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Publisher's version / Version de l'éditeur:

Proceedings of the 7th International Trends in Welding Research Conference 2005, 2005-05-16

Hybrid laser-GMAW welding of aluminum alloys: a review

D. Rasmussen, L. Dubourg
Aluminum Technology Centre, National Research Council Canada, (Quebec) Canada

Abstract

The combination of laser welding with Gas Metal Arc Welding (GMAW) forms laser-GMAW hybrid welding. This process is an attractive tool with a high potential in welding lightweight structure, especially for aluminum alloys. For five years, this technology has increasingly attracted interest in both, industry (aeronautics, automobile, metal industries producing large structures) and academia (universities and research centers). Laser-GMAW hybrid welding process is generally accepted for its robustness, efficiency and flexibility. Coupling of a deep-penetrating laser beam with the heat and molten metal feeding of GMAW significantly expands the original welding application range of lasers. Its main advantages compared to two individual components are deep and stable weld penetration, gap-bridging ability improvement, low distortion and easy filler metal addition. Hybrid welding allows indeed much wider groove tolerance compared to laser welding, especially for aluminum welding. Moreover, the reduction in distortion decreases the post-welding rectification needed and makes the assembly easier since the hybrid welded parts are more dimensionally accurate. In addition, if metallurgical factors are critical, the weld composition can be balanced with filler metal, decreasing the hot cracking susceptibility of some aluminum alloys. The combination of these two welding processes can also improve the weld bead shape quality (including the elimination of undercut), possibly reduce the porosity and increase welding speed. This article reviews the recent works about the laser-GMAW hybrid welding of aluminum alloys. After a brief presentation on the interaction mechanisms between a laser beam and an electric arc, the paper depicts the typical welding processes and experimental methods along with their characteristics.

1. Introduction

The automotive industry is always searching new ways to reduce weight on their products. To achieve that goal, the use of light alloys like aluminum, has greatly increased in the last few years. Aluminum intensive structures are now being produced for the mass consumption [1]. Staufer *et al.* showed a reduction of up to 43% of the weight of a steel car body by using an aluminum space frame instead [2]. The biggest issues for the vehicle makers are the robustness and the profits that can be realized with such an innovation. Presently Gas Metal Arc Welding (GMAW) and Laser Beam Welding (LBW) are the most common welding processes for mass production because of their high speed and their possibility of complete automation [3]. Comparing the welding of common automotive steels and aluminum alloys with any of the two welding processes, the major issues are the large differences between the properties of the two metals [4, 5]. These differences are: *(i)* the higher thermal conductivity of aluminum that removes heat from the weld zone increasing the possibility of creating the defects incomplete joint penetration and incomplete fusion [4, 6, 7], *(ii)* its higher thermal expansion coefficient that increases distortion [6], *(iii)* its lower solubility of hydrogen in the solid state than the liquid state creating weld porosity [6-8], *(iv)* its larger solidification range that promotes hot short cracking [7] and *(v)* its greater possible evaporation losses of important alloying components such as magnesium and zinc resulting in the loss of weld strength [8]. All of the above weld imperfections are discussed in references [3, 6, 7, 9, 10]. In addition, heat applied to the parent aluminum alloys cause a loss of strength whereas in the case of steel there can be a gain of strength. This loss of strength of aluminum alloys due to welding means that strength of these welds are less tolerant of weld imperfections than in the case of steel [10]. The use of a high energy density welding can overcome some of the defects by increasing the welding speed and thus decreasing the energy input in the components. The combination of both processes (LBW and GMAW) in one hybrid process is known since the 70's and can lead to the advantages of the two processes without their drawbacks [11]. Fig. 1.a illustrates the hybrid laser arc welding principle. It was used for the first time on aluminum only in 1984 [12]. The main goals of hybrid welding are to increase the welding speed, to allow weld bead composition adjustment to enhance weldability, to improve the gap tolerance, to assure high reliability of the process and to produce good seam quality [1, 13]. This paper proposes a state of the art about the coupling of LBW with GMAW on aluminum and its alloys.

2. Fundamentals of Hybrid Laser-Arc Welding

2.1. Interactions between LBW and GMAW

Since the overall process is function of two welding technologies, the hybrid laser-arc welding (HLAW) apparatus is influenced by the contribution of each of the two welding processes. In fact, the HLAW weld geometry is controlled by the energy input of each process as shown in Fig.1.b. An increase in GMAW power leads to an increase in the width to depth ratio of the weld [6, 14-18]. However, the HLAW weld is in most cases more laser-like at the bottom and more arc-like on the top due to the two process contributions. This leads to a more process like overall seam than LBW.

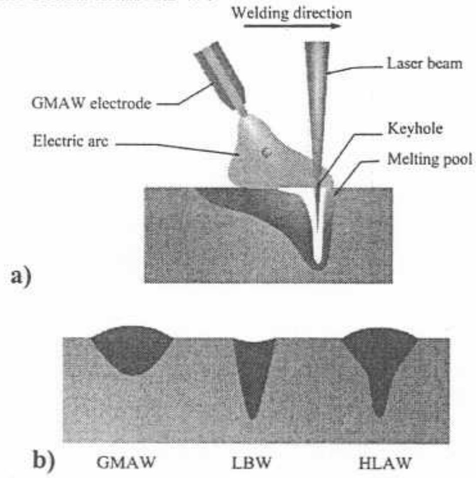

Fig. 1: a) HLAW principle, b) cross section schemes of GMAW, LBW and HLAW.

