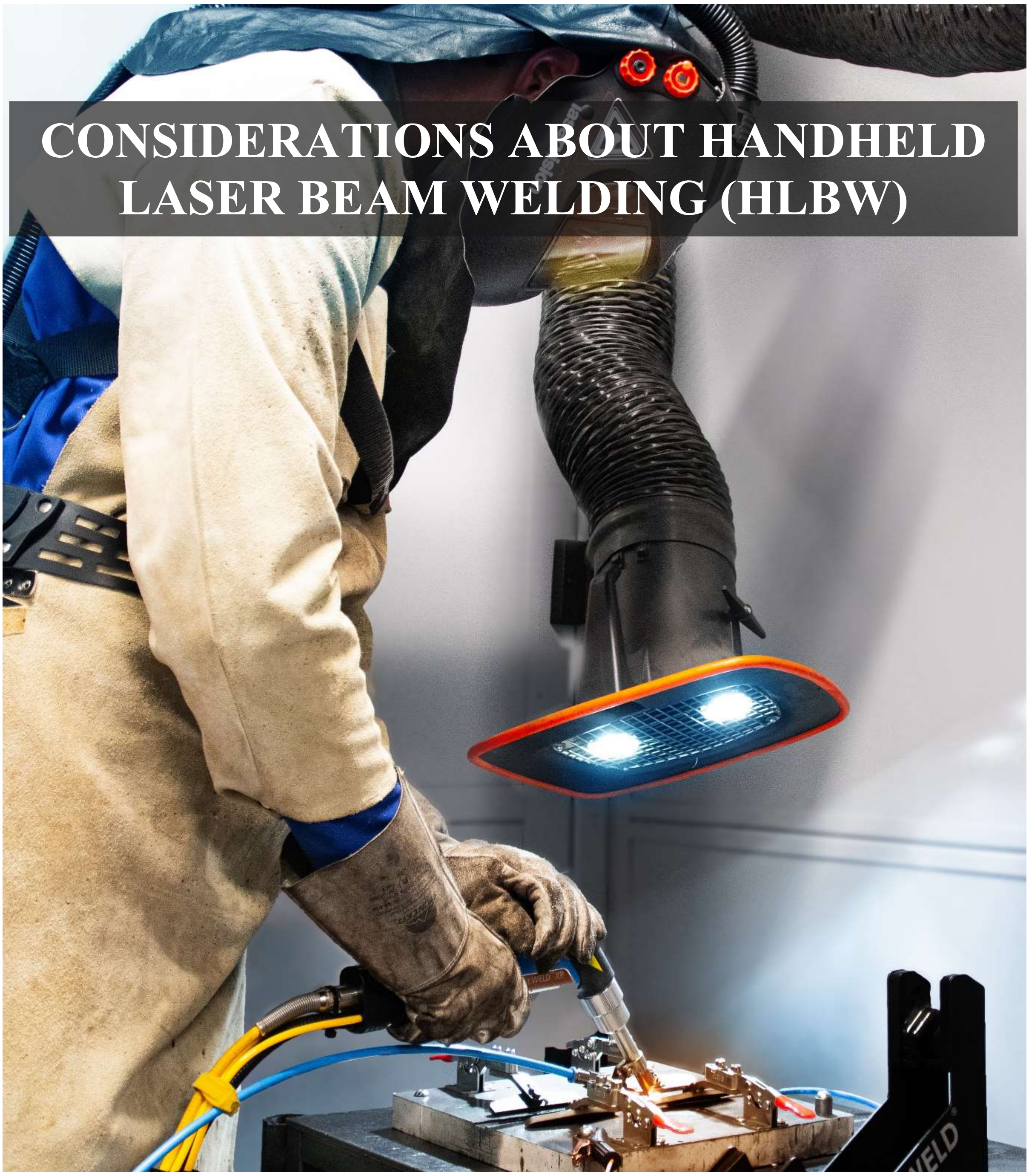
CONSIDERATIONS ABOUT HANDHELD LASER BEAM WELDING (HLBW)



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Considerations about Handheld Laser Beam Welding (HLBW)

Content

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Executive Summary

Since 2023 at the latest, handheld laser beam welding (HLBW), also known as handheld laser welding, systems have become interesting for many companies. This is mainly due to two factors. Firstly, the cost of such a system has fallen significantly in recent years. Secondly, there is economic pressure in the manufacture of welded products, which is partly due to the shortage of skilled workers. This publication addresses various aspects of HLBW, in particular the current state of the art, safety, quality considerations, and qualification.

HLBW offers a wide range of potential benefits, including higher throughput, less straightening work due to the lower heat input, and the use of less experienced personnel. However, welders still need to be qualified, especially to deal with the hazards of laser radiation. Furthermore, the application of the process requires an appointed laser safety officer in the company and a work area designed in accordance with laser protection requirements (Laser Controlled Area, LCA). In addition to welding, many systems for HLBW also have a cleaning function, some even a cutting function. The risks to be considered here are considerably greater, since on the one hand, contact control is often omitted and on the other hand, the beam is conditioned for a larger working distance.

To utilize the full potential for joining, application requirements must be considered during the design including edge preparation. For the design, the process variants have to be taken into account (without filler material, a "zero gap" joint design is necessary, however for a process with filler material the joint design can be similar to arc processes and a more broad range of weld joint designs is possible). This continues during edge preparation. HLBW is a supplement to typical arc welding processes, although arc processes still have their place with small, complex geometries or in terms of accessibility. However, if longer seams (e.g. 1.5 m long weld of 1.5 mm thick stainless steel material for application in food industry) are to be welded and these are prepared accordingly, then HLBW should strongly be considered, especially regarding welding speed when welding by hand.

The purpose of this IIW document is to present general recommendations and best practice examples for laser safety, education, qualification, and metallurgical considerations related to HLBW. The local regulations, e.g. for laser safety, must always be complied with.

Disclaimer:

This document has been provided for informational and reference purposes. Procedures described are currently in use by the authors. However, we offer absolutely no guarantee of their suitability for reader or employer. It is the user's responsibility to check the required standards for compliance or regulations on local as well as on national base.

Introduction

Handheld laser beam welding (HLBW), also known as handheld laser welding, equipment is a high-power Class 4 laser instrument. Class 4 high-power lasers present the most serious of all laser hazards. HLBW is a high power density process (10^5 to 10^{11} W/cm^2) using a coherent beam of light as the source of heat. LASER is an acronym for "light amplification by stimulated emission of radiation." The coherent nature of the laser beam allows it to be focused to a small spot, which gives very high power densities. The availability of high-power continuous-wave (CW) lasers, which may include neodymium-doped yttrium aluminum garnet (Nd:YAG, 1.064 µm wavelength, both lamp lamp-pumped and diode diode-pumped rod), Yb:YAG disc, (1.030 µm wavelength), and Yb:fiber, (1.070 µm wave length), and the limitations of current welding technology have promoted both interest and economic benefit of Laser Beam Welding (LBW) in welding in the last several decades in general. The ability of the laser to generate a power density greater than 10^6 W/cm^2 is a primary factor in establishing its potential for welding. HLBW is comparable to hand-guided arc welding processes. A laser head / handpiece / welding head / laser torch is guided over the workpiece, but the energy used to melt the material is not applied by an arc, but coherent radiation. The laser "torch" is in the welder's hand.

For clarity and consistency, terminology as defined in ASME Section IX will be used in this document. Regardless of the type of welding being conducted, manual welding is defined as welding wherein the entire welding operation is performed and controlled by hand. Many HLBW systems have wire filler metal that is advanced automatically during welding HLBW conducted using filler wire feed controlled by the equipment, while the advance of the welding is manually controlled is referred to as semi-automatic welding. When conducting manual and/or semi-automatic welding, the person conducting the welding would be considered a welder.

