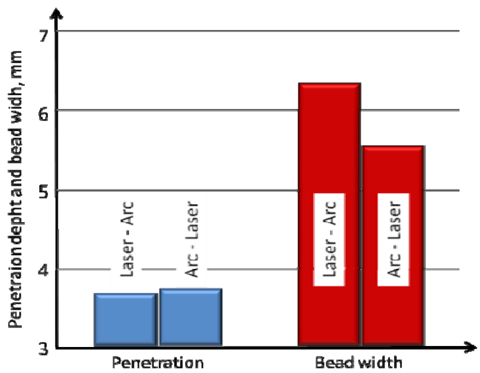

Fig. 6 Comparison of weld cross sections with respect to the penetration depth and bead width of laser and arc leading positions [33]

In laser-arc hybrid welding, the arc presses the molten pool downwards, and due to the large curvature of the molten pool, the focal point position in laser-arc hybrid welding is not the same as in laser welding. The location of the laser beam focal point with respect to the workpiece surface in conjunction with the welding current was found to affect the weld penetration. With a constant laser power and welding speed, the higher the current, the deeper the focal point should be under the workpiece surface in order to achieve the deepest penetration. This is particularly true with GTA/GMA–YAG hybrid welding [11]. The penetration was deeper in a GTA/GMA–YAG weld in the focal point position from -2 to 2 mm. The effects of the focal point position on the penetration and porosity formation tendency were investigated in welding with a YAG laser and hybrid arc sources. Fig. 7 [11] shows a summary of cross-sections and X-ray inspection results in GTA–YAG welding.

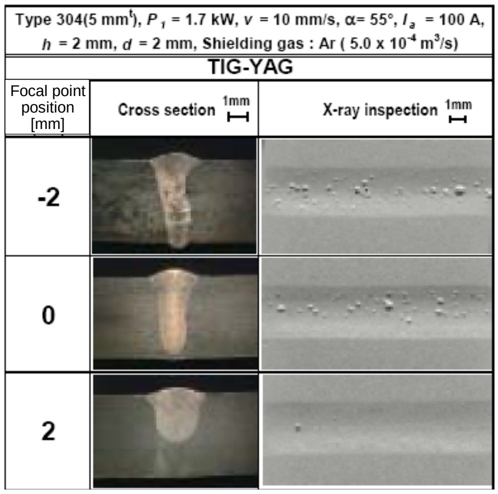

Fig. 7 Cross-sections of laser–arc hybrid welding at various focal point positions [11]

In the case of fiber laser–GMA hybrid welding of the mild steel S355 of a thickness of 6 mm in a butt joint with a 5 kW fiber laser and a GMA source of 450 W, Fellman and Salminen reported [34] that the focal point above the surface will achieve full penetration when trailing the GMA torch with a lower welding speed compared to the focal point below the surface as the molten metal flows to the front of the keyhole, ensuring full penetration. The incorrect position of the focal point easily leads to a lack of penetration. However, laser–arc hybrid welding can bridge joint air gaps, and actually, a better weld quality and higher welding speed can be achieved by having an air gap in the joint [20].

It was explained by Kutsuna and Chen [25] that in CO_2 Laser-MAG hybrid welding, the focal position of the laser beam seems to have an effect on how the molten droplet is transferred into the melt pool. If the focal position is below or on the surface, the droplet spins around the wire end before it is detached and splashes into the melt pool. It may be because the high pressure plasma pushes the droplet away from the keyhole and because the plasma plume fluctuates that the forces at some point allow the melt droplet to move into the melt pool. This phenomenon is not observed when the focal position is above the surface. This may be due to the amount of plasma above the keyhole. When the focal position is below or on the surface, the amount of plasma is greater than with a focal position above the surface. Another possibility is that the forces affecting the movements of the melt droplet are smaller when the focus is above the surface. This phenomenon needs further research. Even though the movement of the droplets looks better with a focal position of +1 mm, the weld quality is poorer than with the focal position on the surface.