Since high density laser beam is involved, the HLAW process is characterized in most cases by a keyhole formation. However, a conduction-like process without keyhole formation is achieved when the laser is used out-of-focus or has insufficient power. At the start point of LBW, the laser beam absorption by the aluminum surface can be as low as 10% when using a Nd:YAG laser [14, 16]. When the metal is molten, absorption greatly increases. Afterwards, when the keyhole state is achieved, the laser power is used at almost 100% for the melting process due to the multi reflection phenomenon inside the keyhole. It has been confirmed that GMAW arc stability is increased when it combines with a laser beam [11, 17]. To acheive this enhancement, the arc must be close enough to the laser beam so they share the same fusion pool. As the liquid aluminum has a lower electrical resistance than the solid state or the oxide layer, the electric arc would favored the less resistant path, therefore the arc is stabilized in the same fusion zone as the laser process [11, 17]. Moreover, an interaction occurs between the keyhole plasma and the arc plasma that increases also the arc stability. In fact, the energy from the laser keyhole generates a metal plasma, which ionizes the gas from the GMAW process and makes it easier to strike and stabilize the arc via this plasma [6, 17, 19]. The HLAW arc has then a higher electrical conductivity, a finer geometry and an increase in the current density up to five times for a lower arc burning voltage compared to the GMAW arc [6]. On the other hand, as the metal plasma comes from the base metal and from the filler in HLAW, there is more metal vapor than in LBW. This subsequently facilitates the keyhole appearance, the laser irradiation input and prevents process dropout [14, 16]. The penetration is subsequently increased compared to LBW due to the facts that higher plasma pressure is available and that laser power is not used to melt the filler wire. As for the larger molten pool of the arc process, the seam is in the liquid state for a longer time in comparison with LBW. This is an advantage compared to LBW because of the high solubility of hydrogen in liquid aluminum. Therefore, the lower solidification rate of the seam gives hydrogen bubbles more time to escape from the molten pool, which can result in a reduction of the porosities [8]. The Fig. 2 illustrates this porosity difference between LBW and HLAW. The filler addition in HLAW has the same effects as in conventional welding processes. For aluminum alloy welding, the filler is mainly used to prevent hot cracking by adjusting the weld bead composition to be outside the high crack sensitivity region [6, 20]. Nevertheless, the mixing of the filler metal with the base metal is different to the GMAW process. As shown in Fig 1.a and 1.b, HLAW molten pool can be simplified by the sum of a deep and narrow laser-like molten pool and a wide and superficial arc-like molten pool. The understanding of mixing phenomenon between the two molten pools is then important to prevent hot cracking. In this way, Zhou *et al.* showed that larger droplets increase the heat input into the molten zone, increasing the solidification time and hence the mixing of the filler metal and the base metal. However, because of the high kinetic energy of the large droplets, a deep hole can be formed [20]. Zhou *et al.* also found that an increase in droplet frequency and a decrease in droplet size lead to an increase in the transversal mixing and a decrease in longitudinal mixing of the filler. Moreover, the impingement points of the laser and the arc should be separated by a maximum of 0.6mm in order to assure a correct weld homogeneity [20]. Nevertheless, changing to GMAW leading process instead of laser leading could increase the distance.

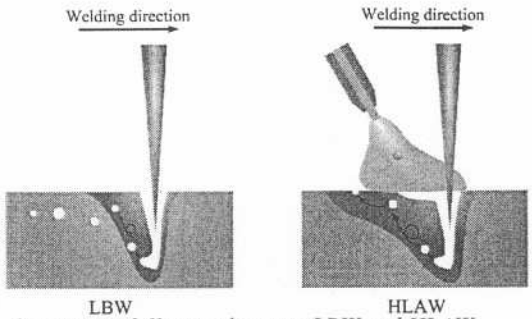

Fig. 2: porosity difference between LBW and HLAW.

As it was generally adopted in the literature, HLAW is characterized by a synergy of the two processes. As discussed previously, interactions take place between the two processes leading to combine effects greater than the sum each process alone [6, 17, 19, 21-23]. The linear energy input for GMAW is between 200 and 300 kJ.mm^{-1}. The linear energy input of HLAW can be as low as 100 kJ.mm^{-1}, which means a reduction of 2 to 3 times of energy needed [6]. Moreover, depending on the welding parameters that will be discussed later, Lee and Park have found that average volumetric energy of molten aluminum is 15.7 J.mm^{-3} for LBW, 17.7 J.mm^{-3} for GMAW, and 13.35 J/mm^{3} for HLAW [24]. This means hybrid welding needs less input energy to melt the same metal volume than GMAW or LBW, showing a higher efficiency.

