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The effect of the relative location of laser beam with arc in different hybrid welding processes

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1. Introduction

Laser-arc hybrid welding is a combination process utilizing laser beam (e.g. CO_2, Nd:YAG or solid state lasers) and conventional arc (MIG/MAG, TIG, PAW, tandem, submerged) welding processes `1-4] or arc-augmented laser welding. In hybrid welding (Fig. 1) the two processes are coupled and works as one process interacting simultaneously in one zone and mutually influencing each other. The resultant processes have several variations by the arc process, the laser type used and the process parameters. The technique was originally developed by the group of Prof. Steen at Liverpool University in the late 1970s [2]. At the moment the process is called either laser-arc hybrid or arc-laser hybrid process. The first process mentioned signifies higher power.

The potential from a combination is to increase weld penetration, the bridgeability gap, welding speed, melting efficiency and process stability, to improve metallurgy and to reach features impossible to either process alone. The resulting process is a new, more complicated process, which still widens the area of suitable applications for laser welding.

The main weld characteristics in a hybrid welding process are the order of processes with either laser or arc leading. Moreover, the distance between the laser beam spot and the filler wire tip (subsequently named *process distance*) is among the most important parameters to control in laser-arc/arc-laser hybrid welding. The choice depends on several effects, e.g., the base material, material surface quality, joint type and preparation, welding position and the shielding gas arrangement. Other important parameters are laser and arc power, the laser beam focus and wavelength and the metal-transfer mode of the arc welding process used (MIG/MAG). For practical reasons and joint conditions, the use of a seam tracking sensor can also be crucial.

In this paper, different hybrid welding processes have been studied on the effect of the relative location of laser beam with the arc. It becomes aware that the choice of the order of processes is made case by case and the choice should be based on the outcome of each process and the system and accessories available.

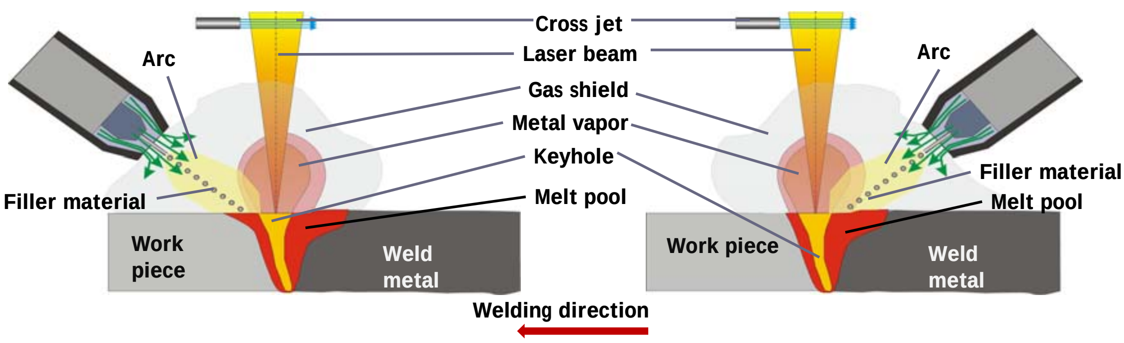


Fig. 1 Schematic representation of hybrid welding with leading arc and leading laser arrangement

