

Hybrid Laser Arc Welding

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HYBRID LASER ARC WELDING (HLAW), also known as laser hybrid welding or simply hybrid welding, is a metal joining process that combines laser beam welding (LBW) and arc welding in the same weld pool. The concept of HLAW was first introduced in the 1970s as “arc-augmented laser welding” that combined LBW with gas tungsten arc welding (GTAW) (Ref 1). Since then, arc processes including GTAW, gas metal arc welding (GMAW), and plasma arc welding have been used; however, GMAW has become the most popular arc process for HLAW. Historically, high-power continuous-wave lasers such as carbon dioxide (CO₂) gas lasers and solid-state neodymium-doped yttrium-aluminum-garnet (Nd:YAG) lasers have been used for HLAW. With advancements in the performance of other solid-state technologies, fiber lasers, thin-disk lasers, and semiconductor diode lasers are increasingly used for HLAW.

Advantages and Limitations

Advantages. Hybrid laser arc welding is a high-productivity welding process that typically combines GMAW with LBW in the same weld pool. This process is used with mechanized or automated welding applications. These process combinations result in a synergy that incorporates the benefits of each individual process. Hybrid laser arc welding can offer the following advantages:

- The high energy density from the laser process can provide deep weld penetration and high processing speeds.
- With appropriate parameters, HLAW can be performed in all welding positions.
- Hybrid laser arc welding can provide lower heat input and less distortion than conventional arc welding.
- Hybrid laser arc welding can produce narrow welds with small heat-affected zones.
- Because of the deep-penetration capability, HLAW can enable less filler-metal usage for a given material thickness or reduce the number of passes required for a multipass joint.
- Filler material from the GMAW process can provide alloying additions and joint filling that is not possible with autogenous laser welding.

- Hybrid laser arc welding has a greater tolerance to joint gaps than autogenous laser welding.
- The laser component of the HLAW process can maintain a consistent weld pool at high processing speeds and reduce weld humping.
- Hybrid laser arc welding is applicable to a wide range of metal alloy systems.
- For reactive metals such as titanium and zirconium, the laser can provide stabilization of the arc welding process.
- Full-penetration HLAW can be performed without a backing material or consumable insert. In some cases, full-penetration HLAW of steel can be performed without root shielding gas.
- Because HLAW is an automated process, precise welds (relative to alignment, width, and penetration) can be obtained.

Limitations. Although HLAW is a productive and advantageous welding process, there are certain limitations that restrict its use:

- Precise alignment and strict part fit-up are required to maintain weld consistency and quality with HLAW.
- Hybrid laser arc welding is only used in mechanized or automated applications.
- Because of the small focal spot diameter of the laser beam, thick-section butt joints with a gap exceeding 1 mm (0.039 in.) are difficult to weld with the HLAW process.
- Due to the low heat input and fast cooling rates produced by HLAW, mechanical properties of the as-welded condition may, in some cases, be poorer than mechanical properties from arc welding processes with higher heat inputs.
- Although combined laser arc processing has been studied for decades, the HLAW process has had limited implementation in production manufacturing until recently. This short history may be an obstacle for implementing HLAW in applications already using established welding processes.
- Due to the expensive laser equipment, capital cost for HLAW systems can be 10 to 50 times higher than conventional automated GMAW systems.
- Compared to conventional arc welding processes, additional safety measures are necessary with HLAW to protect personnel from laser hazards.

Applications and Operating Modes

Hybrid laser arc welding can be used to weld a wide range of metals, including steel, stainless steel, nickel, titanium, aluminum, copper, and other alloy systems. With the high-productivity advantages of HLAW and the broad range of alloys that can be welded, many industries currently using GMAW or submerged arc welding (SAW) could benefit from hybrid welding. The HLAW process is suitable for applications where a productivity increase can justify the high capital cost of an automated hybrid welding system. These can be high-volume production applications or low-volume applications that require an extensive amount of welding. The HLAW process can increase productivity by providing faster processing speeds or deeper penetration.

Thin-section applications, such as automotive components, can benefit from HLAW by an increase in welding speed and a reduction in filler-metal usage (Ref 2). Lap and fillet joints of steel or aluminum sheet metal can be welded at speeds on the order of 4 to 14 m/min (160 to 550 in./min) without humping or lack-of-fusion defects (Ref 2, 3).

Hybrid laser arc welding can also provide an increase in productivity for thick-section welding. In thick-section applications, HLAW can produce deep-penetration welds at travel speeds on the order of 1 to 3 m/min (40 to 120 in./min). In this case, the increase in productivity is generated by deeper weld penetration rather than a drastic increase in travel speed. Using a 30 kW ytterbium-fiber laser, full-penetration HLAW of a 28 mm (1.10 in.) square butt joint has been completed in a single pass (Ref 4). Applications such as oil and gas transmission pipelines, wind turbine towers, prefabricated steel beams, nuclear components, ship structures, heavy vehicles, construction and mining equipment, and rail cars are some example applications that can benefit from the deep penetration of the HLAW process (Ref 5–7). By generating deep weld penetration at productive travel speeds, HLAW can reduce the number of weld passes or decrease weld distortion, compared to GMAW and SAW (Ref 8). To date, the most widely known production application of thick-section HLAW is in the shipbuilding industry.

In 2002, Meyer Werft GmbH in Papenburg, Germany, implemented HLAW for production welding of steel panels and stiffeners for commercial cruise ship fabrication. Using a 12 kW CO₂ laser combined with a 450 A GMAW system, steel plates 6 mm (0.24 in.) thick were welded at speeds of 2.5 to 3.0 m/min (98 to 118 in./min), and 15 mm (0.59 in.) plates were welded in a single pass at 1.2 m/min (47 in./min). By moving to the one-sided, single-pass HLAW process, Meyer shipyard reported welding speeds three times faster than GMAW or SAW and reduced filler-wire usage by an estimated 80%. In addition, HLAW produced less weld distortion and eliminated post-weld flattening processes at Meyer (Ref 9). Hybrid laser arc welding systems using high-power fiber lasers have also been developed for the shipbuilding industry (Ref 10).