2.2. Advantages and drawbacks

Because of the synergy occurring between the two welding processes, there is more advantages then drawbacks. Advantages can vary depending on the welding parameters used, the aluminum alloy and the joint type. First of all, an increase in the welding speed is reported by the majority of the authors [6, 11, 13-18, 23, 25-30]. For example, butt joint welding speed of 2-mm thick extrusions of A6063-T5 alloy can be increase from 0.95 m.min^{-1} (GMAW) or 3 m min^{-1} (LBW) to 5 m min^{-1} by using HLAW [9]. Hybrid welding improves also the penetration of the weld seam [6, 14-16, 25, 26, 28, 31-33]: typical increases are 10-20% compared to LBW [15] and 20-50% compared to GMAW [32]. Moreover, many studies recognize an enhancement of aluminum welding stability in comparison to LBW or GMAW, due to the useful interactions of the two processes [15-17, 19, 23, 26, 29, 32, 34]. Furthermore, heat input applied on the piece is lower due to high energy density and high speed of HLAW [6, 16, 18, 19, 21, 26]. Lowering the heat input directly decreases the distortion of the welded components. Since GMAW produces a large welding seam, HLAW increases the gap bridging in comparison with LBW [6, 13, 14, 16-18, 24-26, 28, 35]. In some cases, HLAW can increase the GMAW gap bridging by 0.14 mm increasing from 1.05 to 1.19 mm [24], while autogenous laser welding has a maximum gap tolerance of around 0.3 mm (Fig. 3). Another advantage of the combine process is the better wire feed misalignment tolerance in comparison with LBW [16, 23, 25, 28, 34]. Since HLAW uses the wire welding by the arc and wire does not have to intersect the fine laser spot size and the small weld pool, the addition of filler material is easier than with cold wire fed LBW [6, 13, 15, 17]. The component distortion reduction, the gap bridging enhancement, the wire misalignment tolerance increase and filler application are four important aspects when automation of the welding is done. As a matter of fact, these four advantages increase the robustness of HLAW for industrial applications compared to LBW or GMAW. From the economical point of view, the HLAW use can lower the capital investment through the reduction of the laser power. By coupling the GMAW apparatus with the Nd:YAG laser beam, it is possible to reduce the laser power by at least 1 kW [16], and as much as 2 kW [2, 9, 14]. In terms of cost, this could result in a reduction of \$130 000 USD to \$260 000 USD on the initial investment of the laser system. The investment for the GMAW apparatus is around \$40 000 USD, consequently, the overall investment reduction can reach up to \$220 000 USD. The operation costs are reduced too. With the hybrid apparatus, the electric energy consumption can be reduced by approximately 35kW per kW of laser power in comparison with LBW [14, 16, 17]. In fact, the electrical efficiency of the GMAW system can reach 80% [13, 36] while the Nd:YAG lasers efficiency are as low as 3% [16]. Moreover, in some cases, the higher welding speed of HLAW reduces production time, hence, the cost of each component [6, 26]. Another advantage is the space reduction. To attain the same productivity with alternative welding techniques, it would require more machines and a large number of welding heads [27]. Also, a product of greater quality can achieve economical advantages. From the metallurgical point of view, the high energy density and high speed, thus low heat input increases considerably the metallurgical properties of the welded components. The most significant increases in the Al alloy properties are the higher seam toughness [18, 23, 26, 29], higher seam hardness [23, 29], lower residual stresses and distortion of the components [6, 16, 17, 19, 27], lower porosity content [23, 29] and greater ductility [14] than laser weldment.

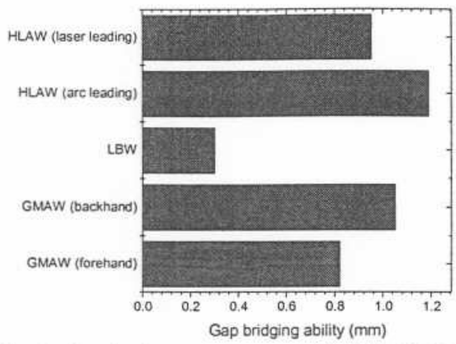

Fig 3: Gap bridging capacities of LBW, GMAW and HLAW (A6061-T6, 2 mm thickness, butt joint, welding speed of 3 $m.min^{-1}$ and welding current of 48A) [24]

Even though the advantages outnumber the drawbacks, there are still issues to overcome. First of all, since the molten zone on the weld top is increased by the arc process, the molten zone and heat-affected zone are greater in HLAW than in LBW [32]. Secondly, as the molten zone is increased, it is more difficult to shield the weld surface effectively and coupled to the high temperature reached by HLAW leads to higher hydrogen absorption. Third, in some cases, the bead appearance was poorer than the one made by GMAW only, mainly because of a rougher bead waves as a result of weld pool instability [33]. Fourth, some of volatile alloying elements e.g. Mg can be vapōrized because of the high heat in the keyhole and lower weld strength. This can be partially compensated by suitable filler adding [37]. Fifth, aluminum and its alloys have a poor ability to support the liquid metal due to its low surface tension. Consequently, the large amount of liquid metal in HLAW compared to LBW can involve difficulties during the full penetration welding of butt joint [21]. Finally, the number of welding parameters in HLAW increases compared to GMAW or LBW and makes the hybrid welding a more complex process to operate. The success of HLAW necessitates an understanding of the interactions of the two processes in order to attain adequate capabilities and reproducibility, i.e. to make the process robust.