2. Order of power sources in hybrid welding

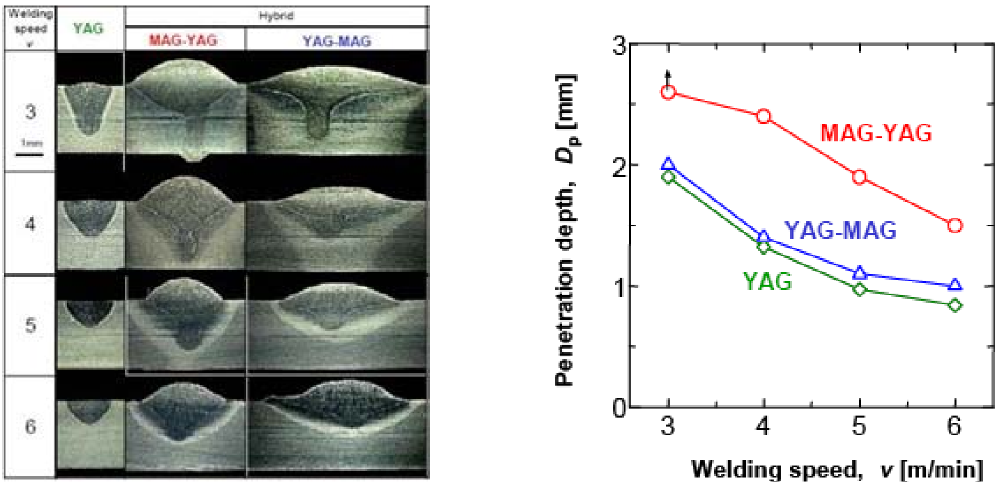
A wide variety of hybrid processes exist, depending on the laser source used and the arc welding with which it is combined [3]. The two basic configurations used are the laser leading hybrid process (the laser beam precedes the arc) [5-7] and the arc leading hybrid process (the arc precedes the laser beam) [8-10]. The arrangement of the two welding processes in the welding direction (Fig. 1) is of significant importance in the hybrid welding process.

2.1. Order of the processes

The laser leading position is often used in the hybrid welding of aluminium, since this set-up removes the oxide layer prior arc welding, resulting in a significantly more stable process [7]. The information about parameter selection in hybrid welding has only occasionally been published, and the literature lacks comparisons between the different hybrid processes. The laser leading process was found to be superior regarding the bead appearance, because the assist gas flow does not affect the molten pool created by the arc, whereas in the leading arc arrangement the shape of the bead surface is disrupted by the assist gas blowing into the molten pool. Still, it was reported that the arc leading arrangement gives a more stable arc [1]. This is reached within a relatively wide range of process distances. The leading arc process gives deeper penetration, probably due to the fact that the laser beam impinges the hot weld pool with better absorption than a solid surface and the energy losses from laser through heat conduction is reduced (Fig. 2, a) [11-14].

In case of high strength steel, MAG laser (2 kW CO_2 laser) hybrid welding gave a similar weld bead as normal arc welding; this is due to the fact that the laser beam makes the keyhole first and then the MAG arc forms the weld bead [15]. Another factor affecting this was naturally the fact that the arc power used was higher than the laser power. However, it was reported that with 17 kW CO_2 laser MAG hybrid welding on 12 mm thick C-Mn steel, the leading laser showed a 10% penetration increase and a smoother weld bead with a process distance of 1-2 mm [8].

The effects of MAG-leading and YAG-leading processes were tested on 590 MPa high tensile strength steel of thickness 2.6 mm on bead-on-plate welding [16]. The tests showed that the bead widths of MAG–YAG welds were narrower than those of YAG–MAG welds. The penetration depths of MAG–YAG weld beads were much deeper than those of YAG or YAG–MAG welds at any welding speed (Fig. 2) [16]. Fig. 2, a shows the macro-sections of weld geometry, whereas Fig. 2, b shows the graph of penetration depth versus welding speed. These results show the effect of base material temperature on the absorption which is increased with temperature only in case of CO_2 laser wavelength. The deepest penetration could be obtained in MAG–YAG hybrid welding at low speeds with the following parameters: laser power 2.6 kW, defocused distance $f_d = 0$ mm, arc current $I_a = 200$ A, angles α = 60º of the welding torch from the work piece, process distance d = 2 mm, and welding speed v = 3 or 5 m/s. A deeper penetration reached with the leading arc can be explained by the fact that since the arc is already melting the work piece surface, the laser beam strikes molten material with higher absorptive capacity, and power is utilized more efficiently enabling deeper penetration. Spatter disturbed laser beam irradiation in YAG–MAG hybrid welding. This phenomenon was observed using a high speed video camera at the side of the experiment. It was concluded in the report that MAG arc-YAG laser hybrid welding was favourable to the welding of higher tensile strength steel.



a b

Fig. 2 Effect of the processes as shown by a) a macro-section of weld geometry and b) speed on penetration, with shielding gas Ar + CO_2 (20%), I = 200 A (pulsed MAG), laser power 2.6 kW and 590 MPa high strength steel