Process Description

Hybrid laser arc welding most often combines LBW with GMAW in a common weld pool (Fig. 1). In HLAW applications, the GMAW process is always used to add filler metal to the weld. However, the laser process can be used for multiple purposes, depending on the laser power density (W/cm^2) at the work surface.

The applications of the HLAW process can be divided into two groups based on the mechanism for which the laser is used. One is a stabilization mode, where the laser is used to augment the GMAW process without providing a significant increase in penetration or speed. The other is a penetration mode, where the laser generates a keyhole in the metal, providing both deep penetration and high processing speeds. These two modes are described in the section “Modes of Operation” in this article.

In addition, the major process variables for either mode of operation include three sets of welding parameters: the variables for the independent LBW and GMAW processes and welding variables that are specific to the HLAW process. The process variables specific to HLAW are:

- Travel speed (typically from 1 to 3 m/min, or 40 to 120 in./min)
- Process orientation
- Process separation

These parameters of the HLAW process are discussed in the section “Hybrid Laser Welding Parameters” in this article, while specific variables for the LBW process (discussed in other articles in this Volume) include:

- Laser power (typically from 200 W to 20 kW)
- Diameter of the focused laser beam (spot size typically 0.2 to 1 mm, or 0.008 to 0.39 in.)

The variables for GMAW, as discussed in the article “Gas Metal Arc Welding” in this Volume, include:

- Arc current, voltage, and polarity
- Wire feed speed
- Electrode diameter and composition
- Electrode extension (contact tip-to-work distance)
- Shielding gas composition

Other variables, such as base-metal composition, joint design, part fit-up, GMAW torch angle, shielding gas flow rate, laser wavelength, position of the laser focus with respect to the work surface, and preheat temperature, can play important roles in hybrid welding but are variables usually defined by the application or the available equipment. For HLAW with other arc processes, the GMAW variables would be replaced by the variables of the alternative arc process. The process separation, or distance between the laser and arc, would remain a critical variable regardless of the arc process used.

Modes of Operation

Stabilization-Mode HLAW. As noted, this mode of hybrid laser welding augments the GMAW process without providing a significant increase in penetration or speed. This mode is sometimes referred to as laser-assisted arc

welding. The method of augmentation can be different depending on the material being welded and the laser power density used. For reactive metals such as titanium and zirconium, the laser can be used to provide arc stabilization. As little as 200 W can stabilize the cathode spot during pulsed GMAW of titanium (Ref 11). For welding steel, stainless steel, nickel, and aluminum alloys, a low-power-density laser spot can be used to produce a wide, shallow weld pool ahead of the GMAW process to stabilize the filler-metal deposition. In this case, the laser process is used to increase the wetting angle of the deposited metal and produce a smooth weld bead. This technique can be used to prevent weld humping at fast travel speeds, increase weld toe angles, improve side-wall fusion in groove welds, or enhance attachment of deposited metal when welding out of position (Ref 12).

Using a low-power-density laser beam for stabilized-mode hybrid welding can provide technical benefits in unique applications. However, this mode of HLAW is usually cost-prohibitive for most production manufacturing applications. Laser equipment is much more expensive than arc welding equipment in terms of price per unit of output power (cost per watt). If the expensive laser equipment is used for stabilization rather than drastically increasing productivity (speed or penetration), the return on investment for a hybrid welding system may not be attractive.

Penetration-Mode HLAW. To fully utilize the benefits of an expensive laser system, HLAW is conducted primarily in penetration mode. This is sometimes referred to as arc-assisted laser welding. In penetration-mode HLAW, the laser generates a keyhole in the metal. Both deep penetration and high processing speeds can be achieved with keyhole laser welding.

A keyhole is formed when a laser beam with sufficiently high power density causes melting and vaporization of the base metal. As the metal is vaporized, it rapidly expands and pushes away from the substrate. This expansion exerts a reactive force on the melted substrate called the evaporative recoil force. This recoil force pushes the melted metal away to form a depression. The melted metal is continually pushed out until the depression has formed into a deep keyhole.

The keyhole can be partially or fully through the thickness of the metal. In the steady-state condition after the keyhole is established, continual vaporization of the bottom and walls of the keyhole holds it open against the forces of surface tension and gravity. The relationship of laser power density and travel speed dictates the penetration and width of the keyhole for a given base metal. Power densities on the order of 10^6 to 10^8 W/cm^2 are typical for keyhole laser welding.

Hybrid Laser Welding Parameters

Knowledge of each variable and the ability to precisely control them are necessary to consistently

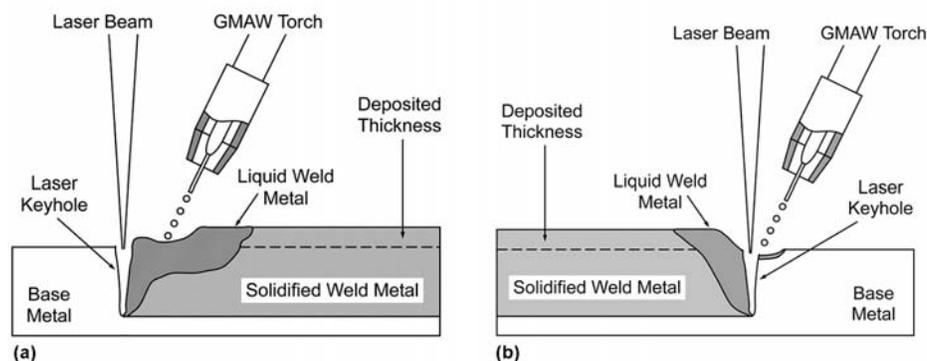


Fig. 1 Schematic of hybrid laser arc welding process orientations. (a) Laser leading. (b) Arc leading. GMAW, gas metal arc welding

produce hybrid welds with the desired quality. These variables can produce competing effects on the weld attributes, and balancing the performance of each variable is essential to successful hybrid welding. Table 1 lists the general effects of each HLAW variable on hybrid weld attributes. The effects listed are typical for welding butt joints over 6 mm (0.24 in.) thick or for welding thinner sections at travel speeds above 3 m/min (120 in./min).