3. Study of hybrid laser-GMAW welding

3.1. Study of laser parameters in hybrid laser-arc welding

LBW is a high density power welding that requires precise adjustments and edge preparation [3, 13, 38, 39]. The main advantages of LBW are the high welding speed [3, 20, 40] and the low heat input on the components that result in a narrow heat affected zone and a low distortion of the parts [6, 11, 13, 20, 35]. However, LBW is characterized by difficulties of alignment and gap of components to weld and deviation of the laser beam itself, mainly with the robot use. The filler wire used for aluminum welding can overcome these drawbacks, improving the seam appearance and the resistance to hot cracking [39]. Nevertheless, a great problem is the melting of 0.9 to 1.2 mm diameter filler wire with a laser beam focus of for example 0.6 mm diameter (case of a Nd:YAG laser beam carried by a 0.6 mm optical fibre and focusing with a 1-ratio focus). Consequently, the wire filler use with LBW needs great and rigid adjustments. Moreover, the use of laser power to melt the wire can lead to a decrease in the welding speed in the range of 20% [35]. HLAW is therefore a great interest for the melting of the wire metal and, consequently, the laser power can be totally used for the welding at high speed. HLAW has a large amount of variables to consider and one of them is the type of laser used.

3.1.1. Type of laser

The type of laser used in HLAW can greatly affect the process. Keyhole condition is preferred for laser welding except for very thin parts. However, conduction condition can be useful in certain cases, event for larger section components [37]. The two major laser types used for aluminum welding are Nd:YAG solid state and CO2 gaseous state laser. Two other types are Nd:fiber and high power diode laser (HPDL). The first three laser devices will be discussed in the following paragraphs, while the last one (HPDL) will be discussed in section 3.1.2. The main difference between Nd:YAG and CO2 laser is their respective beam wavelengths; 10.6 µm for the CO2 laser and 1.06 µm for the Nd:YAG laser [41]. Aluminum absorptivity is around 2-4% for a 10.6-µm wavelength beam and it is twice at 1.06 µm [12]. Consequently, the laser irradiation intensity needed for keyhole initiation is approximately twice for a CO2 laser than a Nd:YAG laser [37]. Moreover, the 10.6-µm wavelength beam is larger absorbed in great proportion by the plasma created by the keyhole [11, 42, 43]. Therefore, the CO2 laser beam is partially blocked by the plasma. In order to minimize this effect, the use of high potential ionization gas like helium has been tried with limited success [42-44]. In the case of Nd:YAG laser, the beam is not influenced by the plume. Even if, CO2 laser has a greater electrical efficiency and lower operating cost at same laser power, the Nd:YAG laser has a greater processing efficiency mainly due to this enhanced coupling to reflective metals [37]. Nd:YAG laser beam radiations can be also propagated over long distances through optical fiber with minimal losses [2, 37, 45]. Therefore, the CO2 laser requires expensive CNC device with rigid arms that guide the laser beam with optical mirrors [45]. Nevertheless, CO2 laser can be scale to higher powers (e.g. 8kW), while Nd:YAG laser is limited to 4 kW [46]. For all these reasons, Nd:YAG laser is preferred over CO2 laser for the welding of aluminum and its alloys with an HLAW apparatus. Different ways exist to generate a Nd:YAG high energy beam. This can either be generated by flash lamp or diode laser pumping. The diode pumping can be applied to rod (diode pumped Nd:YAG) or to fiber (fiber laser or Nd:fiber). Both diode pumped laser sources have a comparable beam quality, which is significantly better than conventional flash lamp pumped laser source [15]. A better beam quality leads to a lower heat input that directly minimizes the thermal distortion [37]. For example, comparison of the welding speeds for a given penetration was done by Vollersten et al. with an autogeneous welding at 4 kW [15]. To obtain a 4-mm penetration, the lamp pumped laser welding speed is 1 m min-1 whereas the diode pumped laser can weld at a speed of approximately 2.5 m.min-1. In the last case, high power diode laser (HPDL) implies a lower investment cost [3], a higher electrical-optical conversion efficiency (around 50%) [37], an average power extending to 4kW and a strong space reduction. However, the major drawback of HPDL is the thick beam waist and hence cannot be used other than for aluminum conduction welding. HPDL can therefore have great utility for aluminum welding when coupled with GMAW and will be discuss in the section 3.1.2.