The effect of welding orders on the distribution of wire feeding elements was investigated in CO_2 laser and pulsed GMA hybrid welding. The molten metal flows for the leading arc and leading laser processes have be schematically drawn in Fig. 3 [17]. When arc is leading, the molten metal flows from the bottom to the top surface behind the keyhole and to the rear end on the pool surface as shown in Fig. 3,a namely, the flow is outward. By contrast, in an inward flow typical of a leading laser arrangement as in Fig. 3, b the molten metal flows from the rear end to the keyhole on the pool surface and then goes down just behind the keyhole. During hybrid welding, the molten wire is fed on the pool surface. Then, if the fluid flow is inward, the wire feeding elements can easily distribute to the bottom of the penetration and attain a homogeneous distribution. This is why a leading laser arrangement improves the homogeneity of the weld metal.

As mentioned previously, the distribution of alloying elements must be affected by the molten metal flow. To understand the mechanism, the molten metal flow was observed on the pool surface and inside the sample. The fluid flow was visualized by the movement of alumina powders.

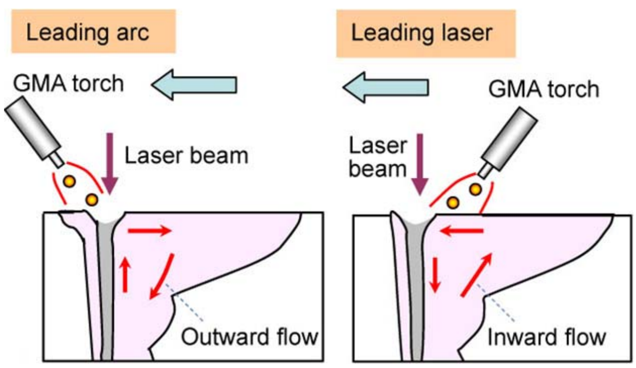


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Fig. 3 Schematic diagram of fluid flow in hybrid welding a) of leading arc and b) leading laser

During a hybrid welding process, the behaviour of the molten metal flow is determined by a combination of driving forces, such as the drag force of the plasma jet, momentum of the droplet, buoyancy force, electromagnetic force caused by the self-magnetic field of the arc current, Marangoni force and drag force of the vapour jet in the keyhole [18]. The buoyancy force and the vapour jet promote an outward flow, whereas the electromagnetic force promotes an inward flow. A change in the temperature coefficient of the surface tension depends on the direction of the Marangoni force. The direction of the plasma jet and the momentum of the droplet also change by the welding direction. The drag force of the plasma jet, the momentum of the droplet and the Marangoni force are the most dominant driving forces affecting the fluid flow in hybrid welding, promoting the inward force in a leading laser arrangement. These forces and the momentum direct towards the keyhole in a leading laser process, whereas they direct towards the rear pool end when arc is leading.

Fig. 4 [17] schematically shows the balance of the driving forces for two welding directions with a He–38%Ar–2%O_2 shielding gas. Owing to the 2% of oxide in the shielding gas, the Marangoni force directs to the keyhole. In a leading arc process, the combination of the drag force of the plasma jet and the momentum of the droplet directing to the end of the molten pool must be stronger than the inward Marangoni force as shown in Fig. 4, a. Accordingly, an inhomogeneous distribution of the weld metal is common in a leading arc arrangement. When laser is leading, by contrast, all of the three forces direct to the keyhole, resulting in an inward flow as shown in Fig. 4, b. Therefore, an almost homogeneous distribution of alloying elements is reached in a leading laser arrangement. Lately, Ribic et al. [19] calculated the fluid flow behaviour in hybrid welding. They revealed that the electromagnetic force also promotes the inward flow only in a leading laser process, since a large amount of molten metal exists just below the arc and the electromagnetic force can induce the inward flow to the molten metal when laser is leading. Moreover, the electromagnetic force can produce a large weld pool behind the keyhole, promoting an inward flow. In a leading arc arrangement, however, the electromagnetic force only produces a small weld pool in front of the keyhole and cannot promote inward flow for the entire weld pool.