Travel Speed. Hybrid laser arc welding is applicable over a wide range of travel speeds. Generally, the determining factor for welding speed is the productivity requirement. As travel speed increases, hybrid weld penetration will decrease. To maintain the required weld penetration at increasing travel speeds, more laser power and an increased rate of filler-metal deposition is required. If the existing laser equipment is limited in power, then a compromise must be made among travel speed, laser power, and weld penetration.

At travel speeds on the order of 4 m/min (160 in./min) or greater, joint-filling capabilities from the GMAW system can be limited. Gas metal arc welding systems are inherently limited to a maximum current output. For a given electrode diameter, there is a maximum wire feed speed at the maximum current rating of the GMAW power supply. This limitation can lead to insufficient filler-metal addition at faster travel speeds. If the required reinforcement or fillet size cannot be met for a given travel speed due to the limitations of the GMAW power supply, the travel speed, GMAW source, wire diameter, joint design, or the number of passes must be reevaluated. Additional GMAW torches with separate power supplies and wire feeders could be used to overcome deposition limitations.

Process Orientation. The HLAW process can be oriented in two directions: arc leading or laser leading. The GMAW process can be positioned behind or in front of the traveling laser keyhole. If the GMAW process travels behind the laser beam, the HLAW process orientation is referred to as laser leading. If the GMAW process travels ahead of the laser, the HLAW process orientation is referred to as arc leading. Figure 1 illustrates the laser-leading and arc-leading process orientations.

The main difference between the two orientations is the angle of the GMAW torch with

respect to the direction of travel. Torch angle can have an effect on the deposited GMAW bead. In the laser-leading HLAW configuration, the GMAW torch is traveling behind the laser beam, positioned at a “push angle.” In the arc-leading configuration, the torch is at a “drag angle,” traveling in front of the laser beam. This difference in torch angle can produce different weld surface geometries. In the laser-leading orientation, the deposited weld bead is relatively wide and flat, with large weld toe angles. With arc leading, the deposited weld bead is more narrow and convex, with sharper weld toe angles. Torch angle can be adjusted for each process orientation, but there is a limitation to how close the torch can be positioned to the beam axis, due to the beam convergence angle and obstructions from the laser-focusing optic assembly. Alternatively, the laser beam axis can be tilted while the GMAW torch is positioned normal to the work.

Another reported difference between the two process orientations is in penetration. If the laser beam is positioned in the arc depression of the GMAW process, the arc-leading configuration can provide slightly more penetration for HLAW. However, there is conflicting data reporting that the laser-leading process provides deeper penetration. In either case, the reported gain in penetration is generally considered insignificant for most manufacturing applications.

Process Separation. A key variable for HLAW is the process separation, or distance between the two welding processes. This is also known as the beam-to-wire distance or process spacing. Process separation can affect the solidification morphology and microstructure of a hybrid weld. Increasing the process separation will eventually separate the two processes into separate weld pools. Even if the weld pools of the two processes appear to be connected on the weld surface, a metallographic cross section of the hybrid weld can show that the fusion profiles from each process may have solidified separately within the thickness of the joint. This separate solidification can affect the weld microstructure and composition gradient of the GMAW filler metal through the thickness of the joint. Changing the process separation can also have an effect on the energy concentration of the hybrid process, affecting weld penetration, spatter generation, and root bead

profile in full-penetration welding. Process separation for HLAW is typically between 0 and 6 mm (0 and 0.24 in.), depending on the material, laser power, process orientation, and travel speed.

Laser Power. The relationship of laser power and focused beam diameter determines the laser power density. In penetration-mode HLAW, laser power density has the greatest effect on weld penetration. For most structural metals, approximately 1 kW of laser power is needed to provide 1 mm (0.039 in.) of penetration at a travel speed of 2.0 m/min (79 in./min). This estimate depends on the absorptivity of material being welded for a given laser wavelength and the diameter of the focused laser beam. For example, when welding low-carbon steel with a 10 kW laser, a full-penetration hybrid weld can be produced at 2.3 m/min (90 in./min) on a 9.5 mm (0.375 in.) square butt joint with no gap. Spot sizes larger than 600 μm (0.024 in.) can reduce the power density and require more laser power to penetrate a given thickness.

The depth and diameter of the keyhole are determined by the laser power and focused spot size, respectively. Large focused spot sizes, greater than 600 μm (0.024 in.), produce large-diameter keyholes with less penetration for a given laser power. Small-diameter spots, typically 100 to 600 μm (0.004 to 0.024 in.), are used more often in HLAW to generate narrow keyholes and produce welds with high aspect ratios (depth to width). Figure 2 is a video still of a steel hybrid bead-on-plate weld using 1.1 mm (0.045 in.) diameter wire. The image shows that the keyhole diameter is relatively small in respect to the width of the weld pool. This is because the GMAW process drives the weld width at the top surface of the material. Through the thickness of the material, the weld width is similar to the keyhole width. Figure 3 is a cross section of a penetration-mode hybrid weld conducted on a 12.45 mm (0.490 in.) carbon steel square butt joint. This weld was performed with 10 kW of laser power, a 333 μm (0.013 in.) laser spot size, and an 8.9 m/min (350 in./min) wire feed speed for a 1.1 mm (0.045 in.) diameter steel wire at a travel speed of 1.52 m/min (60 in./min). Note that the fusion zone resembles the superposition of a GMAW weld profile and a laser weld profile.