3.1.2. Out of focus length of the laser beam and spot size

Most of the studies about aluminum HLAW concentrated their efforts on keyhole formation, the laser beam focus point being directly on the surface [25, 31] or slightly inside the material (about 1 mm) [41]. Other studies had purposely increased the beam spot diameter from 1.09 mm to 6.92 mm to study the hybrid welding in conduction mode with a Nd:YAG laser [1, 3]. Thong *et al.* showed that even with 1.09 mm beam spot diameter, keyhole formation was not observed and bead appearance was reasonable. Hence, keyhole mode is not essential in aluminum and its alloys welding [3]. Tong *et al.* also reported that with an increase of the beam spot diameter resulted in an increase in the torch aiming deviation as shown in Fig. 4 [3]. This improvement can be explained by the increase of deposit metal wettability with the increase spot diameter. Moreover, as the laser radiations do not penetrate inside the material in conduction mode, less perturbation were observed, and therefore conduction welding is less susceptible to gas entrapment. Indeed, porosities in the keyhole regime can result from the sporadic closure of the keyhole [37]. Even with a large beam diameter of 6.92 mm, a synergetic phenomenon was found: the HLAW heat input was 16-20% superior than the sum of LBW and GMAW. Thong *et al.* stated that laser beam diameter had only little effect on the heat input in conduction condition [3]. Jokinen *et al.* also found that a smoother weld bead was achieved when the power density is decreased. However, the welding speed decreases as well [31]. Due to the speed reduction, laser beam with large focus point as well as HPDL can be utilized when it is coupled with appropriate GMAW apparatus for the welding of thin aluminum alloys plates (i.e. below 2 mm) [1]. In fact, the laser beam is used to preheat the thin aluminum surface and thus stabilizes the AC pulsed GMAW process at high speed (4 m.min^{-1}) which is discussed in section 3.2.1 [1, 3].

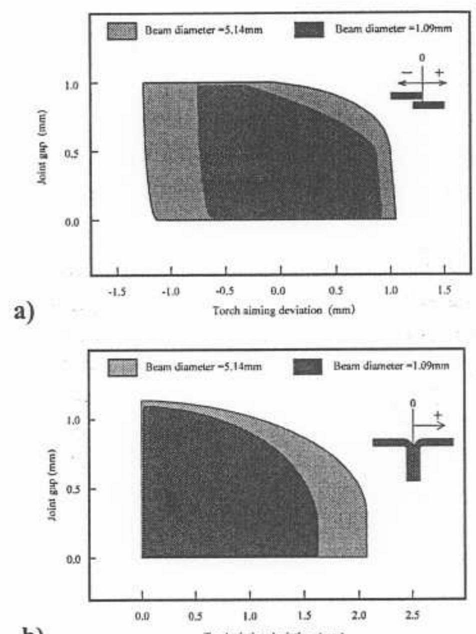

***Fig. 4**: Gap bridging and aiming deviation vs. beam diameter for: a) lap joint configuration and b) flare bevel joint configuration. Courtesy of Thong et al. [3]*

3.1.3. Welding speed

HLAW tends to increase the welding speed with increasing gap, which is opposite to LBW. In fact, the welding speed is significantly increased when the gap size is 0.6 mm or larger, which lowers the heat input in the components. HLAW with 0.6-mm gap or larger compared with autogenous laser welding showed a welding speed increase of 200% for AA5083 (Al Mg4.5 Mn0.7), in 5-mm butt joint configuration. The welding speed at 0.0-mm gap was 1 m.min^{-1} whereas it reaches 3 m.min^{-1} for a gap of 0.6 mm [25]. The gap imposition should be done very precisely and should not be oversized, which can cause the laser to go through the gap.

3.2. Study of gas metal arc welding parameters in hybrid laser-arc welding

Compared with LBW, GMAW has an inferior energy density, around 10^4 $W.cm^{-2}$, which is lower by two orders of magnitude [14, 47]. However, GMAW is still an attractive welding process, mainly due to its low investment cost, high electric efficiency of around 80% [13, 36], great ability to gap bridging, misalignment capabilities and the relative ease of filler metal application [16, 21]. Nevertheless, for the welding of aluminum thin sheet, DC GMAW encounters difficulties such as burn through, formation of holes and low gap tolerance. On the other side, AC GMAW can solve these problems with fine regulation of the electrode negative (EN) ratio [3]. However, insufficient penetration problem arises at welding speeds higher than 2 $m.min^{-1}$ [1, 3]. Since the energy density of the GMAW is lower than LBW on, the seam width tends to increase, which introduces a great amount of heat into the pieces, causing a weld distortion that has to be rectified [13]. The majority of the difficulties in both LBW and GMAW can be overcome with coupling the two processes in one HLAW process. The arc process compensates the difficulties of wire feeding in LBW, while laser beam compensates the low penetration and welding speed in GMAW. However, since two processes are implied, the numbers of parameters are greatly increased. Hence a better knowledge of HLAW is required.