With all arc welding processes, the orientation of the welding torch/electrode with respect to the weld joint affects the weld bead shape and penetration. The electrode orientation affects the bead shape and penetration to a greater extent than the arc voltage or travel speed. The electrode orientation is described by the relationship of the electrode axis with respect to the direction of travel, and the angle between the electrode axis and the adjacent work surface. When the electrode points opposite to the direction of travel, the technique is called backhand welding with a torch angle less than 90^o. When the electrode points in the direction of travel, the technique is called forehand welding with a torch angle less than 90^o. The penetration increases and the bead width decreases when the welding technique changes from forehand to backhand. Maximum penetration is obtained in the flat position with the drag technique, at a drag angle of approximately 25^o from the perpendicular line. In laser–GTA/GMA hybrid welding, the torch angle was set at 50–60^o from the surface of the specimen, and a greater penetration was obtained. The GMA torch inclination was determined by taking into account that there was a high probability of spatter with a low inclination (i.e. a low angle between the torch and the surface of the workpiece) and interference with the laser at a high inclination.

Campana et al. [28] have reported that the penetration of the weld increases when the inclination angle of the electrode to the workpiece surface is up to 60^o. The DC mode is preferable to the AC mode in an arc welding source in laser–arc hybrid welding. The arc source is often operated in a pulsed mode since this has been shown to reduce the amount of spatter whilst maintaining a deep penetration of the weld**.** The experiment was carried out with a 3 kW CO_2 laser and a GMAW source on a butt joint of an AISI 304 stainless steel sheet 8 mm thick with the following parameters: GMAW torch inclination 65, shielding gas mixture 40% He, 57% Ar, 3% O_2, shielding gas flow 20 l/min, welding speed 1 m/min, the welding direction laser–leading with a 1.0 mm filler wire.

By increasing the pulse frequency, the droplet size can be decreased. This, however, also increases the arc power. When the arc current is increased, the penetration depth will decrease. This is thought to be due to the suppression of the irradiation of the laser beam into the bottom part of the bead because of the increasing amount of molten metal caused by the high arc current. According to a study on the Nd:YAG–GMA hybrid welding of an aluminium alloy, in order to achieve a stable and highly productive process, the pulse frequency should be increased by 30% [35].

The focal length has an effect on the penetration in autogenous laser welding. For example Vollertsen and Grünenwald [36] have reported on their experiments carried out with 8-kW fibre laser power in bead-on-plate welding at a 2 m/min weld speed with focal lengths of 150 mm and 280 mm. The maximum penetration achieved was 11 mm and 8 mm for the focal lengths 280 mm and 150 mm, respectively, at the focal position of -2 mm. There was an increase in penetration of about 35% when using a longer focal length. Fig. 8 [36] illustrates the comparison of the penetration depth with the focal lengths 150 mm and 280 mm in autogenous welding.

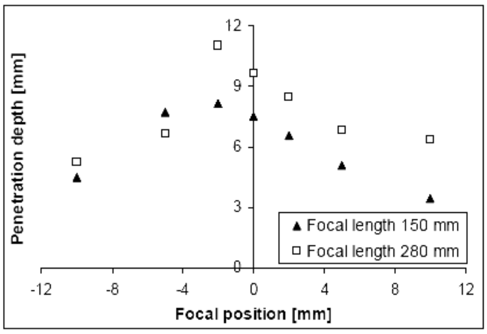

Fig. 8 The penetration depth of 150 mm and 280 mm focal lengths at different focal positions in autogenous welding [36]

It would be logical to expect similar effects by focal length also with hybrid welding. We still lack systematic results about hybrid welding of high power and effect of focal length or focal point size. Fig. 9 [27] presents the results of bead-on-plate welding at two focal point sizes under identical conditions in a penetration range of less than 5 mm. Approximately a 1.3 times greater penetration depth is obtained at a small spot diameter of 0.6 mm. This raises the magnification of the optical system used for image formation to ensure a focal point diameter of 0.6 mm, but presently smaller focal points can be reached with new generation lasers. Roepke *et al.* [37] recently used a 1.8 kW ytterbium fiber laser beam perpendicular to the work piece and a GMA torch which trailed behind the laser 30^0 from the perpendicular on 6.35 mm A36 steel in beam-on-plate welding. It was found that increasing laser power and decreasing laser spot size increased the melting efficiency of the hybrid process over the additive melting efficiency of laser and arc welding alone. This was observed at a laser-arc separation of 1-3 mm and up to a travel speed of 25.4 mm/s. Increasing the laser power also reduced the current of the free burning arc, but did not affect the voltage [37]. The comparison of the focal length and focal point diameter is not typically reasonable when the thickness is changed. The results showed that with thinner material the smaller focal point and therefore the shorter focal length can improve the process efficiency in hybrid welding.