Table 1 Effects of hybrid laser arc welding process variables on weld attributes

Welding variable to change	Desired change in weld attribute							
	Penetration		Deposition		Cap bead width		Root bead width	
	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease
Travel speed	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase
Laser power	Increase	Decrease	No effect	No effect	Minor effect	Minor effect	Minor effect	Minor effect
Laser spot size	Decrease	Increase	No effect	No effect	Minor effect	Minor effect	Increase	Decrease
Wire feed speed and arc current	Minor effect	Minor effect	Increase	Decrease	Minor effect	Minor effect	No effect	No effect
Arc voltage	No effect	No effect	No effect	No effect	Increase	Decrease	No effect	No effect
Wire diameter	Minor effect	Minor effect	Decrease	Increase	Minor effect	Minor effect	No effect	No effect
Process orientation	Minor effect	Minor effect	No effect	No effect	Laser leading	Arc leading	Minor effect	Minor effect
Process separation	Minor effect	Minor effect	No effect	No effect	Minor effect	Minor effect	Decrease	Increase

Shielding Gas. The primary function of the shielding gas is to protect the molten weld metal from the surrounding atmosphere. Shielding gas for HLAW should be selected based on the material being welded; however, additional considerations are necessary based on the laser wavelength and the desired GMAW arc characteristics.

During LBW with a CO₂ laser, the vapor plume or plasma generated by the laser process can absorb and scatter the laser beam. This interference can cause a loss in weld penetration. Therefore, when hybrid welding with a CO₂ laser, it is necessary to remove or suppress the plume with gas usually containing some percentage of helium. In some cases, this can be done with gas delivered by the GMAW torch. In other cases, a secondary plume-suppression gas may be necessary. When hybrid welding with solid-state lasers such as Nd:YAG, fiber, thin-disk, or diode lasers, the shorter wavelengths are not significantly affected by the vapor plume, and a secondary gas for plume suppression is usually not necessary.

Shielding gas delivered from the GMAW torch is generally sufficient to protect the molten weld metal from the surrounding atmosphere. In some cases, a second gas trailing the welding process is needed to shield the weld as it cools. A trail shield device is generally used when welding reactive metals such as titanium or in applications where discoloration due to surface oxidation is unacceptable.

For the GMAW process, the shielding gas plays an additional role in determining weld profile, arc characteristics, and mode of metal transfer. Inert gases, active gases, and blends of the two can be used for HLAW. (For information about shielding gas compositions and which gases to use for specific applications, see the article “Shielding Gases for Arc Welding” in this Volume.)

Gas Metal Arc Welding Current, Voltage, and Polarity. Depending on the arc current, electrode diameter, electrode extension, and shielding gas composition used for the GMAW process, three general modes of metal transfer can be achieved: short-circuiting, globular, and spray transfer. Due to the fast travel speeds used in penetration-mode HLAW, spray transfer or pulsed GMAW are typically used. In pulsed mode, the GMAW power supply provides a controlled electrical output that pulses the welding current to detach individual droplets with each peak current pulse. Because of the advanced control provided by newer GMAW power supply technologies, most HLAW applications now use pulsed GMAW sources. However, spray transfer can be used to produce higher arc heat input for fast travel speed applications.

Arc voltage can be adjusted to increase or decrease the arc length. A longer arc length generally produces a wider melt width at the top surface of the weld. However, a long arc length can allow the deposited metal to wander from the weld centerline at fast travel speeds. A short arc length constricts the arc and limits weld pool width, reducing the wander of the deposited bead at high speeds.

The polarity of the GMAW system can be changed to affect the heat balance between the electrode and the work. However, the vast majority of GMAW and HLAW applications use direct current electrode positive (DCEP) polarity. The DCEP for GMAW provides good arc stability and low spatter generation. Direct current electrode negative and variable polarity (alternating current) have been tested with HLAW but have had limited commercial acceptance.

Wire Feed Speed. The consumable GMAW electrode is fed into the welding process at a predetermined speed. This wire feed speed is selected to provide a specific volume of deposited metal for joint filling, gap bridging, or producing the required reinforcement at the cap and root of the weld. With conventional GMAW power supplies (constant voltage), wire feed speed and arc voltage are set while the power supply adjusts arc current and electrode melt rate to maintain a constant arc length. With modern pulsed GMAW power supplies (constant current), a waveform is designed for a specific wire feed speed. The pulsed waveform dictates the arc current that affects droplet frequency, droplet size, and arc voltage targets. If the wire feed speed is increased, the amplitude of the pulsed waveform is synergically increased.

Joint Designs

Many joint designs can be welded with HLAW, including butt, groove, lap, flange, and fillet joints. Using the appropriate parameters, hybrid welding can be conducted in all welding positions. Hybrid laser arc welding can be performed on linear joints, circumferential joints, or two- and three-dimensional curvilinear joints. Figure 4 illustrates example joint designs for HLAW.

The primary difference in joint design between HLAW and conventional welding processes is that HLAW can provide both joint filling and deep penetration into the base metal. Typically in arc welding, a groove is prepared and then filled with molten metal deposited by the process. In autogenous laser welding, a square butt joint with no groove preparation is welded by penetrating through the joint thickness and fusing the two base metals together. The HLAW process is applicable to both methods of joint fusion.

A multipass V-groove joint that was previously welded with conventional GMAW could be redesigned as a single-pass HLAW joint.