3.2.1. Polarity and power of GMAW

Direct current electrode positive (DCEP) is the most employed setting for aluminum GMAW. Positive polarity is useful to remove the non-conductive oxide film on aluminum alloys [48, 49]. The arc is more stable and axial spray transfer is easier to obtain, compared with direct current electrode negative (DCEN) [8, 48, 49]. DCEP can be pulsed, which can lower the average power, hence the heat input in the components. GMAW can be used in alternative current mode (AC), which changes polarity each half cycle and therefore, lowers the heat input in the pieces because the arc is extinguished and reinitiated each half cycle. Each of the two modes, DCEP (pulsed or not) and AC has its advantages and is complementary when coupled with a laser beam. In fact, the DCEP mode is more efficient in HLAW for the welding of 3-mm thickness and higher [1, 3], while the AC mode can improve the welding of thicknesses below 3 mm [1, 3, 50]. Jokinen *et al.* found that the keyhole is disturbed when an excessive arc voltage is used. In fact, the authors obtained the deepest penetration using the arc voltage suggested by the GMAW machine with synergy control [31]. The study was performed on Al Mg3 alloy of 4-mm thickness with a butt joint configuration including a 0.8-mm gap and with a 3 kW Nd:YAG laser leading. Diebold *et al.* reported that the arc intensity in HLAW affects significantly the weld seam: sensitive response of the pulsed arc happened with small variation in laser parameters [13]. Moreover, the increase of current decreases the porosity in the weld [28]. These experimentations were performed on 3-mm and 4-mm thickness A5052 alloy plate, with Nd:YAG laser of 3.1 kW and varying speeds. The X-ray inspection reveals a decrease in the porosity level with a GMAW current varying from 0 to 240A for plates of 3 mm and 4 mm with speeds of 2.4 and 4.8 $mm.min^{-1}$. As a matter of fact, for both thicknesses and speeds, porosity was not found at 240 A. Uchiumi *et al.* explained that the molten pool could be easily depressed with increasing the GMAW current because the molten pool becomes larger and longer [28]. For components thinner than 3 mm, DCEP can lead to burn through [3]. However, AC mode can solve this problem with HLAW. For this purpose, the laser beam leads the arc and preheats the joint before the AC GMAW welds the components [1]. When adjusting the electrode negative ratio, it becomes possible to melt enough filler metal with relatively low arc force [1, 3]. The lower arc force also helps to increase the stability of the arc [3]. Since the laser beam only acts as a preheating source, it is not necessary to use a high power nor a small focus diameter. In fact, Tueyama *et al.* used a defocused laser beam coupled with an AC GMAW device to weld A5052 sheets of 1.2-mm on 1.5-mm thickness in lap joint configuration at speed of 4 $m.min^{-1}$ [1]. These authors obtained also good results up to 1-mm gap. The defocused beam could be a HPDL, which is cheaper and extremely smaller than Nd:YAG laser.

3.2.2. Shielding gas of GMAW

The gas used influences the beam-aluminum interaction in LBW and influences the arc voltage and stability in GMAW [6, 48]. Therefore, the gas has a great influence in HLAW. As it is reported in the section 3.1.1, the absorption of the beam irradiation by the plasma can be neglected for a Nd:YAG laser, while the beam of a CO_2 laser is blocked partially by the plasma. As aluminum is a very reactive metal, inert gas is required: even small amount of reactive gases such as oxygen can lead to smutting problems [8]. The most commonly used shielding gases are argon and helium. The main differences between these two gases are the ionization potential, the density and the cost. Helium has higher ionization potential than argon, respectively 24.46 eV and 15.68 eV [41]. However, argon is denser than helium and thus needs lower flow rate for the same shielding. In addition, argon is less expensive than helium, which again lowers the operation costs. Nonetheless, helium is used with a CO_2 laser because of its high ionization potential, minimizing the absorption of the laser beam by the plasma. On the other hand, when the welding is done with a Nd:YAG laser, argon is advised as it is less expensive and the plasma does not affect the Nd:YAG beam. The gas used greatly affects the arc behavior in HLAW. The use of helium can increase the arc voltage by 20%, which increase the heat input on the components, hence the penetration [8, 51]. On the other hand, the use of argon stabilizes the arc in comparison with helium. Hu reported that helium has a higher breakdown voltage than argon for both electrode polarities, which could be related to the heat conductivity of the gases [52]. However, a preliminary mixture of the two gases can be used to accommodate the laser beam and the electrical arc for different needs.

3.2.3. Set-up of HLAW

The setup of the two processes are greatly influenced by the material properties and the joint configuration [23, 29]. Fig. 5 shows the schematic set-up of the hybrid system.