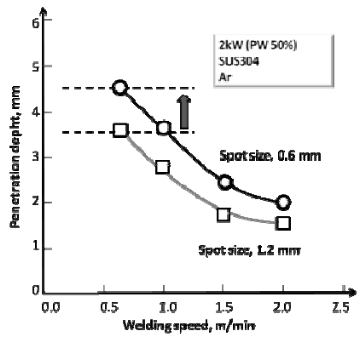

Fig. 9 The influence of the spot diameter on penetration [27]

2.2. Bridging ability

The ability of hybrid welding to bridge gaps more effectively and accept poorer gap preparation than autogenous laser welding has been a strong motivator for the use of this process. In a manufacturing application, it is likely that gaps will occur and vary in size and quality throughout the joint, and it is desirable to develop a single set of processing conditions to accommodate this condition. By combining the laser beam and the arc and filler wire feed, a larger molten pool compared to the laser beam welding process is formed, and extra material is available to compensate for the inaccuracies. Consequently, joints with larger gaps can be welded.

When there is no air gap in the joint, the resulting weld will be slightly wider than the one with a small air gap. If there is no air gap in the joint, sometimes the keyhole is blocked because of the extra material of the arc process or too much molten metal in the weld area. This is because the molten metal cannot flow to the groove since there is no air gap and the arc process feeds filler material to the surface. The arc does not seem to strike as straight towards the keyhole or laser beam when there is no air gap (Fig. 10). In the existence of an air gap, it was seen that the arc penetrates the groove, and therefore, the air gap helps the interaction between the arc and the laser. When there is an air gap in the joint, the arc turns more strongly towards the keyhole and the laser beam inside the groove.

It is believed by many researchers that the cross-sectional area of a weld increases with an increase of the voltage in arc sources in the laser–arc hybrid welding process. An experiment was carried out to see the effect of arc voltage on the penetration depth when the laser power is 5 kW. Fig.10 [11] shows that in bead-on-plate welding the penetration remained the same, but the cross-sectional area increased as the arc current increased. From these results, it is apparent that the penetration depth in the hybrid process does not depend on the arc current (in the case of 200 A or less), but rather on the laser power. It was also identified that the penetration bead width increased with an increasing GMA arc current [24]. The YAG–GMA hybrid weld bead surface quality was better than that of the GMA–YAG hybrid weld. This is in all likelihood caused because the vaporized substances generated during GMA–YAG hybrid welding were blown onto the bead surface due to the GMA torch gas. In contrast, the cleaning action of the trailing GMA arc acted upon the bead surface during YAG–GMA hybrid welding. The arc current belongs to the TIG-YAG process only.

Steel type AISI304 (thickness = 5mm), laser power 1.7 kW, welding speed 10 mm/s, focal point position 0 mm, arc torch angle 55°, wire height 2 mm, process distance 2 mm, shielding gas Ar $5*10^{-4}$ m^3/s		
Cross-section		TIG current
YAG	TIG-YAG	
		100 A
		150 A
		200 A

Fig. 10 Cross-sections of austenitic stainless steel 304 subjected to the YAG laser only and GTA–laser hybrid welding at various arc currents [11]

A recent study by Webster *et al.* [17] involved extensive investigations with CO_2 lasers up to 20 kW and Nd:YAG lasers up to 7.2 kW in order to expand the prevailing state of the art regarding, e.g. the weldable thickness and bridgeable gaps. The aim was to develop process procedures for the laser hybrid welding of structural steels with yield strengths of up to 690 MPa and wall thicknesses of up to 30 mm. Most welds were carried out with the integrated hybrid welding nozzle developed by ILT [38]. For improving gap bridging capabilities regarding the weldable plate thickness, it was then reported that the maximum gap width for a butt joint is influenced by the plate thickness and the position of welding, as depicted in Fig. 11[17]. The transition to wide gaps of up to 3 mm is achieved successfully by reducing the laser power, increasing the filler wire deposition and decreasing the welding speed in the PC (horizontal) or transverse position. These are, in fact, the control functions to be considered also in practice when gap variations occur.