Machine welding is being performed when welding with a mechanical device that holds the source of energy (torch), and that has controls that can be adjusted by the welding operator in response to changing welding conditions. When HLBW systems are used in conjunction with a robot, collaborative robot/cobot or other mechanical device used to control to the advance of the welding, the process is considered as machine welding. When welding is conducted with equipment that performs the welding operation without adjustment of the controls by the welding operator, this is referred to as an automatic welding process. It is common for high power CNC or robotic laser welding to be qualified as automatic welding where the welding operator is not permitted to make adjustments to the process. When conducting machine or automatic welding, the person conducting the process would be considered a welding operator.

In comparison with HLBW, the term "manual welding laser" refers to systems in which the laser head is fixed and the welding movement is carried out by manually sliding or moving the workpiece. This process would be considered manual welding as it is being controlled by hand. Often, the same systems can be used in which the laser head is mechanized/partially automated and the motion of the laser head or the workpiece is controlled via a controller or joystick. A welding procedure using the mechanized features would be considered machine welding.

Scope

The scope of this document is to address the safety, quality, qualification, and metallurgical considerations related to HLBW to allow for a common approach related to this relatively new process. Since safety should always be the primary consideration, this document will address the safety aspects prior to the qualification aspects and the metallurgical/materials science aspects. This document will be useful to international welding associations for quickly addressing these three areas through standards and other documents to provide a pathway for safely implementing HLBW. The requirements for laser beam cleaning as pre or post processing with contact between part and laser head are the same as for HLBW.

The local regulations, e.g. for laser safety, must always be complied with.

This document is not applicable to contactless laser beam cleaning, cutting, or etching.

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HLBW Equipment

The HLBW equipment components for this process are given below:

Laser head: The laser head typically depends on the manufacturer and may contain wire feeding components. They can vary in design and included features. A selection of different types is given in the following Figure.

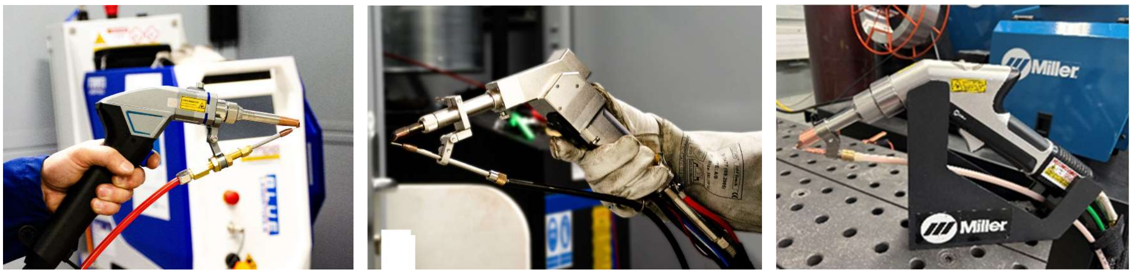


Figure 1. Laser heads with single-axis (left) and two-axis (middle) beam oscillation and with active plasma monitoring (right) [courtesy of ifw Jena, Germany, and Miller Electric Mfg LLC, USA].

Laser Power Source (Fiber, Diode): Different types of laser sources are in use for HLBW system. The wavelength of the laser depends on the type of laser source being used. This can be a fiber laser source as single mode or multi-mode type or a diode laser source. Depending on laser source and type, the radiation can be emitted in pulsed mode and continuous wave mode. The typical maximum laser power ranges between 800 W and 3 kW. Note that the focal point is typically set by the manufacturer internal to the laser. Often the laser source is combined with the control and cooling in one casing onto a cart or trolley.

Figure 2. Different HLBW systems [courtesy of ifw Jena, Germany, and Miller Electric Mfg LLC, USA].

Wire feeder: In order to fill or bridge gaps, often filler material is used. If welding is to be carried out with filler metal, a wire feeder is required. The designs of such feeders differ in terms of continuous or pulsed wire feed and wire retraction.

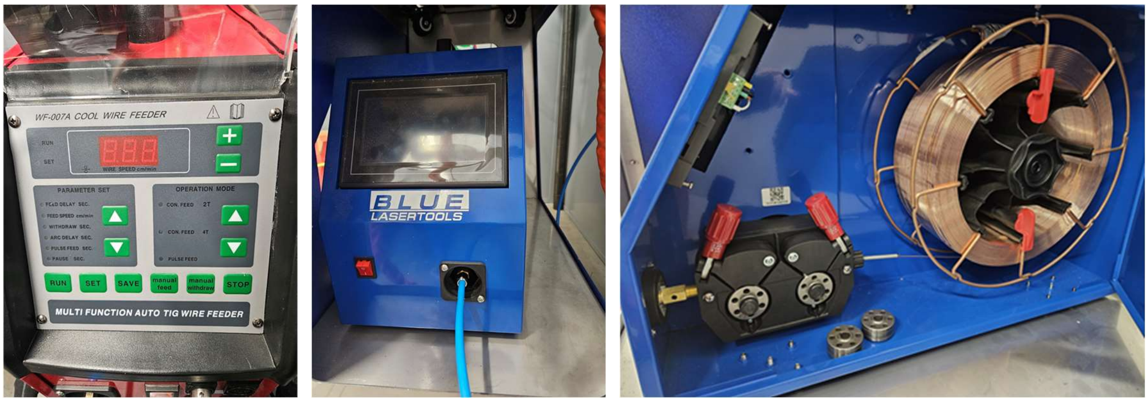


Figure 3. Different wire feeder for HLBW systems [courtesy of ifw Jena, Germany].

Advantages and disadvantages of HLBW

Handheld laser beam welding (HLBW) offers several advantages over traditional manual arc welding processes, such as MIG/MAG and TIG welding, particularly in terms of efficiency, precision, and ease of use. However, it also has some limitations that must be considered when selecting the appropriate welding method.

HLBW Advantages

1. Increased welding speed – the high energy density of laser welding enables significantly faster welding speeds compared to manual arc welding, improving productivity.
2. Lower Heat Input and Reduced Distortion – compared to arc welding, the lower heat input minimizes material warping and distortion, making it ideal for thin sheets and precision applications.
3. Minimal post-weld processing – Due to the high-quality weld seam with reduced spatter and a cleaner finish, there is often little to no need for post-weld grinding or polishing.
4. Simplified operation and training – HLBW requires less operator skill than TIG welding, as there is no need for precise electrode control. Training time for new operators is shorter.
5. Versatility in material compatibility – HLBW can be used on a wide range of materials, including stainless steel, aluminum, and carbon steels, often without the need for filler material.
6. Lower cost for fixtures and tooling
7. Lower time to go from design to component

HLBW Limitations

1. Laser safety requirements – due to the high-powered laser beam, strict laser safety measures are necessary, including Laser Safety Officer (LSO), an LCA, protective eyewear, enclosed welding zones, and trained personnel.
2. Lower power of HLBW systems compared to automated laser welding systems – while HLBW has better penetration than manual arc welding, its penetration depth is still lower than that of fully automated laser welding systems due to the lower power output of handheld devices.
3. Less control on travel speed compared to machine controlled laser beam welding
4. Reflectivity challenges with certain materials – highly reflective metals such as aluminum and copper require careful parameter selection to ensure stable welding conditions.
5. Limited Laser Safety Officer (LSO) availability for inspection of laser welding area

6. Process understanding (beam diameter, beam quality, focus setting, influence of different welders and different HLBW systems) is today lower than for machined controlled laser beam welding and verification methods are not as straightforward

Pfaller recently outlined some of these in a recent publication on HLBW for aerospace manufacturing [1]. HLBW is a promising alternative to manual arc welding, particularly for applications requiring speed, precision, and minimal heat input. However, its implementation requires proper training, safety measures, and process optimization to maximize its benefits.

History of Handheld Lasers

Historically, one first patent for HLBW was registered in Germany in 1971 [2] and in the USA in 1972 [3], and results on welding were published by Nath in 1974 [4]. This described welding with pulsed laser radiation.

Nath's idea is based, among other things, on patent US3382343A [5]. The machine described uses a radiation source to generate the laser radiation as well as “a fiber bundle light guide” that directs the laser radiation to the processing location [6].