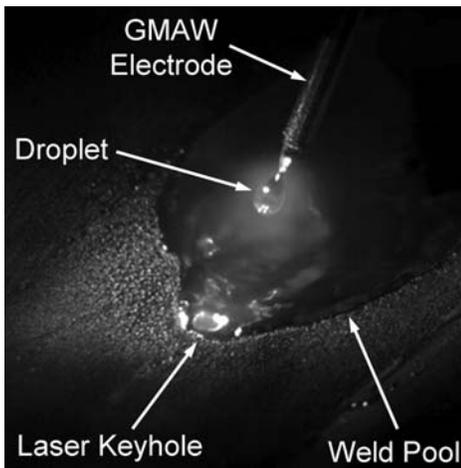


Fig. 2 In-process video image of penetration-mode hybrid laser arc welding on steel. GMAW, gas metal arc welding. Courtesy of Edison Welding Institute

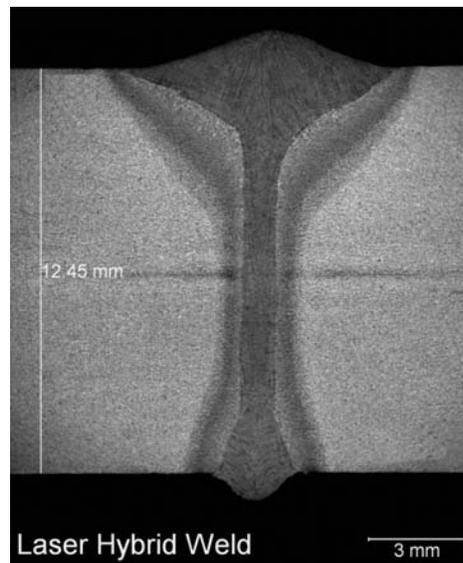


Fig. 3 Cross section of hybrid laser arc welding on a carbon steel square butt joint. Courtesy of Edison Welding Institute

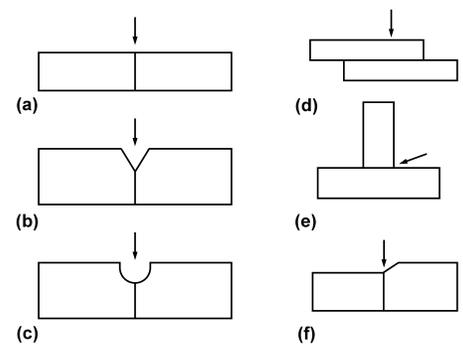


Fig. 4 Example joint designs for hybrid laser arc welding. (a) Square butt. (b) V-groove. (c) U-groove. (d) Lap weld. (e) Fillet weld. (f) Dissimilar-thickness joint

By using the high energy density of the laser process, HLAW can penetrate a square butt joint in a single pass while adding filler metal to produce positive weld reinforcement. To maximize productivity gains with HLAW, the weld joint should be designed to use the available laser power and maximize penetration or travel speed while maintaining weld quality.

Because the majority of the HLAW penetration is produced by the laser, HLAW is best suited as a root-pass process for thick-section multipass operations. After the root has been fused, subsequent passes with penetration-mode HLAW will only remelt and solidify the existing root weld. The only joint filling provided by the HLAW process is the deposition from the GMAW process. If the available laser power is unable to weld the entire joint thickness in a single pass, the joint should be designed to use a deep-penetration HLAW root pass, with subsequent fill passes using a different process (Fig. 4b, c).

The limitations on part geometries that can be welded with HLAW are based primarily on the limitations of the motion system and the access to the joint. For some applications, the combined size of the laser beam and GMAW torch can be too large to fit into tight corners or inside small-diameter pipes. Due to the required process separation length, turning sharp corners with the HLAW process should be avoided. To maintain consistent quality around a sharp corner, intersecting welds could overlap at the corner. Alternatively, the hybrid weld head can be designed to have a mechanized axis that rotates the GMAW torch about the laser beam.

In penetration-mode HLAW, small changes in the repeatability of the joint can have a large effect on weld quality. A variation in joint thickness, a mismatch in height between the two parts, a gap in the joint, or misalignment with the weld path can all affect the quality of the weld. To minimize the effects on weld quality, the consistency of the weld joint preparation should be strictly controlled.

Joint Gap. Fluctuations as little as 0.25 mm (0.010 in.) in the joint gap can require adjustments in weld parameters for deep-penetration HLAW. As the gap increases, maintaining weld stability with HLAW is challenging. Gap sizes above 1.0 mm (0.039 in.) are difficult to weld in a single pass for joints 6 mm (0.24 in.) or thicker. When welding on any gap, small variations in process separation or other welding parameters can have a large impact on weld quality.

Ideally, there should be no gap in the joint, because this is the easiest condition to prepare and keep consistent along the length of the joint. However, hybrid welding on a joint with no gap can cause poor mixing of the filler metal through the thickness of the joint (Ref 13). When a gap is present, more filler metal reaches the root of the joint, but higher wire feed speeds are required to fill the volume of the gap. Welding can be performed on a joint with a designed

gap; however, ensuring that the prefabricated gap remains constant may be difficult.

Joint Mismatch. In a butt or groove joint, mismatch is the measured distance between the top surfaces of the two parts being welded. This is also called vertical mismatch or high-low. Mismatch is common in the pipe-welding industry due to out-of-roundness or eccentricity between the two pipes to be welded. In penetration-mode HLAW for a full-penetration weld, the cap of the weld can generally tolerate a large amount of mismatch because of the deposited metal from the GMAW process. However, the weld bead is relatively small at the root, and the ability to bridge a mismatch is limited. Hybrid welding of joints with a mismatch greater than 2 mm (0.079 in.) is difficult for full-penetration welding of thick sections.