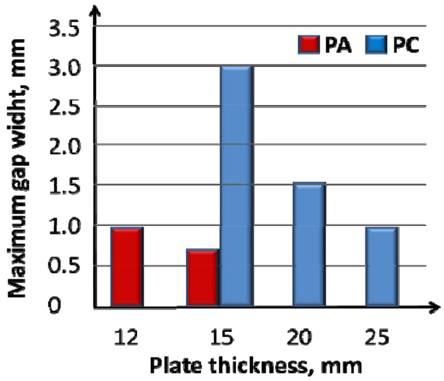

Fig. 11 Plate thickness and maximum gap width in different welding positions [13]

A large number of processing parameters are available when the laser and GMAW processes are combined. Petring *et al.*[38] proposed the formula W_{max} (1) to determine the wire feed rate required to fill a joint of a given geometry (i.e. a given thickness, land height and bevel angle) and other conditions.

$$W_{max} = \frac{2\sigma}{\rho\left(gt + V_m^2/2\right)} \tag{1}$$

The formula considers the gravitational force (gravitational constant g) due to the mass of the melt column (density ρ and height t) above the root with width w_m, the dynamic pressure of a "downward" melt flow component with the velocity v_m and the supporting capillary forces due to the surface tension s of the root melt. The arc pressure could also be included in the balance equation, but its contribution can be neglected compared to the other terms. The gap width w determines the minimum possible root width. On the other hand, the root width determines the minimum possible root radius $w_m/2$ which occurs at the contact angle a = 90° (Fig. 12). By setting the gap and root widths identical, the balance equation can be resolved for the maximum gap width.

To adjust the process, first of all an appropriate wire feed rate has to be set to properly fill in the missing volume. It is also clear that in order to fulfil the above condition of minimizing the root width w_m to the gap width w, the laser beam power has to be adapted, namely minimized, accordingly:

- adapted laser power reduces root width w_m to gap width w.

Equation (1) presents three possibilities to maximize the allowable gap width w_{max}, which can be implemented by corresponding measures:

- increasing surface tension s by root protection with inert gas (if two-sided access is accepted);
- reducing melt velocity v_m by ensuring a stable process with low melt dynamics, mainly achieved by a proper basic parameter configuration;
- avoiding the effect of gravitation by using a position PC.

The appropriate amount of filler wire deposition depends on the groove and gap volume as well as on the welding speed and can easily be estimated and adjusted. The amount and the distribution of the energy input due to the laser beam power and the focal position influence the root formation.

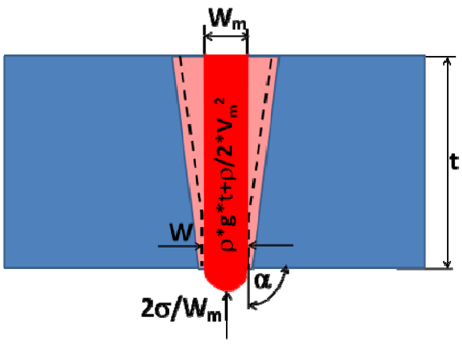

Fig. 12 The pressure balance at the root [38]

2.3. Welding speed

While keeping all of the other parameters constant, the welding speed significantly influences weld quality, arc behaviour and process stability. Moreover, it was demonstrated that laser power has an influence on the weld quality, arc behaviour and process stability. It is safe to say that for each laser power at given arc parameters, an optimum welding speed exists beyond which the weld quality and process stability rapidly deteriorate.

The addition of the arc power and process stabilization in laser–arc hybrid welding leads to a significantly higher welding speed compared to autogenous laser welding. The heat input per unit of length actually remains almost constant in comparison with autogenous laser welding when the arc efficiency is considered to be similar to that in arc welding [20].

A useful way to visualize the effect of the air gap width in butt welding is by plotting the maximum welding speed to the gap width, as shown in Fig. 13[39]. The laser welding process displays a clear drop in speed at a gap wider than 0.1 mm with a thin sheet. For the GMA process, no change is evident at variable gap widths. For the GMA–CO_2 laser hybrid welding process, a decrease in the maximum welding speed is observed with increasing gaps. At a gap width of 0.6 mm, a 22% reduction in speed (from 4.5 m to 3.5 m/min) is seen. The GMA–laser hybrid welding process bridges gaps of up to 0.6 mm in width with a welding speed of 3.5 m/min (78% of the welding speed at a zero gap) when the thickness is 2.13 mm. This may, in some cases, be due to the low available wire feed rate of the arc machine, which can be a restriction in utilizing the potential of available laser power in hybrid welding.