Since the turn of the millennium, there have been repeated changes in which the topic of handheld laser welding has come to the fore. Laser heads existed that completely shielded the laser radiation from the environment. However, the disadvantages were the weight, size, and the resulting difficulty in handling. It was only since the beginning of the 2020s that the costs for 1 kW laser sources fell to a level, which allowed the process to be more widely used. Furthermore, the laser heads were made smaller and easier to manipulate. Complete systems are currently much more affordable.

Safety Requirements and Considerations

Safety in HLBW is paramount. Much information has already been published and will be integrated within this document [7-17]. All persons using welding processes already should be aware of the necessary precautions, such as electrical, fumes and gases, fire or explosion, burn, arc rays, noise, and electric and magnetic fields (EMF). In addition to the above listed arc welding hazards, users should understand that HLBW equipment creates laser beam hazards that can be hazardous to a person’s eyes and skin. The laser beam can also be a fire hazard due to its ability to ignite flammable materials.

In addition to the hazards associated with arc welding, direct, or reflected, high-power laser beams are hazardous to view under any condition. High-power lasers typically emit multiple kilowatts of high intensity visible or invisible (near-infrared) light.

Most of the commercially available HLBW systems are equipped with laser sources of 1070 nm wavelength and therefore are invisible to the eyes. The visible red dot of the pilot laser can be misleading in that it is at a much lower power level but does track along with the high-power Class 4 laser.

Like arc welding, laser welding also emits UV radiation (the rate of which is dependent on the material being welded). Please see Figure 4.

Eye Hazards

Exposure to laser light can inflict severe retina and/or cornea injuries leading to permanent eye damage. Some laser light, including the welding, cutting, or cleaning beam (e.g.1070 nm), is invisible. Laser safety eyewear is designed to protect against direct, reflected, scattered laser beams and radiation. Users must follow the local regulations (mandatory!) and equipment manufacturer’s recommendations for the appropriate wavelength and Optical Density (OD) or protection level (LB) according to EN 207 in Europe for protective eyewear. The ‘LB numbers’ (LB5, LB6, LB7 etc.) refer to the maximum power or energy density which the eyewear is specified for.

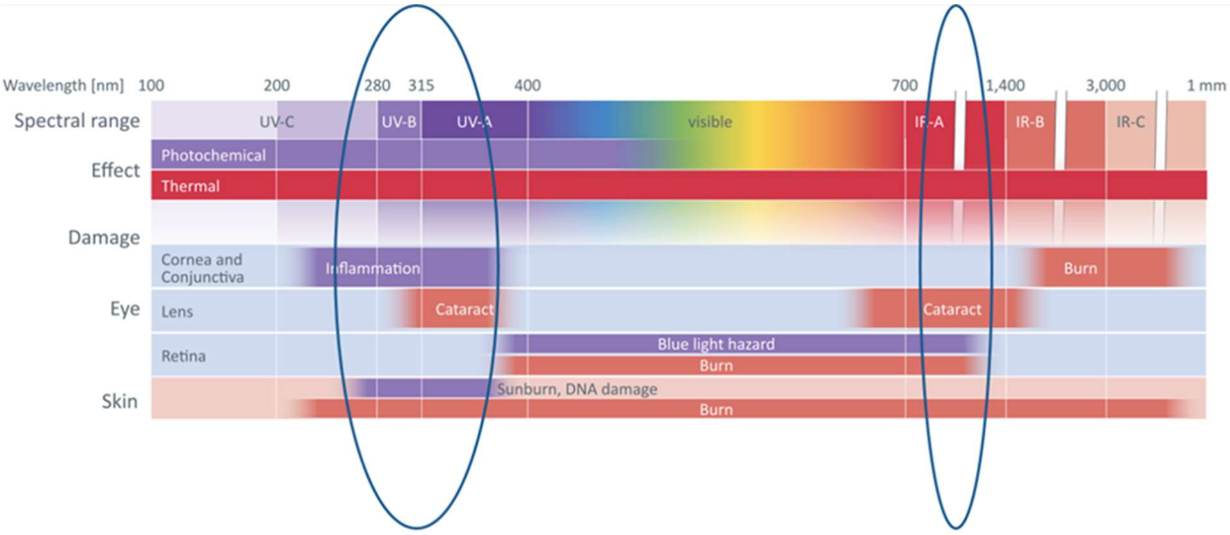


Figure 4. Injuries that can occur as a function of radiation wavelength [courtesy of ifw Jena, Germany].

The protection level for a specific laser will depend on several variables such as maximum power and spot size. Laser manufacturers should specify the minimum protection level, and this should be validated by a qualified LSO working for the organization using the laser, who must also ensure safe use of PPE and assurance of other safety features such as the LCA.

Always inspect eyewear for damage or improper fit before use. Direct beams are the most hazardous. Depending on the power level of the laser beam, laser safety eyewear is designed only to protect from incidental (i.e., very brief) direct and reflected beams. Never look directly into a laser aperture, even if wearing full eye protection. Never point the torch at another person.

It is mandatory to wear laser safety glasses at all times, for all individuals who are inside the LCA. If the laser safe welding helmet has integrated eye protection (integrated seal), then the helmet alone is adequate. If more than one person are working inside the LCA, such a helmet cannot be opened unless additional laser safety glasses are worn. It is important to understand that standard safety eyewear and standard welding helmets do not provide adequate protection from laser beam hazards. When a welder is using both laser and arc welding processes, it is recommended to use a hybrid style of welding helmet (applicable for both, arc and laser welding processes). In addition to laser safety eye protection, the use of an appropriate welding helmet is critical to protect the skin of the welder in the face area due to the hazards of high energy reflection hazards as described in the following section.

Reflection Hazards

In laser beam welding in general, scattered and direct laser beam radiation hazards must be considered.

Highly reflective metals can produce hazardous reflected beams by "specular" (mirror-like) (see Figure 5). The intensity of the reflection will vary based on the material type and surface finish. Also, very thermally conductive metals (e.g., aluminum and copper) can cause some portion of the laser beam energy to be reflected from the target weld site since the plasma ignition is delayed (see Figure 5). Once the plasma is initiated, specular reflection is minimized.

In conduction mode welding, the reflection hazard is higher compared to keyhole welding mode after the keyhole is established.

The user needs to assess the work site prior to using the hand-held laser welding equipment to understand the surfaces where hazardous reflected beams can exist. This assessment shall include a complete review of the LCA.

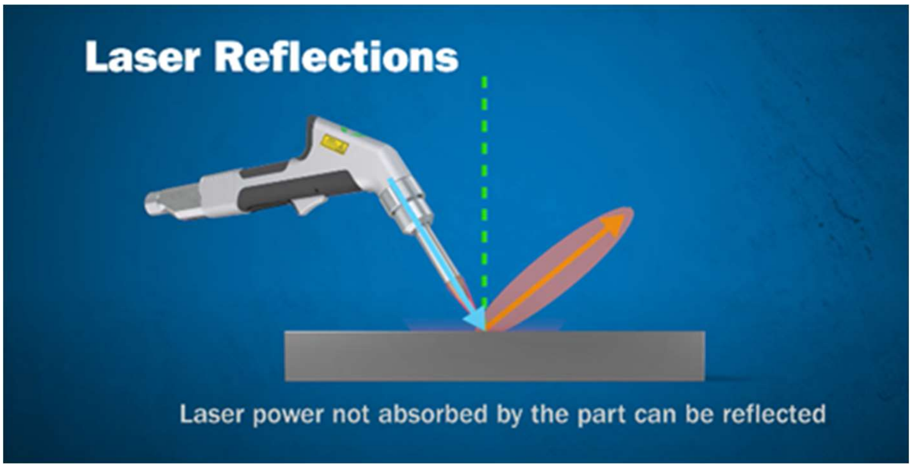


Figure 5. Schematic drawing showing reflection during laser welding [courtesy of Miller Electric Mfg LLC, USA].

The normal direction of the laser reflection from a metal surface can produce a hazardous beam reflected from one surface of the targeted weld site (see Figure 6, Detail A).