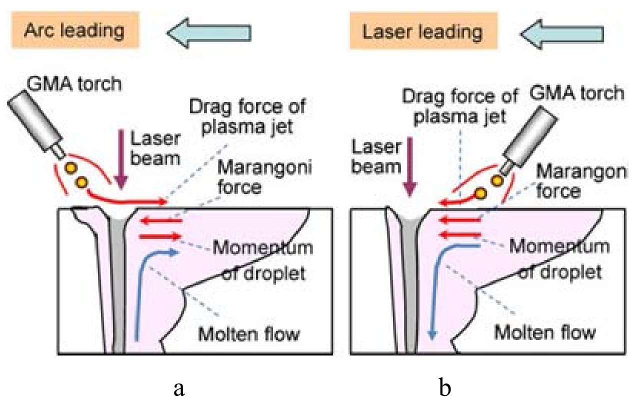

Fig. 4 Driving forces of the molten metal flow for welding directions of (a) leading arc and (b) leading laser.

When comparing the stability of the processes by measuring the current and voltage of the arc during welding, Sugino et al. found that the leading laser gives a more stable process, like shown in Fig. 5, b [20]. This is due to the metal vapour in the space between the wire and molten pool. In the leading laser arrangement, the molten pool exists already just below the wire, and the metal vapour from the keyhole is supplied in the space between the wire and the work piece. Consequently, there are numerous free electrons between the wire and the workpiece, and the arc ignites easily between the wire and the work piece during the electricity peak. The interaction between the arc and the laser plume is determined by the arc voltage from the keyhole and the location of the molten pool, i.e., process distance.

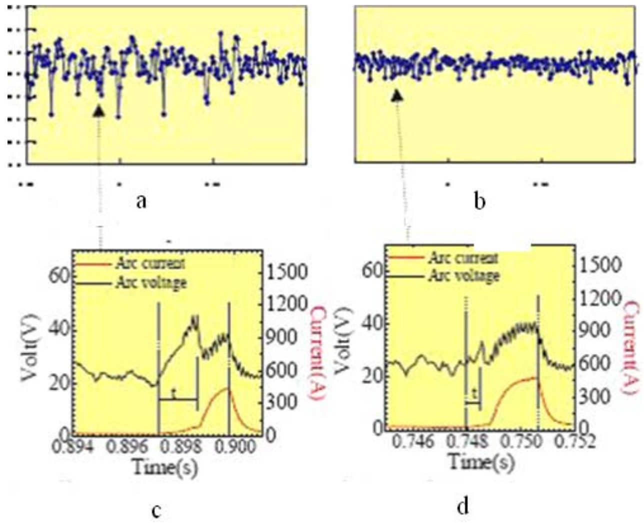

Fig. 5 Influence of welding direction on the variation of voltage and arc current; 5 kW CO_2 laser and a pulse MAG power inclined at 35 degrees, shielding gas 20 l/min via MAG torch, arc pulse frequency 111 Hz, process distance 3 mm and welding speed 3 m/min. The letters a and c represent the leading arc direction with droplet to pulse frequency ratio of 91%, and b and d represent the leading laser direction with droplet to pulse frequency ratio of 100%,

To compare the efficiency of each welding process, the melting efficiency of laser autogenous, forehand/backhand welding in arc welding and MIG arc leading and laser leading processes in hybrid welding were investigated in an A6061-T6 aluminium alloy experiment with a thickness of 2 mm and A4043 welding wire with a diameter of 1.0 mm. The joint type was butt with a 0.4 mm gap. The welding speed was 3 m/min, welding current and voltage were each 48 A, 17.3 V. In the study, melting efficiency is a value of the used energy per volume of molten material (J/mm^3). The experiment results are shown in Fig. 6 [21]. The efficiency of arc welding did not reach the level of autogenous laser welding. When applying the same arc welding parameters to hybrid welding, efficiency was at its highest; the arc leading process showed an efficiency of 13.1 J/mm^3 which was about 0.5 J/mm^3 higher than in the case of leading laser. The order of highest melting efficiency is arc leading hybrid welding, laser leading hybrid welding, laser welding (autogenous), arc welding (backhand) and arc welding (forehand).

As 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. Electrode orientation affects the bead shape and penetration to a greater extent than arc voltage or travel speed.