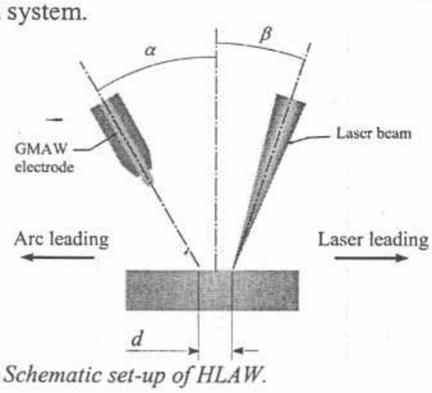

***Fig. 5**: Schematic set-up of HLAW.*

The high reflectivity of the aluminum surface implies an angle *(β)* between the beam and the normal to the surface to avoid the direct beam reflection inside the laser head that can damage the optical fiber [42]. Nevertheless, the laser beam must be as perpendicular to the surface as possible to assure a deep penetration. Moreover, the angle *(α)* between the arc and the normal to the surface and the angle *(β)* must not be equal so that the beam reflection does not interfere with the GMAW process [1]. Ueyama *et al.* showed the best results with an opening angle of 45° between the laser and the arc. They used an angle *(β)* of 30° while the angle *(α)* is 15° [1]. However, many studies did not take into account the damage risk of the optical components and thus, utilized the laser beam perpendicular to the surface. These studies found different optimum angles *(α)* that vary from 15 to 30° [23] and from 20 to 30° [13, 28, 29]. The distance *(d)* between the impingement points is an important parameter and affects strongly the HLAW synergy (see Fig 6.a and 6.b).

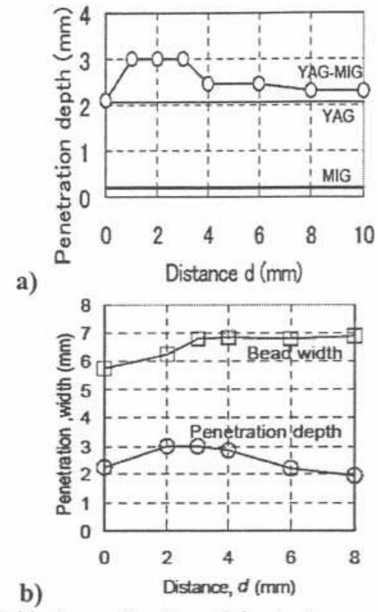

***Fig. 6**: Weld size as function of the impingement distance (d). Welding parameters: butt joint configuration, A5052 sheets of 3-mm thickness, welding speed of 2.7 m.min^{-1}, laser power of 3.1 kW (Nd:YAG). The arc current was respectively 120A and 180A for Fig. 6.a and 6.b. Courtesy of Uchiumi et al. [28].*

In fact, too close coupling results in keyhole disturbance by the arc that decreases the penetration [21, 28, 31, 42, 43]. On the other hand, if the distance increases so that each process has its own molten pool, the penetration decreases also due to the synergic loss [21, 28, 31, 42, 43]. These last phenomena are true for both the arc leading and the laser leading. Depending on the welding parameters, the optimum distance between the two processes is around 2 to 3 mm [25, 42]. Fig 6.a shows the influence of the distance *(d)* on the penetration in comparison with LBW and GMAW [28]. When the laser and the arc are too close ($d < 1$ mm), the penetration becomes the same as LBW due to the keyhole disturbance. Alternatively, when the distance is too large ($d > 4$ mm), the HLAW penetration becomes almost the same as the LBW. The small difference of penetration observed for the values *(d)* higher than 4 mm can be explained by the arc heating due to the low power density of GMAW and the high heat conductivity of aluminum. However, Uchiumi *et al.* found a correlation between the distance *(d)* and the arc current: the distance *(d)* needed for the highest synergy (deeper penetration) increases with the current increase [28]. When the welding is done at 120A, 180A and 240A, the respective optimal distances were 2, 3 and 4 mm. In the same way, Fig. 6.b shows the influence of the distance *(d)* on the penetration and the bead width [28]. The bead width is increased when *(d)* is lower than 3 mm and the laser and the arc share the same molten pool.

The welding direction or the process leading (laser or arc, see Fig. 5) does not greatly affect the HLAW. In fact, the studies prove the synergy in both case and only a small difference on the penetration can be observed [28, 42, 49]. At constant arc current, the penetration increases for arc leading as shown in Fig. 7.a [43]. However, when the distance *(d)* is constant, the welding direction giving the highest penetration evolved with the arc current (see Fig. 7.b). Uchiumi *et al.* [28] found, like Hu [52], that penetration increases with arc leading for low arc current ($I < 120A$), while penetration increases with laser leading for high arc current ($I > 120A$).

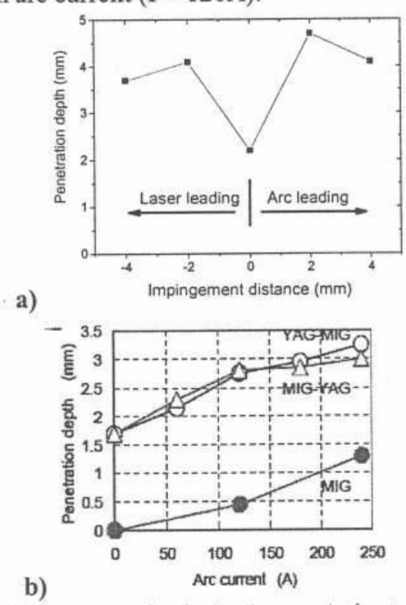

***Fig.** 7: Penetration depth (mm) vs.: a) the impingement distance and the process leading, laser power of 3kW, arc intensity of 140A, arc voltage of 24V and welding speed of 1m.min^{-1} [43], b) the arc current and the process leading, courtesy of Uchiumi et al. [28].*