Additionally, the normal direction of the laser reflection can produce a hazardous beam reflected from two surfaces oriented at an angle (termed a "retroreflection") (see Figure 6, Detail B).

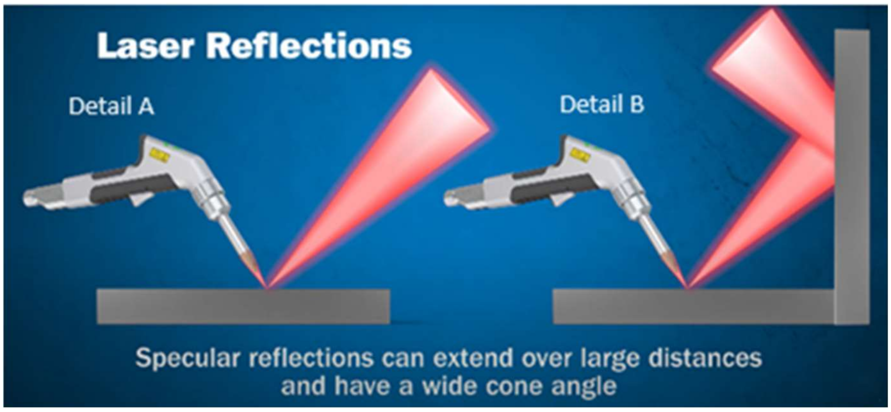


Figure 6. Schematic drawing showing multiple reflections during laser welding [courtesy of Miller Electric Mfg LLC, USA].

Specular reflections can present eye and skin hazards to the operator and other people in the LCA as a portion of the beam can be reflected from multiple surfaces. A recommendation for operator are given in the next Figure.

Beside the reflection on the top side of the parts, in keyhole welding mode beam power can pass through the workpiece, especially if it is required to capture the root in the welding process. In the following picture (blind seam welding) it can be, seen that there is enough energy for the beam to ignite cardboard after passing through the steel sheet and provides a direct laser beam radiation hazard.

As a consequence, the area behind the part to weld has to be considered as well for laser safety. In addition to the figures above, laser welders should be trained to understand the changing hazards while welding actual production parts with more complex geometries than flat surfaces.

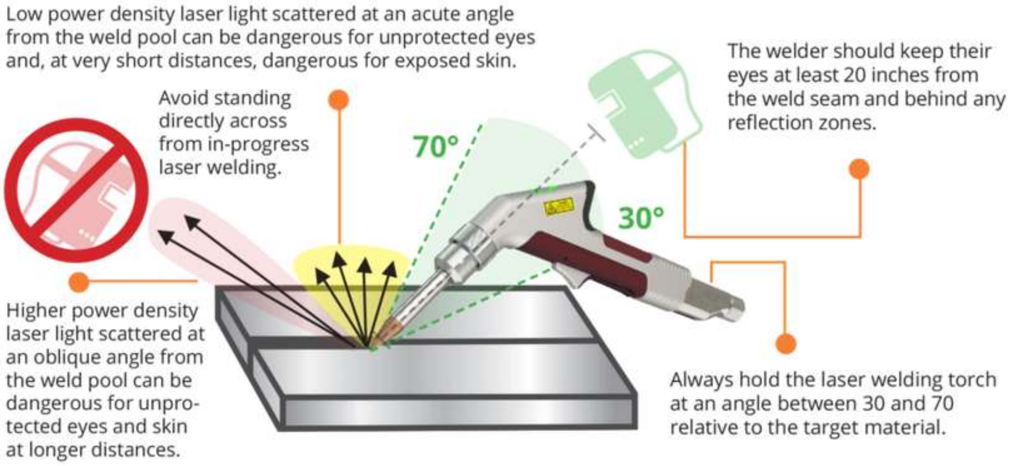


Figure 7. Schematic drawing showing recommendations regrind reflections during HLBW [courtesy of IPG Photonics Corporation, USA].

Figure 8. Beam energy passing the sheet in blind seam welding and ignites cardboard on the wall [courtesy of ifw Jena, Germany].

During the welding process, the direction of specular reflections can change based on part geometry. A trained laser welder should be able to predict these challenges and manage the welding progression to avoid reflections directed towards the hands or face, in particular when welding aluminum and copper.

High reflectivity materials such as copper may not be appropriate to use as backing material as they could create new hazards that do not exist with arc welding processes. A steel or stainless steel backing plate would not create such and intense reflection in this case.

HLBW equipment safety features

Users shall ensure HLBW equipment incorporates important built-in safety features required for all Class 4 laser products as follows:

1. Key switch to secure the equipment and control unauthorized operation.
2. Emergency stop button to terminate laser emission immediately.
3. Connection for an external interlock to shut down the laser if someone other than the operator unexpectedly enters the LCA.

Manufactures and users of HLBW equipment have to consider safety features as required in ISO 11553 part 1 and 2, international standards for laser processing machine, to protect operators and bystanders. The following are typical risk mitigation measures designed in accordance with the ISO 11553 series, other applicable safety standards or invented by actors in the market

1. Two-stage trigger on the torch to help prevent unintentional laser emission, including visible laser ready indicator and visible warning device in the field of vision of the operator for laser emission. The visible indicating devices must also be clearly visible when indicating the need for personal eye protection.
2. Workpiece contact circuit to make sure that the laser can only be enabled when the torch tip is in contact with the part being welded.
3. In addition to the first two features, a third feature raises laser safety significantly and is required by some local regulations. This can be for example a plasma detection sensor where the handheld torch includes a photo sensor to monitor plasma. If there is not sufficient plasma light created after the start of a weld, the equipment will automatically turn laser emission off. Another option is to use a foot-control, which has to be pressed in addition to activate the laser emission.
4. The fourth feature is an optical interlock circuit in the fiber optic cable set to verify the integrity of the connection between the welding torch and the laser power supply.

Examples of common misuse

Figures 9-12 below show photographs of unsafe work practices related to HLBW.

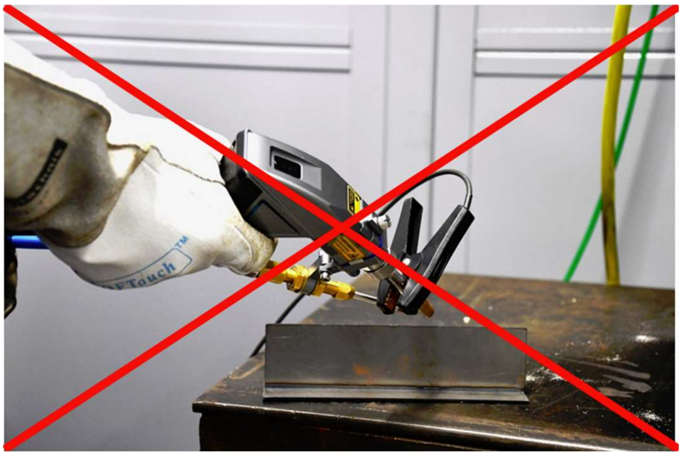


Figure 9. Photo showing contact tip to work bypass [courtesy of ifw Jena, Germany].

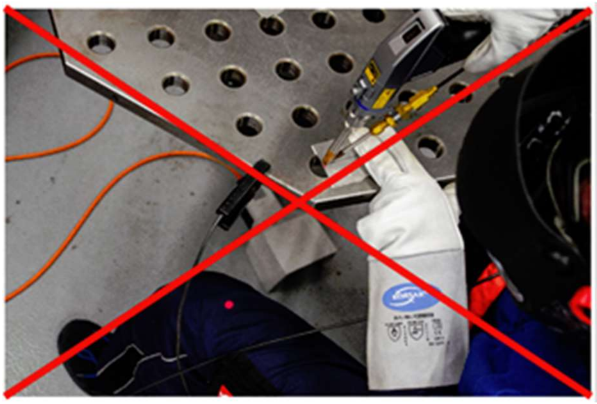


Figure 10. Photo showing HLBW considerations (workbench with holes, clamping, hand placement, etc.) that are not recommended [courtesy of ifw Jena, German]).