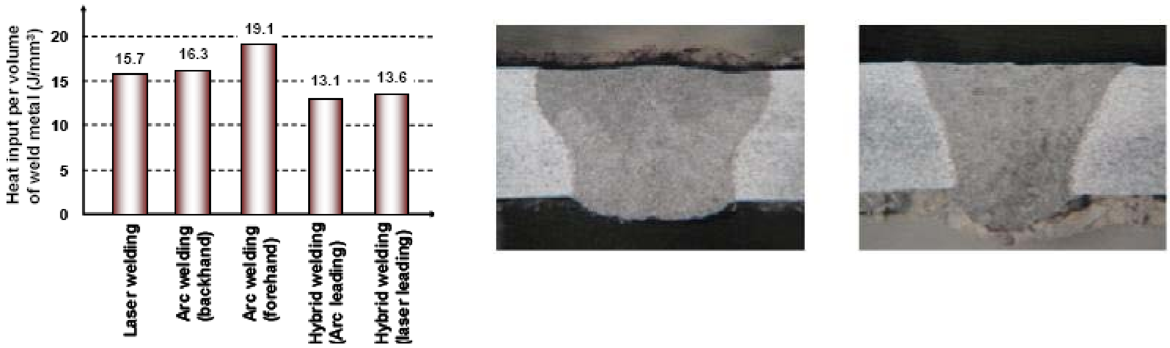

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Fig. 6 Shows the comparison of a) Melting efficiency for different welding processes, and b) resulting weld cross-sections with laser leading and arc leading processes

The result of the influence of the leading process and torch angles was studied with HSLA-590 steel using 2.4 kW CO_2 laser and a 350A GMAW welding machine (presented in Fig. 7) [22]. During trials, the torch angle of 45° or 30° (i.e. angle of the GMA torch from the work piece) and the leading process were changed. The trial with laser leading and torch angle of 30° failed. The torch angle was so small that the distance between the torch nozzle and the specimen was less than the height of the weld bead reinforcement. The torch nozzle hits and moves the deposited metal to other parts. The torch angle of 45–60 degrees from the surface of the specimen has been accepted in many papers [5, 7, 22, 23]. Fig. 7 shows the typical shape of hybrid welds welded bead-on-plate. Since there is no room for filler material, the reinforcement of the weld bead is typically high and the shape of the weld is strongly widened from the top.

The effect of the order of power sources of different laser-TIG hybrid welding processes is similar like the one with laser-MIG hybrid welding, but it also depends on the material and the surface properties. The penetration depth is still dependent on the laser power as shown in Fig. 8 [16] with the following parameters; 10 mm SUS 304 steel, current 100 A, welding speed of 10 mms^{-1}, focus point position 0 mm, torch angle, measured from the workpiece 55°, TIG-YAG (process distance 5 mm), YAG-TIG (process distance 1 mm), the height of the tip of the electrode to the workpiece 2 mm and shielding gas Ar (5.0×10^{-4} ms^{-3}. With non-optimized hybrid parameters the penetration is lower than that with autogenous laser welding.

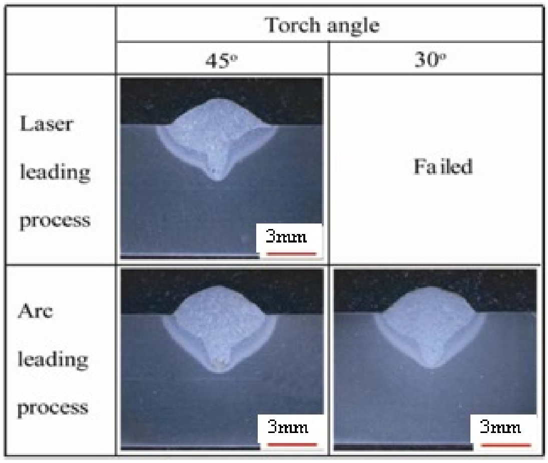

Fig. 7 Influence of the leading process and torch angle; 2 kW laser power, focal point position – 2 mm, MAG current 140 A, voltage 16.5 V and process distance 2 mm