Joint Thickness. The total joint thickness that can be penetrated is determined by the laser power. For a zero-gap joint, the effective throat of a finished weld is approximately the sum of the laser penetration and the deposited thickness provided by the GMAW process. To maximize the effective throat that can be produced with HLAW, the weld joint is usually designed to have a root face or land thickness that is appropriate for the available laser power. The remaining thickness of the joint can be filled by the GMAW deposition.

Dissimilar joint thicknesses can be welded with the HLAW process (Fig. 4f). If the difference in thickness is small, 2 mm (0.079 in.) or less, a bevel preparation of the thicker section may not be necessary. Usually in dissimilar-thickness joints, the mismatch should be set at the cap of the weld rather than the root. At the cap, there is a larger weld pool and therefore more tolerance to mismatch geometries. At the root, there is a limited amount of molten metal to bridge the transition between the dissimilar thicknesses.

Even when welding similar thicknesses, the actual base-metal thicknesses can vary in production. A small increase in part thickness can require more laser power to maintain full penetration. The HLAW parameters and equipment must be designed to accommodate thickness variations that can be seen in production.

Equipment and Consumables

There are four major components of an HLAW system: the laser source, the GMAW source, the hybrid welding head, and the motion system. The consumables used for HLAW are the same as the consumables used in the individual laser and GMAW processes.

Laser Sources

Continuous-wave lasers are most often used for HLAW because they generate a constant laser power for the duration of the weld. The laser source is selected based on power and

wavelength. The output power capability is chosen based on the desired weld penetration for a given application. Travel speed, power density, base-metal absorptivity, and joint design can also affect the determination of laser power.

Multiple factors influence the selection of the laser wavelength. Table 2 lists the wavelengths of common high-power laser technologies that can be used for HLAW. Semiconductor diode lasers can also be used for HLAW; however, the output power and beam quality of diode lasers is currently not suitable for deep-penetration hybrid welding applications.

Carbon dioxide (CO₂) lasers produce a wavelength of 10.6 μm and must be transmitted to the work by reflective optics. Because CO₂ lasers are limited to reflective optic delivery, HLAW applications using CO₂ lasers are typically limited to linear welds on gantry-style motion equipment. Carbon dioxide lasers can have wall-plug efficiencies exceeding 10% and can have high output powers. Carbon dioxide lasers are typically on the order of 20 kW or less for welding applications but can be focused to small spot sizes to provide high power densities.

Solid-state lasers, including Nd:YAG, ytterbium-fiber, thin-disk, and diode lasers, produce wavelengths near 1 μm. The shorter wavelength allows solid-state lasers to be transmitted through flexible fiber optic cables to the work. Fiber optic delivery enables hybrid welding of complex contours and flexibility for welding multiple-part designs.

The Nd:YAG lasers are typically limited to 6 kW or less in output power. Due to the inherent characteristics of the technology, Nd:YAG lasers exhibit poor beam quality and therefore have limited power density. Lamp-pumped Nd:YAG lasers have wall-plug efficiencies (electrical-to-optical power efficiency) of less than 5%; however, diode-pumped models have better efficiency.

Fiber and disk lasers are also referred to as high-brightness lasers due to the excellent beam quality and high power densities they can produce. Both technologies can generate output powers above 20 kW and are excellent laser sources for HLAW. Both fiber and disk lasers are diode-pumped and have wall-plug efficiencies exceeding 25%. Fiber and disk lasers have become the most cost-effective high-power lasers in terms of price per watt and

Table 2 Wavelengths of various high-power laser technologies used for hybrid laser arc welding

Laser type	Wavelength, μm
CO ₂	10.6
Ytterbium fiber	1.070
Disk (ytterbium: yttrium-aluminum-garnet, or YAG)	1.030
Neodymium:YAG	1.064

maintenance costs. As the efficiency of pump diodes continues to increase, the overall efficiency of diode-pumped solid-state lasers will continue to increase.

Gas Metal Arc Welding Sources

Modern pulsed GMAW power supplies are typically used in most HLAW applications. Pulsed GMAW sources enable advanced control of arc stability, arc length, metal transfer, droplet size, droplet frequency, and spatter generation. Modern digital power supplies also enable intimate integration with the controllers of automated motion systems that are typically used for HLAW.

Due to the fast travel speeds used for HLAW, wire feed speeds and average current levels may be higher than typical GMAW applications. For this reason, the GMAW system should be capable of the maximum wire feed speed and current rating for the desired HLAW application. Because of the high average current used in HLAW, considerable heat is generated in the GMAW torch. In addition to the heat produced by the arc, the GMAW torch receives additional heat radiated by the laser process. To reduce damage from the heat generated during hybrid welding, the GMAW torch should be water cooled.

Push-type wire feeders are conventionally used for GMAW and HLAW. Push-pull wire feed systems that use drive rolls at the wire feeder and in the torch were conventionally used for soft electrode materials such as aluminum. Because push-pull feed systems offer increased control and consistency, they are being used more often in HLAW applications for both stiff and soft electrode types, including steel, stainless steel, aluminum, nickel, and titanium.

Hybrid Welding Head

The processing head for HLAW is a combination of laser-focusing optics and a GMAW torch.

Laser-Focusing Optics. The focusing optics should be selected to produce the desired spot size at the work. The optical assembly can consist of reflective or transmissive optics. In both cases, the lenses or mirrors are very sensitive to contamination. Dust, dirt, fingerprints, scratches, or other sources of contamination on the optical surfaces can cause a loss in transmitted laser power, an increase in the focused spot diameter, a change in power distribution, a shift in the focal position, or a combination of these effects. A transmissive cover window or debris shield is typically used to protect the optic assembly from contamination. A compressed air cross-jet, or air knife, is also used between the work and the optics to protect the cover window from weld spatter and fume.