Figure 11. Photograph showing an unsafe HLBW hand welding practice [courtesy of ifw Jena].

Figure 12. Photograph showing a case of using insufficient PPE where facial hair is exposed [courtesy of ifw Jena, Germany].

Organizational and Workplace safety requirements

Each organization or any sole operator outside an organization, operating Class 4 lasers shall:

1. Appoint a qualified Laser Safety Officer (LSO) or be trained as such.
2. Have a documented Laser Safety Program.
3. Have a Laser Controlled Area (LCA) for each point of use.

Operators and all persons in the LCA shall wear specified personal protective equipment (PPE), laser safety eyewear, including laser welding helmet, heat-resistant gloves, and flame-resistant clothing.

An LCA is a light-tight enclosure with laser-blocking panels, an access door with an interlock switch, and "Laser On" warning sign and/or light. An information sign is also required on the outside of the LCA listing the maximum laser power and wavelength. Any barriers or windows used in the welding area shall be made of a laser-safe material that can withstand direct and reflected beams. Figure 13 shows a photograph of an LCA with safety features.

Appropriate laser warning signs shall be posted throughout the controlled area, especially any entrances to and from the area.

Access shall be restricted to the LCA only to those individuals who are trained in laser safety while operating a laser.

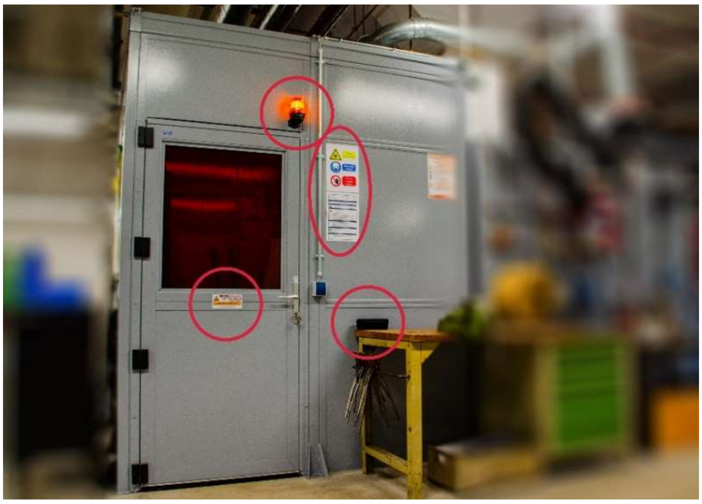


Figure 13. Example of a Laser Controlled Area (LCA) with safety features [courtesy of ifw Jena, Germany].

Welding fumes

In the HLBW process, welding fume particles are also generated from the base and filler material vaporizing in the laser beam during cooling. These are very fine and generally respirable. As with arc welding, the type of potential health hazard depends on the materials used. The same health and safety regulations therefore also apply to the HLBW process as to arc welding. As a general rule, the limit values for the substances in the person's breathing air must not be exceeded. Further information can also be found in the EWA information brochure "Introduction to methods of prevention and extraction of welding fume" [18]. If the release of hazardous substances cannot be prevented or sufficiently reduced, they must be extracted close the point of origin before they enter the breathing zone. Supportive general ventilation can reduce the concentration in the entire room and thus also protect persons not involved in the welding process. If such technical or organizational methods cannot be used or are not sufficiently effective, the only option in many cases is for the welder to wear personal respiratory protection equipment. However, it should be kept in mind that this only protects the person wearing it.

Although preliminary welding fume analysis shows that the fume generation rate of laser welding is very low compared with arc-based welding processes such as GMAW [19], hazards still exist with fumes generated from HLBW. In addition, as power levels increase, the rate of fume generation also increases. Due to the known risks of carcinogenic and neurotoxic fumes generated during welding of certain metals and alloys, an abundance of caution should be taken when laser welding in order to protect the health and safety of the welder.

HLBW Personnel

LSO qualification

Each organization shall have a qualified LSO who is responsible for the safety of operators and observers, which includes but is not limited to:

1. Conducting a hazard evaluation of all beam and non-beam hazards
2. Ensuring that all control measures are implemented and followed
3. Approving operating procedures related to the use of lasers
4. Ensuring that every operator and observer who uses lasers or is exposed to laser hazards has information and training on the safe use of the equipment and potential hazards.

Welder qualification

A manual dexterity test is also necessary for HLBW. This manual dexterity test can be carried out as a special test based on the ISO 9606 series of standards [20]. Additionally, it is to be mentioned on the certificate that the process 521 for fiber laser sources was carried out manually. No further set of rules is necessary, only an update, especially to name the "new" process. The aim, therefore, is to integrate HLBW into the standards as an own process. Initial activities have been started at ISO level for this purpose.

As an alternative, performance qualification for manual and semi-automatic laser beam welding can be conducted in accordance with table QW-358 of ASME Section IX (since Version 2023).

The time and training required for an untrained individual to become a safe and proficient laser beam welder using HLBWB has been demonstrated to be substantially less than that required for arc welding processes.

Beside the demonstration of welding skills, each welder should gain knowledge in the following areas:

- Basics and properties of laser radiation
- Laser safety
- Laser weldability of materials
- HLBW systems
- Process parameter, weld preparation and resulting weld properties

It is recommended to test the welder's theoretical knowledge with a written exam.

Weld Qualification and Quality Considerations

This section outlines weld qualifications and quality considerations. These considerations may be required in certain instances. Much of this section was adapted from existing standards and handbook chapters [19-21].

Weld Qualification

Qualified welds should be made with an authorized welding procedure that captures the customer's design requirements and safety considerations. The records for this qualified welding procedure are those needed by the welder, the employer, and the customer. They should refer to and follow the national or international standard body. If appropriate, the welding procedure should address any repair scenarios that were found to be possible during the development of the welding procedure. The development of the welding procedure should be performed with design requirements and specifications. These are typically base metal specification (if not designated by the customer), weld drawings and weld joints to be used, penetration and weld anomaly limits, mechanical properties requirements, etc. If a repair process is part of the welding procedure, then the repair should address these as well.

The welding procedure should list the following (not exhaustive):

1. Base metal(s) to be welded, including specification and dimensions
2. Filler metals to be used including specification and dimensions
3. Cleaning method for base metals
4. Tooling and fixtures to be used
5. Shielding gas specification and required flow rate
6. Laser welding equipment includes manufacturer, type of laser, and model of laser generator, optics used within the handheld device (as applicable), wire feeding system (if separate from the HLBW equipment), gas delivery system (if separate from the HLBW equipment), etc.
7. Weld joint specifics, including geometry, tolerances, etc. If possible, use drawings.
8. Laser process parameter, e.g. spot size at the workpiece, power dial settings, cw or pulsed mode, and, if possible, method used to calibrate/verify power
9. Beam oscillation parameter such as frequency, width and if applicable figure type or power compensation mode
10. Wire feed parameter, e.g. feed rate and calibration/verification of wire feed rate

To develop the welding procedure, test welds should be made to ensure that they can be made consistently. For HLBW, these test welds should be made with the intended base metals, filler metals, and laser system by a proficient welder. Once these welds are made consistently with the number of welds decided by either the customer or a national standard, then they should be inspected to verify that the welds meet the design requirements. The inspection should include both destructive and non-destructive testing. Methods may include the following depending on the design requirements: Metallographic examination (for weld dimensions, depth of penetration, weld anomalies, etc.), ultrasonic testing, mechanical testing (strength, impact toughness, hardness, etc.), radiographic inspection, etc. the use of a certified welding inspector during development may be useful in developing the inspection methods needed for ensuring the weld meets the design specifications.

Please note that the welding procedure qualification may be void if it is found that the welding performance no longer can meet the design requirements. This could either be an equipment issue or an issue with the welding personnel. If this occurs, the process and/or the operator(s) will need to go through qualification activities again to ensure the process with the operator(s) is in control from a quality-of-weld perspective.