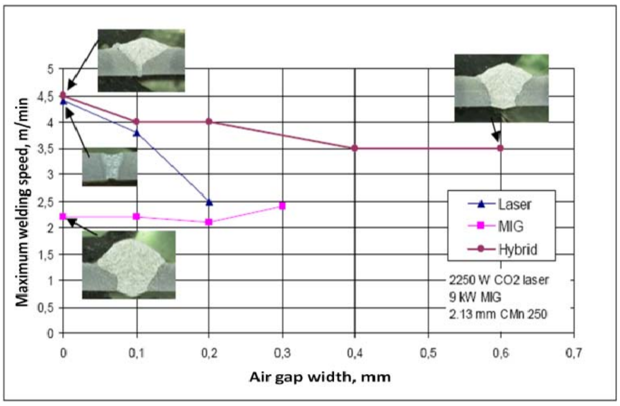

Fig. 13 Sensitivity to gap width, measured at maximum welding speed [39]

Webster *et al*. [17] have also reported that the laser beam power as well as the welding speed must be adapted to the plate thickness and the gap width. Fig. 14 [17] shows a general overview based on this study of the required beam power and the achieved process capabilities regarding the weldable plate thickness, the welding speed and gap width for butt joints in welding positions PA (i.e. horizontal welding in a flat position) and PC.

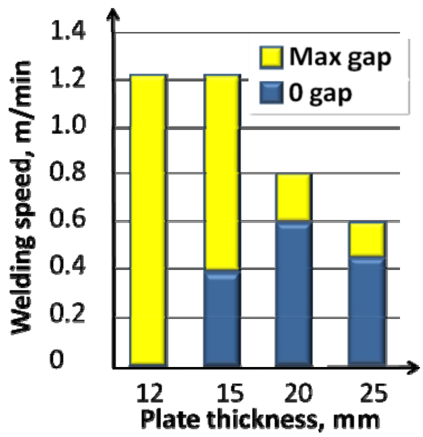

Fig. 14 Effect of thickness on optimized joint configuration and welding speed of single-pass laser–GMA hybrid welding of structural steel [17]

3. Fundamentals of parameter set-up

There are some issues worth taking into account when starting the parameter set-up for a new case. When the laser process starts shortly before the arc welding process, the available metal vapour helps the automatic easy noncontact ignition of the arc welding process. Melting in the beginning of the joint, the laser eliminates the normal lack of fusion in the beginning of the joint which is typical of arc welding.

When welding a fillet joint, the laser beam should be positioned higher by half the width of the gap onto the web, and the arc process in the middle of the gap. Typically also the incidence angle of the laser beam to the horizontal line should be as low as possible, whereas for the arc an angle of 45° is often suitable. In addition, the heat input of the processes together with the wire feed rate have to be adapted to the gap and required fillet dimensions.

In most cases, a pulsed arc should be used in hybrid welding to be able to achieve as low a spray arc as possible. The shielding gas and its parameters should be selected for each specific task and system used.

4. Conclusions

It is worth mentioning that the laser–arc hybrid welding process is without a doubt a process of great industrial interest thanks to its extensive applicability and versatility. However, in order to obtain a reliable and repeatable process, many issues must be taken into consideration.

Laser–arc hybrid welding requires that several parameters be adjusted in order for high quality welds to be obtained. This may be seen as a disadvantage because the large number of parameters complicates the implementation of the process. On the other hand, the number of parameters enables the use of the process in various applications by adjusting the parameters case by case, which can be seen as an advantage. Also, the set-up of other welding parameters, for example the laser and arc power, the laser beam focal position, the laser beam focal length and the welding speed, may have an effect on which direction yields the best results. Thus, it has also been noticed that the process distance plays an important role in achieving deeper penetration and synergy between the processes. Consequently, the process distance of approximately 2 mm might exert the greatest effect on the formation of deeper penetration. The penetration depth increased with a decreasing process distance, but it again became almost equivalent to that of single laser welding at the process distances of 6 and above.

The penetration depth is affected mainly by laser power and the welding speed, while bridgeability is influence mostly by voltage and the wire feeding speed.

Nevertheless, the number of industrial applications is still limited. One important reason for this is the lack of references, experiences, standards, and therefore, the necessary confidence among product designers to apply laser–arc hybrid welding.