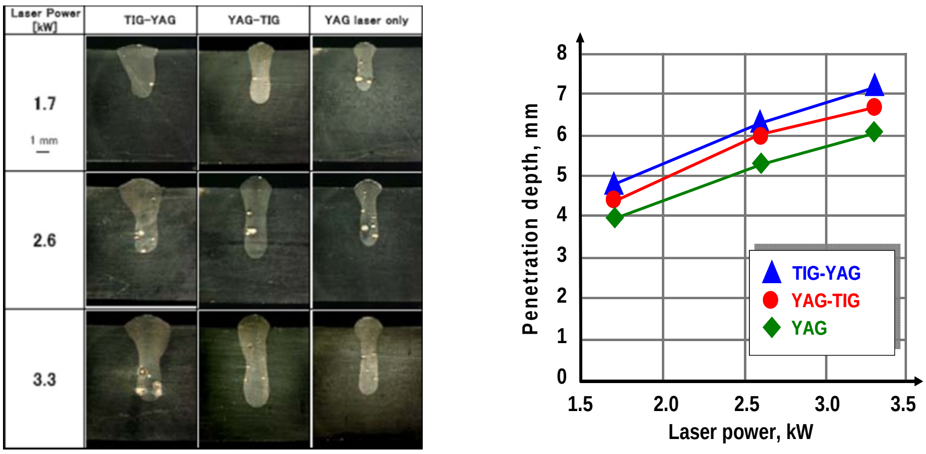

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Fig. 8 Shows the comparisons of a) line energy of different welding processes and b) laser power on the penetration depth of bead-on-plate

Tests about process behaviour with 0.4 and 0.8 mm thick AISI 316L stainless steel sheets with a butt joint configuration have been carried out with TIG welding combined with 4.4 kW DPY laser. The laser melted pool stabilizes the TIG arc. With a leading TIG, the arc is not as stable as with a trailing TIG. Laser trailing welding speeds as high as 15 m/min can be achieved [24]. The laser leading position is most popular in the hybrid welding of aluminium, since through the application of this technique the oxide layer has been removed from the arc attachment point by the laser which results in a significant increase in process stability [14]. The quality of the welds would depend on the different welding parameters, from both laser and TIG.

2.2. Process distance

In comparison, the trailing arc arrangement with small distances to the leading beam is also capable of increasing the efficiency and stability of the laser beam welding process owing to interactions between the laser and the arc within a common process plasma and a modified thermal impact on the material being welded. Applying greater distances, moving towards a tandem process, to the leading laser beam, the post-running variant can be applied to act as a short-time post-heat treatment of the laser weld seam that can favourably change the microstructure and improve the properties of the weld [14].

Naito et al. [25] carried out an experiment with SUS 304 austenitic stainless steel plate (5 and 10 mm) on bead-on-plate welding. A YAG laser equipment (maximum power of 3.5 kW) and a TIG welding machine (maximum current of 300 A) were employed for the experiment. Fig. 9 [25] indicates the effects of the process distance on the penetration depth. TIG-YAG hybrid welding always gave deeper penetration than autogenous laser welding, the deepest penetration achieved with the process distance of 5 mm. By contrast, YAG-TIG hybrid welding reached the deepest penetration with a process distance of 1 mm.

There is a difference between the molten pool formation location due to the arc alone in TIG-YAG hybrid welding and YAG-TIG hybrid welding but, in both cases, when the YAG laser was irradiated onto the moltenpool, easily formed by the action of the arc alone, a deep penetration could be formed, except that all the welds were not fully penetrated welds [25].

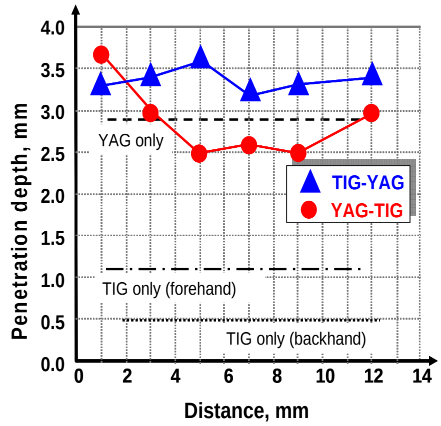

Fig. 9 Effect of distance between the laser beam axis and TIG electrode on penetration depth in Nd:YAG laser-TIG hybrid welding of AISI 304. Thickness 10 mm, I = 100 A, v = 0.6 m/min, focal point position 0 mm, process distance TIG-YAG hybrid 5 mm, YAG–TIG hybrid 1 mm, shielding gas Ar (5.0×10^{-4} m^3/s)