ASME provides specific essential variables for performance qualification of manual and semi-automatic laser beam welding in Table QW-358. Although this list is not exhaustive, it provides a good starting point for qualification of welders.

To qualify the welding personnel, typically a representative number of welds should be made with a qualified welding procedure. The operator, dates, and results of test welds should be documented. This will likely be similar to qualifying welding operators for other manual welding processes. Formal training may include the following:

1. Safety. Laser and electrical (previously covered for laser safety above)
2. Operation of the HLBW system including power settings and wire feed speed
3. Verification of laser power (if applicable)
4. Reading weld drawings
5. Setting up tooling/fixtures
6. Visual inspection

Weld Joints

The types of weld joints for HLBW will include those used in machine controlled laser beam welding as well as those that are possible with manual welding and semi-automatic laser beam welding. The types of joints that are used in the machined controlled laser beam welding include the following (see Figure 14):

1. Butt Joints (square groove or slight step to self-align); single- or double-sided
2. Corner Joints (multiple variations possible including square, stepped, and flanged)
3. T-Joints (either single- or double-sided)
4. Lap Joints (lap, seam, fillet)

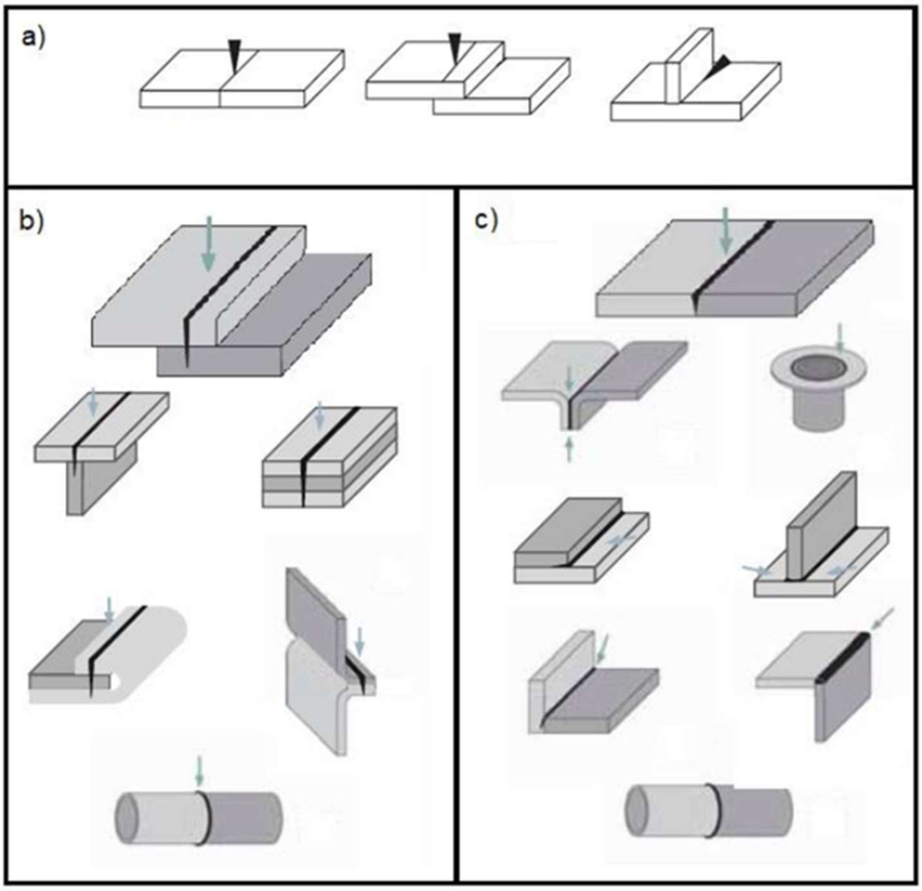


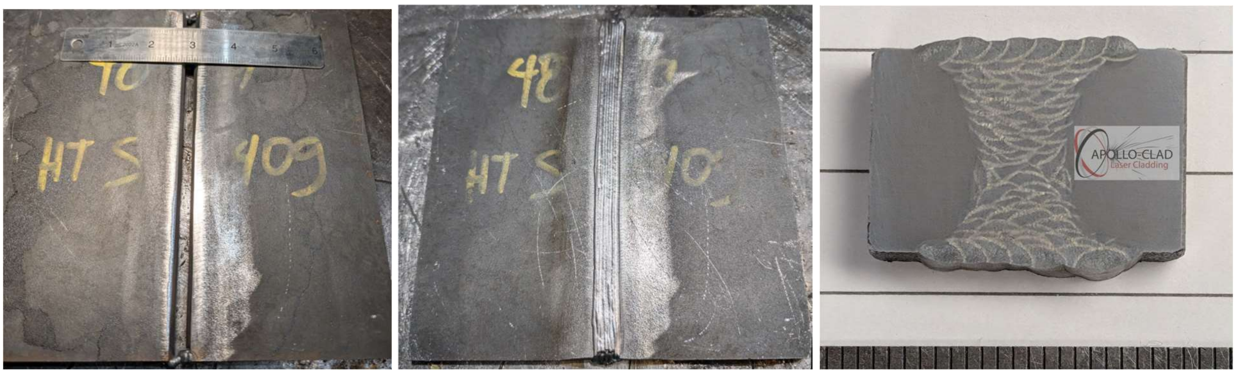
Figure 14. Most common joint designs for laser beam welding in general (a) as well as lap joints (b) and in detail (c) [courtesy of University of Oulu, FMT group, Finland].

HHLBW using filler material allows a wide variety of joint geometry including all those used for arc welding, along with joint geometry that would not be possible with arc welding, or autogenous machine or automatic laser beam welding. Weld joint geometry should be considered in conjunction with the specific weld procedure being used.

Other welding positions are able to be welded with HLBW that are not possible with the typical machine controlled laser beam welding. Figure 15 shows a photograph of an overhead weld using HLBW that would be very difficult with a typical machine controlled laser beam welding configuration. The environment for welding is within a large (10 x 30 m²) LCA inspected and approved by the local authority. The laser controlled area does not need to be a small box provided all safety features required are satisfied (like here it is).

Figure 15. Overhead welding with HLBW [courtesy of Apollo Machine, Canada].

When using HLBW systems with filler wire, conventional arc-based welding joint geometries can be used if required. With appropriate selection of welding parameters and laser welder skills, open root welding without backing can be successfully performed. Figure 16 shows a welding procedure qualification test coupon, 12 mm thick with an open root of 5 mm before and after HLBW.



(a) (b) (c)

Figure 16. Open root HLBW (a) prior to welding, (b) after welding (c) etched cross section of weld shown in b [courtesy of Apollo Machine, Canada].

Similar to other welding processes such as GTAW or gas metal arc welding (GMAW), HLBW using wire feeding can bridge higher gaps in the weld joint when compared to autogenous laser welding. Although easier with 'zero gap', multiple pass welding using filler metal of a 5 mm open root on 12 mm thick steel plate has been demonstrated successfully using HHLBW, and a procedure qualified to all the requirements of ASME IX. A challenge is not necessarily a limitation.

Additionally, HLBW typically is used in keyhole mode, but conduction mode welding is also possible. However, certain safety features, such as the plasma sensor, may not allow for conduction mode welding depending on system used and selected welding parameters.

Heat Input and Distortion Control

HLBW is inherently a low heat input welding process. In continuous wave (CW) mode, it is common to conduct HLBW using filler wire with heat input of 50 J/mm (1.2 kJ/inch) or less. At this heat input, it is possible to weld complex thin walled structures with minimal distortion. The double start cylindrical spiral (double helix) component shown below was manufactured from 316L SS using 2 mm thick material. A GTAW fabricated equivalent is shown for reference.