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LAZERINIO HIBRIDINIO SUVIRINIMO PARAMETRŲ ĮTAKA Į PRAVIRINAMUMĄ, GREITĮ IR NESUVIRINAMUMĄ

R e z i u m ė

Vis daugiau domimasi lazerinio hibridinio suvirinimo taikymu metalo pramonėje storasieniams gaminiams gaminti, nes šis suvirinimo būdas yra pranašesnis, nei suvirinimas tiktai lazeriu. Vienas iš pagrindinių pranašumų yra tai, kad šiuo atveju tarpai tarp suvirinamų detalių gali būti didesni. Norint šį suvirinimo būdą sėkmingai taikyti gamyboje aukštos kokybės gaminiams suvirinti, reikia išnagrinėti parametrus, lemiančius įvirinamumą, suvirinimo greitį ir nepravirinamumą.

Tyrimas remiasi literatūros, kurioje yra išnagrinėtos įvairios kelių tyrėjų grupių publikacijos, apžvalga. Ši apžvalga nagrinėja specifinius atvejus: įvirinamumą, suvirinimo greitį ir nepravirinamumą hibridinio lazerinio suvirinimo procese. Kai yra daug parametrų, procesą galima panaudoti įvairiems tikslams, kiekvienu konkrečiu atveju parenkant tinkamiausią. Nustatyta, kad proceso trukmė turi svarbią reikšmę įvirinamumo gyliui ir procesų tarpusavio sąveikai. Įvirinamumo gylis daugiausia priklauso nuo lazerio galios ir suvirinimo greičio, o nepravirinamumui ypač daug įtakos turi įtampos bei pridėtinės vielos ir pastūmos greičiai. Šis darbas sukuria gerą pagrindą vėlesniems tyrimams ir teikia informaciją metalo konstrukcijų gamintojams, kaip padidinti šių gaminių gamybą ir pagerinti kokybę taikant hibridinį lazerinį suvirinimą.

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THE INFLUENCE OF PARAMETERS ON PENETRATION, SPEED AND BRIDGING IN LASER HYBRID WELDING

S u m m a r y

Increasing interest has been expressed in the application of the laser hybrid welding process by the metal industries producing thick sections because it possesses advantages compared with laser welding alone. One major benefit is that larger joint gaps can be accommodated. For the successful implementation of laser hybrid welding technology in high quality welds in industrial application, the parameters that influence the penetration depth, the welding speed and the bridgeability gap should be studied.

The study is based on literature review of the results of a variety of publications carried out by several research groups. This review concentrates on specific cases: penetration, welding speed and bridging capabilities of the laser hybrid welding process. The large number of parameters enables the use of the process in various applications by adjusting the parameters case by case, which can be seen as an advantage. Thus, it has been noticed that the process distance plays an important role in achieving deeper penetration and synergy between the processes. The penetration depth is mainly affected by the laser power and the welding speed, whereas the bridgeability of the air gap is mostly influenced by the voltage and the wire feeding and travel speeds. This study provides a good foundation for future research and creates awareness among the metal industries to maximize their productivity and quality in the field of laser hybrid welding.

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ВЛИЯНИЕ ПАРАМЕТРОВ ЛАЗЕРНОЙ ГИБРИДНОЙ СВАРКИ НА ПРОПЛАВЛЕНИЕ, СКОРОСТЬ И НЕПРОВАР

Р е з ю м е

Все больше внимания привлекает использование лазерной гибридной сварки в промышленности при производстве толстостенных изделий, в связи с тем, что этот способ сварки является предпочтительнее по сравнению со сваркой только лазером. Одно из основных преимуществ – это возможность применения больших зазоров между свариваемыми деталями. Для успешного использования на производстве этого способа для сварки изделий высокого качества, необходимо рассмотреть параметры, определяющие проплавление, скорость сварки и непровар.

Исследование опирается на литературный обзор, в котором рассматриваются публикации разных групп авторов. В этом обзоре рассмотрено специфические случаи: глубина проплавления, скорость сварки и непровар в процессе лазерной гибридной сварки. При наличии многих параметров можно использовать рассматриваемый процесс для разных применений, в каждом контрольном случае применяя наиболее подходящий. Определено, что продолжительность процесса имеет особое влияние на глубину проплавления и взаимодействие между процессами. Глубина проплавления в основном зависит от мощности лазера и скорости сварки, а непровар – от напряжения тока и скорости подачи присадочного материала и сварки. Эта работа создает хорошую основу для дальнейших исследований и информирует производителей металлических конструкций, как увеличить продуктивность и качество таких изделий используя лазерную гибридную сварку.

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