In high power welding the process distance plays an important role. This was shown in an experiment using (400 A/34 V) MAG–CO_2 laser (10 kW) hybrid welding with a 10 mm thick 316L base material. The process distance (arc leading) was found to influence weld penetration: the smaller the distance, the deeper the penetration [8]. The process distance play an important role together with the focal point position and torch direction also in fibre laser-MAG hybrid welding. A leading torch tolerates and even in some cases needs more distance between the processes than a trailing torch. In case of fibre laser hybrid welding and a trailing torch, too long a process distance will causes sagging [26].

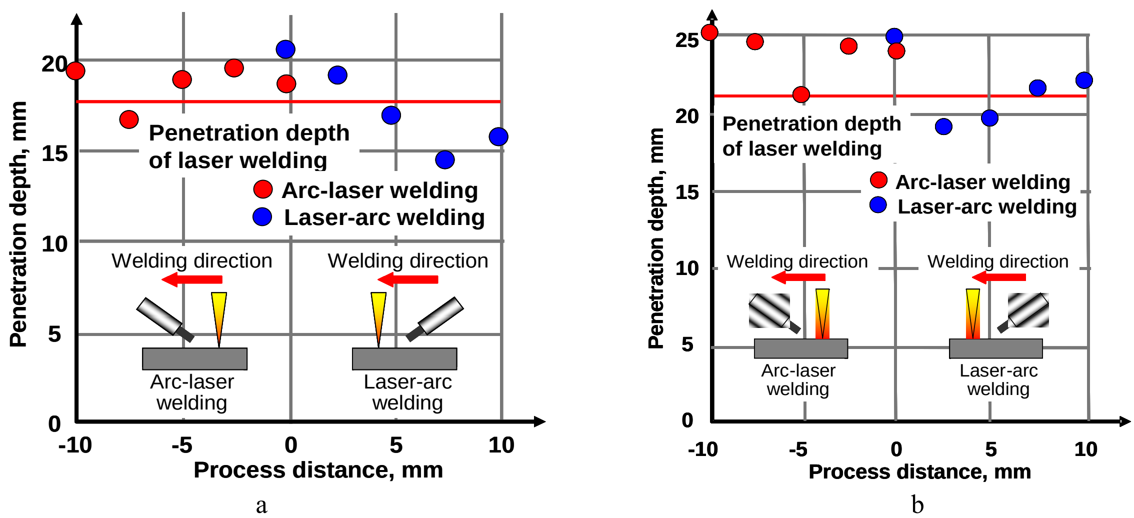

Fig. 10 Effect of process distance on the penetration depths of welds produced in a) a flat position and b) a horizontal position in arc-laser/laser-arc leading hybrid welding with laser power of 30 kW, MIG welding current of 500 A, 47 V and welding speed of 1.02 m/min, bead-on-plate welding

It was reported that the penetration depth in the flat position in both configurations tends to increase with a smaller process distance in case of CO_2 laser and high power of 30 kW. The maximum penetration depth, namely, 2.8 mm greater than the penetration depth found during laser welding alone, was obtained in the leading laser arrangement at a distance of 0 mm in both positions. Fig. 10 [27] shows the penetration depths as a function of process distance. In the leading arc process, the maximum penetration was reached with some distance. The penetration depth in the horizontal position was about 3 mm deeper than in the flat position under all welding conditions. This is due to the effect of gravity in the flat position; it moreover produces an inferior bead shape [27].

If a trailing arc is used, too long a distance between the processes is an even more serious problem. This is because the wire gets stuck more easily into the surface of the solidifying melt pool and, in the worst case, even the whole torch will be twisted due to this, if the pulsing is not correct [5, 6].