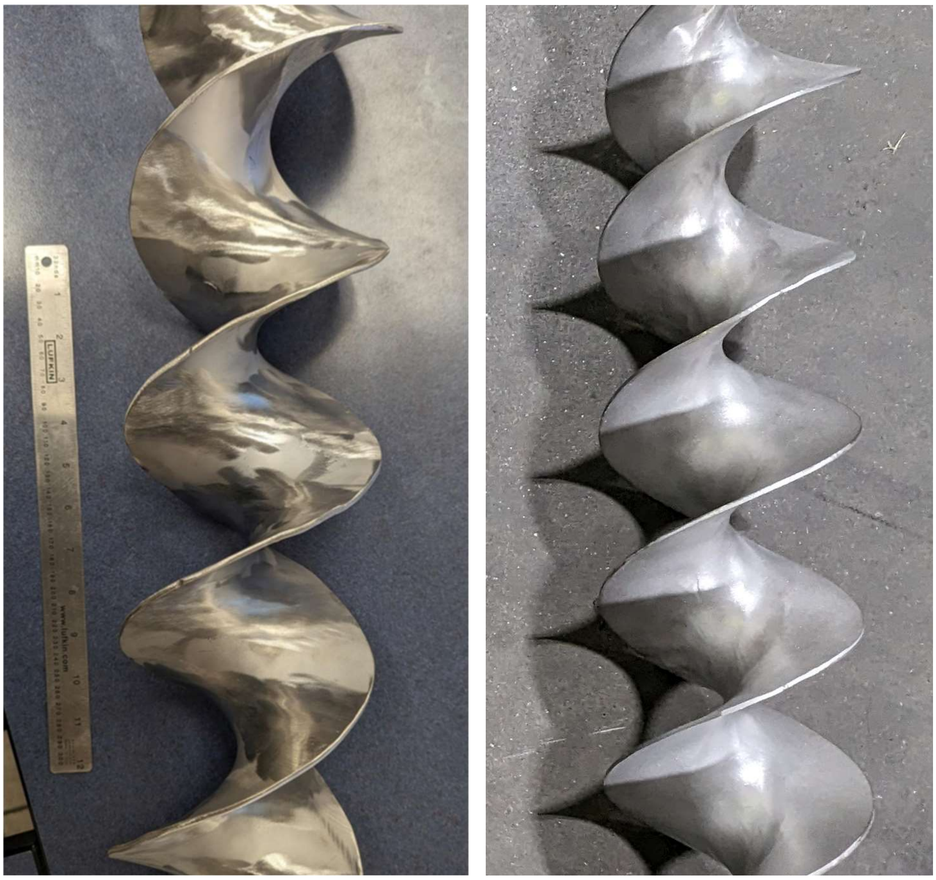
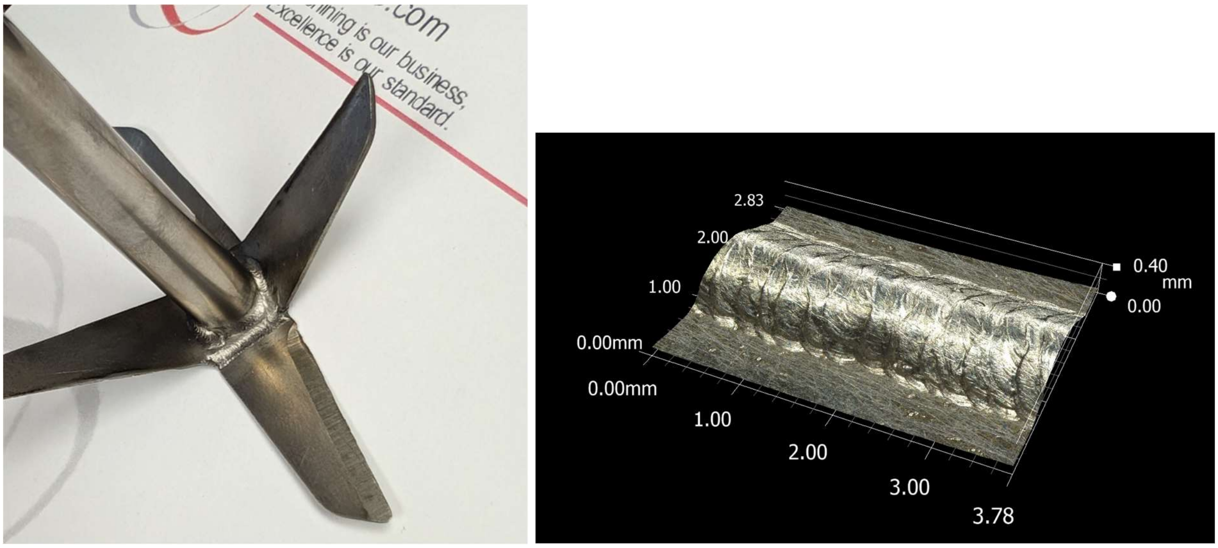


Figure 17. Double start cylindrical spirals manufactured using (a) GTAW with 3mm thick 316L SS and (b) HLBW using 2 mm thick 316L SS [courtesy of Apollo Machine, Canada].

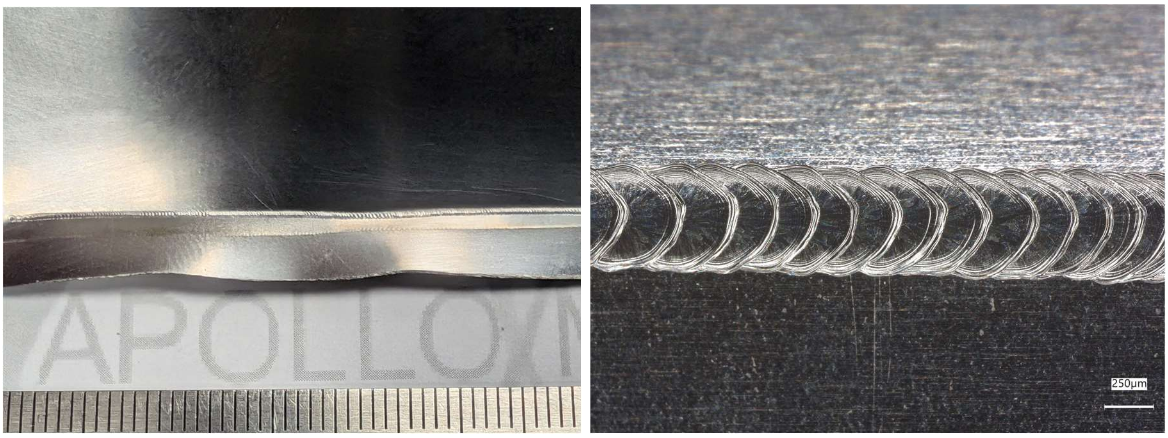


(a) (b)

Figure 18. (a) Thin-walled 316L SS welded assembling fabricated using HLBW employing pulsed welding parameters with filler wire and (b) high resolution 3D scan of corresponding weld procedure qualification test coupon [courtesy of Apollo Machine, Canada].

Further reductions in heat input can be realized by using the pulsing technology built in to most HLBW systems. When welding thin sheet materials or complex thin-walled assemblies with filler wire, pulsing is required to prevent the deep penetration capability of HLBW systems to burn through the base metal. The assembly shown below using blades made from 0.75 mm (0.030") 316L SS.

When filler metal is not required, the heat input can be decreased dramatically allowing for welding of materials as thin as 0.13mm (0.005"). The autogenous weld shown below was produced with a heat input of less than 1 J/mm.



(a) (b)

Figure 19. Autogenous weld produced using pulsed HLBW to join 0.13 mm (0.005") thick sheets of 304L SS (a) photograph and (b) stereo micrograph to show detail of weld bead [courtesy of Apollo Machine, Canada].

Metals and Alloys – HLBW Weldability

In LBW, the laser beam is the heat source similar to other welding processes. The base metal is melted and resolidified to form the weld, and the same metallurgical phenomena occur during laser welding as in fusion welding processes, however due to the concentrated energy density of the laser, the solidification and cooling tends to be much faster than fusion welding processes with higher heat input. HLBW is no different in this respect. LBW, like other high-power density welding processes such as electron beam welding (EBW) allows for a narrowly focused beam, which, in turn, may result in a much narrower and perhaps deeper weld. As such, the fusion zone and associated heat-affected zone (HAZ) may be much narrower depending on such as laser focus conditions, laser power, travel speed and other parameter.