On the other hand, Zhou *et al.* found a poor mixing of the filler/base metal when the distance *(d)* is 1 mm or more. They state that the droplet must impinge where a lot of liquid metal is present, hence at approximately 0.6 mm from the laser beam [20]. However, this study has been done with laser leading. Therefore the element mixing can be improved by arc leading as the laser imports the filler all around the keyhole as shown by Lee *et al. [24]*. Fig. 8 shows the input energy per volume of molten material for LBW, GMAW (backhand and forehand) and HLAW (arc and laser leading). The arc leading allows a slightly higher energy efficiency (13.1 J.mm^{-3}) than laser leading (13.6 J.mm^{-3}). The same authors also found that porosity level was decreased in the case of arc leading [24]. This enhancement can be explained by the arc cleaning.

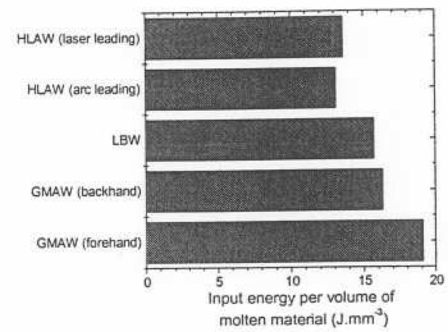

***Fig 8**: input energy per volume of molten material for LBW, GMAW (backhand and forehand) and HLAW (arc and laser leading). Welding parameters: butt joint configuration, A6061-T6 sheets of 2-mm thickness, welding speed of 3 m.min^{-1} and welding current of 48A [24]*

5. Conclusions

(i) Because of the synergy phenomena, aluminum HLAW can attain the advantages of LBW and GMAW without their drawbacks. Moreover, the welding speed, the component distortion and mechanical properties can be enhanced. However, the higher number of parameters increases the complexity of the process.

(ii) For aluminum welding, Nd:YAG laser is advantageous because the beam can be propagated through optical fiber and weld plume does not interfere with the beam. The welding of thin sheets (thicknesses below 3 mm) can be done with a large laser beam (defocused Nd:YAG laser beam or HPDL beam) and alternating current power source, while the welding of sheets thicknesses of 3 mm and higher have better results with the use of DCEN (pulsed or not) with small focus laser beam.

(iii) Gap bridging can be augmented compared to autogeneous laser welding and can, sometimes be higher than GMAW.

(iv) Arc leading process increases the penetration for small arc current while laser leading increases the penetration for higher arc current. Gas used can be adapted to any needs; while argon stabilizes the arc, helium increases the arc voltage and therefore a mixture of the two can be made to attain the protection and arc voltage needed.

(v) Laser welding plan can easily upgrade to hybrid and thus increase the production time and metallurgical properties.

(vi) Future research should be focused on better control of the process and better understanding of the physical phenomenon occurring in HLAW, such as

the mixing of the filler wire, angle of the heads and solidification rates of the weldment.

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Laser-GMA hybrid welding of aluminium alloys: a review

Statut du document Général

Types de document

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Laser-GMA hybrid welding of aluminium alloys: a review

D. RASMUSSEN[a], L. DUBOURG[a, 1]

[a] Aluminium Technology Centre, National Research Council Canada, 501, Boul. de l'Université, Saguenay (Québec) G7H 8C3 Canada,

[1] Corresponding author: Tel. +1 418 545-5098; Fax +1 418 545-5345
E-mail: laurent.dubourg@cnrc-nrc.gc.ca (L. Dubourg)

Abstract

Laser-GMA hybrid welding is formed by combining the laser welding with the gas metal arc welding. This technique is an attractive tool with a high potential in welding lightweight structure, especially for the aluminium alloys. For five years, this technology has increasingly attracted interest in both industry (aeronautics, automobile, metal industries producing large structures) and academia (universities and research centres). Laser-GMA hybrid welding process is generally accepted for its robustness, efficiency and flexibility. Coupling of a deep-penetrating laser beam with the heat and molten metal feeding GMA significantly expands the original welding application range of lasers. Its main advantages compared to the conventional welding methods are deep and stable weld penetration, gap-bridging ability improvement, low distortion and easy filler metal addition. The hybrid welding allows indeed much wider groove tolerances compared to laser welding, especially for the aluminium welding. Moreover, the reduction in deformations decreases the post-work needed and makes the assembly easier since the hybrid welded parts are more accurate. In addition, if metallurgical factors are critical, the weld composition can be balanced with filler metal, decreasing the hot cracking susceptibility of aluminium alloys. The combination of these two welding processes can also improve the weld bead shape quality (including the elimination of undercut), reduce the porosity and increase welding speed. This article reviews the recent works about the laser-GMA hybrid welding of aluminium alloys. After an introduction on the interaction mechanisms between a laser beam and an electric arc, the paper depicts the typical welding processes and experimental methods along with their characteristics. Finally, the emerging applications of hybrid process in aluminium alloy welding are discussed. Recent works have spurred a number of very interesting applications. Described examples include front door, frame part, cast materials, shipyard components and other products.