3. Conclusions

The basic parameters and their selection are often based on feelings rather than facts. It is obvious, according to the literature review that the decision of the order of processes is made case by case and the decision should be based on the outcome of each process and the system and accessories available. The required throughput time and quality set limits for performance, and the available system (laser beam, material, arc source, the function of filler wire) should be evaluated. The process should then be balanced with regard to the welding speed, wire setting, laser and arc power and process distance. Another important consideration is the workpiece parameters: material, thickness, joint type, edge preparation, joint quality and welding positions. With a leading arc arrangement, gas shielding seems to work better, but a trailing arc gives wider welds with a smoother junction to the base metal.

Joint type consideration should always neglect tests performed bead-on-plate. A butt joint with no air gap should be welded using a leading arc which allows higher welding speeds. With an air gap present, air gap bridging is more effectively achieved by using a trailing arc because of the lower arc power needed, the wider arc, and the movement of droplets towards the joint edges.

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LAZERINIO-LANKINIO SUVIRINIMO SIŪLIŲ SANTYKINIO IŠDĖSTYMO EFEKTAS NAUDOJANT ĮVAIRIUS HIBRIDINIO SUVIRINIMO PROCESUS

R e z i u m ė

Lazerinis-lankinis hibridinis suvirinimas yra pažangus sunkių surinkimo vienetų suvirinimo metodas. Aukštai suvirinimo kokybei pasiekti taikant šį metodą, reikia tinkamai parinkti keletą parametrų. Šių parametrų parinkimas iš dalies priklauso nuo numatomų suvirinimo rezultatų: užvirinimo tarpelio, įvirinamumo gylio, suvirinimo greičio, išsilydymo efektyvumo, proceso stabilumo, siūlės pločio kontrolės, poringumo sumažinimo ir siūlės išvaizdos. Šiame straipsnyje nagrinėjama, kokią įtaką šie veiksniai turi lazerinio-lankinio hibridinio suvirinimo bendrai kokybei.

Tyrimas atliktas naudojant ir įvairių tyrinėtojų grupių literatūros šaltiniuose paskelbtais analizės duomenimis. Detaliai išnagrinėta minėtų parametrų ir įrangos įtaka. Remiantis šia analize gali būti įvertinti ekonominio pagrįstumo ir organizacijos kvalifikuotumo veiksniai.

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THE EFFECT OF THE RELATIVE LOCATION OF LASER BEAM WITH ARC IN DIFFERENT HYBRID WELDING PROCESSES

S u m m a r y

Laser–arc hybrid welding is a promising technique for the welding of heavy sections. To achieve high weld quality with these processes requires several parameters to be properly adjusted. The selection of suitable parameters partly depends on the results desired for welding whether it be gap bridging, penetration depth, welding speed, melting efficiency, process stability, control of the weld width, porosity reduction, or weld appearance. This paper studies how the position of the different sources in laser–arc hybrid welding influences overall weld quality. The aim of the assessment is to make it easier to choose which relative position is appropriate for a specify metal.

The study is based on a critical literature analysis of the results of a variety of publications carried out by several research groups. The effects of parameters and set-up are detailed in the analysis. Especially economic feasibility and quality management factors as the basis of analysis can be assessed.

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ЭФФЕКТ ОТНОСИТЕЛЬНОГО РАСПОЛОЖЕНИЯ ШВОВ ЛАЗЕРНО-ДУГОВОЙ СВАРКИ ПРИ ИСПОЛЬЗОВАНИИ РАЗЛИЧНЫХ ПРОЦЕССОВ ГИБРИДНОЙ СВАРКИ

Р е з ю м е

Лазерно-дуговая гибридная сварка является прогрессивным методом при изготовлении тяжелых узлов. Для достижения высокого качества сварки используя этот метод необходимо правильно подобрать несколько параметров. Подбор этих параметров отчасти зависит от ожидаемых результатов: заполнения шва, глубины проварки, скорости сварки, эффективности проплавления, стабильности процесса, контроля ширины шва, минимизации пороситости, вида шва. В этой статье анализируется, как вышеупомянутые факторы влияют на общее качество лазерно-дуговой гибридной сварки.

Исследование проведено на основе анализа литературных источников различных авторов. Детально проанализировано влияние вышеупомянутых параметров и оборудования. Факторы экономического обоснования и квалификации организации на основе проведенного анализа могут быть оценены.

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