In addition to spot size, the standoff distance of the focusing optic should be considered when choosing welding optics. If a longer focal

length focusing lens is selected, the expensive optic assembly will be farther from weld spatter. However, longer focusing optics generate a larger spot size. Larger spot sizes have lower power densities and produce less weld penetration or slower travel speeds. This trade-off must be managed to provide sufficient weld productivity while reducing the risk of damaging the expensive laser optics. Focal lengths of 200 to 300 mm (7.87 to 11.81 in.) are typical for HLAW.

Gas Metal Arc Welding Torch. The water-cooled GMAW torch should be capable of handling the appropriate current rating for the desired application. The contact tips, liner, and other consumables should be selected for the appropriate filler-metal alloy and wire diameter. If a small process separation (beam-to-wire distance) is used for HLAW, the GMAW nozzle may need to be modified so that the laser beam does not strike the nozzle. Alterations to the gas nozzle should be kept to a minimum so that the flow of the shielding gas is not significantly disrupted. If a large process separation is used, the GMAW gas nozzle does not need to be modified.

Because process separation, torch angle, electrode extension, and alignment of the two processes are critical, the method of mounting the GMAW torch with respect to the laser beam is critical. Off-the-shelf hybrid processing heads can be purchased that incorporate both the optics and the torch into one assembly. Custom hybrid welding heads can also be assembled by combining standard laser-focusing optics to a standard GMAW torch with a custom mounting bracket.

Whether custom-built or commercially purchased, the components of the hybrid welding head should have certain degrees of freedom. Based on the application, the GMAW torch angle and work angle can be fixed or variable relative to the beam. The torch should be able to move laterally to align with the beam along the weld joint, vertically to adjust the electrode extension relative to the beam focus, and horizontally to adjust the process separation from the beam axis. These adjustments can be manual or mechanized. The overall assembly should be rigid and capable of withstanding the travel speed, acceleration, and changes in position that may be used during processing.

Motion Systems

The motion systems that can be used for HLAW are dictated by the application. For linear welding, a linear beam or gantry system can be used. For complex geometries, a six-axis robot is generally used. In pipe-welding applications, the hybrid head could be mounted on a track system to traverse around the circumference of the pipe. The part or the hybrid welding head can be moved to achieve welding motion. In all cases, the dynamic accuracy and path repeatability of the motion system are significant variables. In particular, the standoff

distance of the hybrid welding head and alignment with the joint are critical for HLAW.

Hybrid Laser Arc Welding Consumables

Consumable Parts. The GMAW consumables include contact tips, gas nozzles, liner, guide tubes, and drive rolls. For different wire diameters, the contact tips, liner, guide tubes, and drive rolls should be changed. The contact tips should be changed periodically as the internal bore is eroded by the moving electrode. The internal bore of the contact tip is important because the wire must feed smoothly through the tube while making good electrical contact. As the bore of the contact tip wears away, poor electrical contact can result in erratic arc characteristics.

For welding with steel wire, a spiral steel liner is typically used to guide the wire through the torch cable. For soft wires such as aluminum, nylon or synthetic fluorine-containing resin liners are used. When welding with titanium wire, graphite liners are used to reduce contamination of the weld.

The primary consumables of the laser system are the cover windows that protect the focusing optic assembly from contamination and weld spatter. Other consumables depend on the type of laser source used for HLAW.

Filler-Metal Consumables. The chemical composition of the consumable GMAW electrode must be properly selected to achieve the desired properties in the hybrid weld metal. Of particular note with HLAW is that the heat input is typically lower than GMAW, and the cooling rate is much faster than conventional arc welding processes. This means that HLAW can significantly affect the solid-state transformations in the weld zone and that an acceptable electrode composition for GMAW applications may not always be acceptable for the fast cooling rate of the HLAW process, particularly in high-strength steels or other alloys with high hardenability.

For deep-penetration HLAW with little or no joint gap, the dilution of filler metal may not be homogeneous through the thickness of the joint. In some cases, weld-metal composition can be primarily filler metal near the cap of the weld and primarily base metal near the root. Knowledge of the heat input, cooling rate, and filler-metal dilution from the HLAW process and their effects on weld-metal microstructure is essential to producing high-quality HLAW welds.

Sources of Defects

Typical defects for HLAW are porosity, undercut, concavity, root humping (root bead instability), incomplete fusion, and incomplete penetration. Other defects can occur but are driven more by the application (joint design, alloy selection, travel speed, and cooling rate) than by the nature of the process.

Porosity. Assuming there is no source of contamination (oxidation, oil, foreign metals, weld

surface, joint interface, wire surface, shielding gas), porosity is generally attributed to the keyhole laser process used in penetration-mode HLAW. The keyhole is a column of metal vapor surrounded by the liquid weld metal. Turbulence in the keyhole can introduce gas pores into the molten weld. Aluminum and titanium are particularly susceptible to weld porosity from the HLAW process.

Partial-penetration HLAW occurs when welding in penetration mode but not fully penetrating through the joint thickness. Partial-penetration HLAW is highly susceptible to internal weld porosity due to instability at the root of the keyhole. Porosity caused by keyhole instability is typically seen in the bottom half of a partial-penetration HLAW cross section. To reduce the occurrence of porosity from keyhole instability, the weld can be redesigned to fully penetrate the joint thickness. Full-penetration welds are less likely to have porosity from keyhole instability. Increasing the spot diameter or modulating the laser power has been shown to reduce porosity from keyhole instability in partial-penetration laser welding.

Undercut and Concavity. Geometric defects such as undercut and concavity are typically caused by a gap in the joint that could not be filled by the deposited wire. Undercut at the toes of the weld surface can also occur due to the high travel speeds. In full-penetration welding, the molten weld can drop through the joint. This results in concavity or undercut at the top surface and excessive root reinforcement on the back surface of the weld.

Root Humping. In full-penetration HLAW of steel, improper welding parameters can result in irregularities in the profile of the root bead. This defect typically appears as a longitudinal humping profile at the weld root on the back side of the joint. This defect most often occurs in steel, but it has been seen in stainless steel, nickel, and titanium alloys as well. The physical phenomena that cause this defect are not fully understood; however, increasing the laser power reestablishes a stable full-penetration keyhole and eliminates the root-humping defect. Root-humping defects usually coincide with undercut or concavity defects at the weld cap.

Incomplete Fusion. Deep-penetration hybrid welds generally have very narrow weld profiles. Small deviations in joint alignment can cause the laser beam to miss the weld joint and result in an incomplete fusion defect. This can be a particularly troubling defect because the weld may appear to have complete fusion from a visual inspection of the top and bottom surfaces, but in the center of the thickness, the weld may not fuse the entire joint.

Incomplete Penetration. If there is a loss in laser power or an unexpected increase in the joint thickness, the hybrid weld may not fully penetrate the thickness, resulting in an incomplete-penetration defect. Loss in laser power or changes in the power distribution are usually the causes for incomplete penetration.

Contamination of the cover window or other optical surfaces can cause changes in laser power density at the work. The gas nozzle, air knife, or GMAW torch can clip the beam and reduce the laser power that reaches the work. If the process spacing has been reduced to zero, the deposited droplets from the GMAW process can impinge on the keyhole and decrease penetration depth.

Quality Control and Inspection

Hybrid laser arc welding is an automated process that requires strict controls on repeatability of the parts and of the welding system. To ensure the parts are repeatable, upstream processes should be addressed to accommodate the HLAW process. Improving upstream preparation of the parts and weld joints will only improve the productivity gains possible with HLAW.

Even with strict control on upstream processes, weld joint preparations are never perfect. To adjust for variations in joint fit-up, gap, and mismatch, real-time seam tracking and joint sensing should be implemented. With advanced control systems, the welding parameters and joint alignment can be adjusted on-the-fly to compensate for the variations in the joint. If a complex control system is not feasible, a path check could be conducted with a camera system coaxial to the laser beam to verify the joint alignment prior to welding.

To ensure consistent weld quality and penetration, periodic laser power measurements should be conducted. Scheduled preventative maintenance should be conducted on the GMAW and laser systems to ensure optimal working condition. Periodic inspection should also be conducted on the welded parts to ensure weld quality.

Inspection by destructive analysis could evaluate fusion profile, hardness, tensile strength, fatigue performance, or impact toughness of the hybrid weldment. Inspection by nondestructive evaluation (NDE) could search for centerline defects, incomplete fusion, porosity, solidification cracking, and incomplete penetration. The NDE methods typically used for HLAW are radiographic testing and ultrasonic testing.

Safety

The greatest safety concerns are from the laser welding equipment. Because high-power laser beams are invisible to the human eye, the hazards may not be readily apparent to inexperienced personnel. With exposed laser beams, personnel may be exposed and permanently injured before the existence of the hazard is even recognized. For this reason the American National Standards Institute specification ANSI Z136.1, "Safe Use of Lasers" (latest edition), requires that each facility using lasers designate an individual as the laser safety officer. This individual should be familiar with laser safety, ANSI Z136.1, and

potential hazards at the designated facility. Special precautions must also be taken to protect personnel from arc welding hazards.

Training. Employers of facilities using HLAW are responsible for providing training to all operators, engineers, technicians, maintenance, and service personnel. ANSI Z136.1 requires that training in the potential hazards and control measures be provided to all personnel involved in laser use. ANSI Z136.1 provides a model safety training program in Appendix D of the standard. Refer to the article "Safe Welding Practices" in this Volume and ANSI Z136.1, "Safe Use of Lasers," for more information on training.

Electrical Hazards. Both laser equipment and GMAW equipment employ high voltages and currents capable of lethal shock. Only qualified and authorized personnel should install and service equipment with the appropriate procedures, tools, and protective equipment. Refer to the article "Safe Welding Practices" in this Volume for more information on electrical hazards.

Eye Hazards. Eye injury is readily caused by laser beams. With laser beams operating in the visible or near-infrared spectrum, a 5 mW beam can inflict permanent retinal damage. Proper safety precautions must be taken to protect personnel from direct, scattered, reflected, and diffuse laser radiation. Depending on the laser wavelength employed, different safety measures and personal protective equipment are required. Consult ANSI Z136.1 for the appropriate safety measures for specific laser wavelengths.

The GMAW process produces intense visible and ultraviolet (UV) light. Appropriate protective equipment is required to protect personnel from this intense radiation generated by the electric arc. Eye protection is required for each of the welding processes used in HLAW to protect personnel from both laser and arc radiation. Refer to the article "Safe Welding Practices" in this Volume and ANSI Z136.1, "Safe Use of Lasers," for more information on eye hazards.

Skin Hazards. Skin exposure to the primary laser beam can result in severe burns and must be prevented by safety enclosures and operator training. There is no personal protective equipment rated to protect personnel from direct exposure to the primary beam. Enclosures should be designed to prevent operators or spectators from placing any body part near the beam path. Unless a sufficient enclosure is constructed, exposure to reflected and scattered laser light is possible. Intense UV light produced by the GMAW process can cause skin damage. Spatter and hot metal parts are burn hazards for HLAW personnel. Refer to the article "Safe Welding Practices" in this Volume for more information on skin hazards.

Fume Hazards. Both the laser and GMAW processes produce welding fumes. Fume hazards are dependent on base-metal composition, filler-metal composition, shielding gas composition, and welding parameters. Welders, operators, spectators, and other personnel in the welding area must be protected from overexposure to

fumes and gases produced during welding. Refer to the article "Safe Welding Practices" in this Volume for more information on fume hazards for various welding applications.

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