During laser welding, the fusion zone is created from the high-energy density of the laser beam; however, the heat input is low causing a steeper thermal gradient between the molten surface of the weld pool and the underlying base metal. This may result in a high aspect-ratio weld with a minimal amount of heat input. When using LBW in a standard configuration as a machine controlled process, the welding mode can range from conduction mode (lower depth-to-width ratio) to keyhole mode welding (higher depth-to-width ratio). If HLBW is performed without filler material and a small width or no beam oscillation, the weld seam looks much like ones done by machine controlled welding. In typical HLBW with filler material and wobble width larger than 2 mm, however, the dimensions of molten area as well as of the HAZ may be like more conventional higher heat input welding processes. So HLBW welds can range from conduction mode to keyhole mode, however the welding parameters combined with the manual control of the process (ie: skill of the welder), in particular consistency of travel speed, can result in variability in the finished weld.

Metallurgical phenomena such as microsegregation/centerline segregation, compositional changes due to vaporization, porosity, cracking, grain coarsening in the HAZ, solid-state phase transformations, etc., may take place during LBW depending on the metal or alloy. In LBW, the width of the HAZ is typically substantially smaller in laser welds than in other fusion joining processes. However, during laser welding, whether manual or machine controlled the width of the HAZ depends very heavily on the welding parameters that are selected. During HLBW, the width of the HAZ may be like more conventional higher heat input welding processes. The HAZ size and properties depend strongly on the materials being welded and the specific weld procedure being used. Due to the wide range of capabilities, the technology itself is not limited to keyhole or conduction mode welding only.

Figure 20. Light micrograph showing the approximately 0.2 mm wide heat affected zone (HAZ) between carbon steel weld metal (left) and unaffected base metal (right) produced using HLBW [courtesy of Apollo Machine, Canada].

The HAZ may have a range of metallurgical responses from the heat of welding like heat treating which may include recovery, recrystallization, grain growth, precipitation phenomena, etc., depending on the metal or alloy and its condition. Phase transformations that occur during laser welding may influence the weldability and resulting properties of the weldment. Since handheld laser welds may use matching filler metal, the composition of the fusion zone will be close to that of the base metal. Subsequent heat treatment of weldments will usually result in consistent properties from the base plate into the fusion zone. Finally, when using arc processes to weld, experience is needed for qualified welds – especially when welding carbon steels. When welding stainless steels with HLBW, obtaining qualified welds appears to be much easier with little experience [21].

Several metals and alloys are typically welded with machine controlled laser beam welding. These metal systems behave similarly when using HLBW, however metal systems that have a very small operating window for parameter selection may be very challenging due to the variation that naturally comes with manual welding processes. Reminders of the weldability of these metals and alloys are given below.

Carbon Steels and High Strength Steels

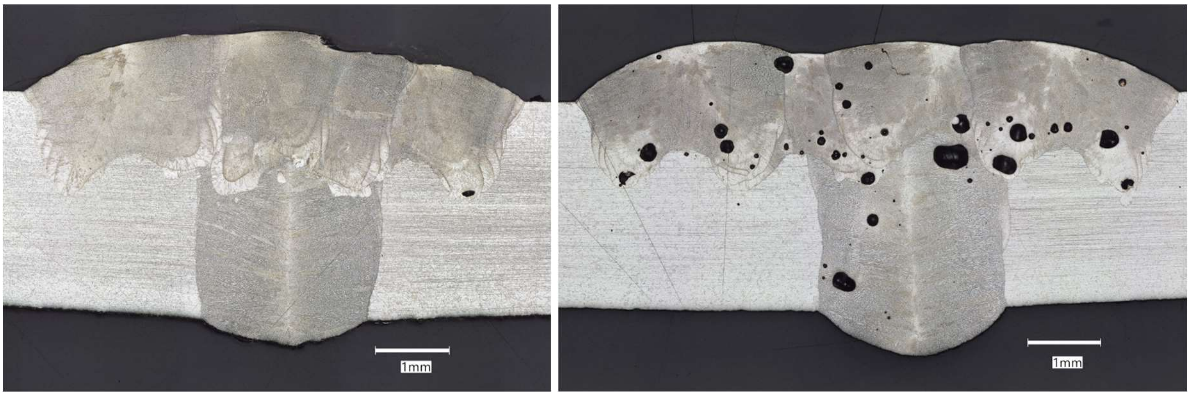
Martensitic transformations may occur in certain types of steels. In carbon and low-alloy steels, an increase in the hardness of both the fusion zone and the HAZ results in causing a steep gradient in strength, where the fusion zones are typically harder than the HAZ or base metal, which depends strongly on the hardenability of the specific grade of steel being welded. Additionally, the presence of hydrogen may cause cold cracking in the welds of high strength steels. If the shielding gas is insufficient or if the filler metal has a source of hydrogen during HLBW of high strength steels, cold cracking may result. Due to the rapid solidification and cooling rate associated with HLBW, the weld metal typically has a very fine grain structure. This fine structure will increase strength of the weld metal (Hall-Petch grain size strengthening) compared with higher heat input welding processes using the same filler metal composition. It is known that fine grain size in steels improves low temperature fracture toughness and notch impact toughness.

Stainless Steels

Stainless steels are typically Fe-Cr alloys with a nominal chromium content of at least 11 weight percent that provide resistance to corrosion because of the chromium oxide layer that forms. The alloys discussed here include austenitic stainless steels, martensitic stainless steels, ferritic stainless steels, and precipitation-hardenable stainless steels [22]. Other stainless steels were not discussed in this document. Typically, stainless steels are the easiest alloys to be welded using HLBW compared to other ferrous alloys and aluminum alloys.

Austenitic Stainless Steels

Austenitic stainless steels are usually known as 18Cr-8Ni stainless steels, typically contain chromium contents of over 16 weight percent, and have a total chromium, nickel, manganese, and silicon content of greater than 25 weight percent. These alloys may be susceptible to weld solidification cracking depending on the composition and the solidification or restraint stresses. Solidification cracking typically takes place at the end of solidification of the weld when a low liquid fraction is found between solidifying grains. The liquid is typically enriched with alloying or tramp elements, and this may cause a depression in the solidus temperature. The solidification stress caused by localized shrinkage will allow the solidification cracks to form. These types of cracks have been observed in machine controlled laser welds and may also occur in HLBW if the austenitic stainless steel is susceptible. Because of the high cooling rates during solidification of laser welded metals, the solidification modes may be changed. To avoid solidification cracking in austenitic stainless steels, the weld should solidify as primary delta ferrite as this phase has a high solubility and low diffusivity of tramp elements such as sulfur, phosphorus, and other elements. The work of Lienert and Lippold [23] has shown that the change in the solidification mode of austenitic stainless steels during pulsed, autogenous LBW and displayed this on their modified Sutuula Diagram. In addition, autogenous rewelding of austenitic stainless steels may alter the chemistry from multiple weld cycles [24]. After as few as four welding cycles, it was found that the solidification mode was observed to change from a primary delta ferrite to primary austenite solidification and solidification cracks were observed to form after rewelding.



(a) (b)

Figure 21. Light micrographs showing microstructure and porosity resulting from HLBW of 316L SS using (a) nitrogen and (b) argon cover gas while keeping all other process variables constant [courtesy of Apollo Machine, Canada].

HLBW of 316L SS can produce high quality welds with or without filler metal. The most common defect observed by metallography is small scale porosity, associated with keyhole instability for partial penetration weld passes when the laser power used is too high. High purity nitrogen is commonly used as a cover gas for HLBW of SS, since the use of argon, which is commonly used for GTAW cover gas for 316L SS welding, can result in significantly higher levels of porosity when used for HLBW. It has been proposed by Wu et. Al [25] that keyhole induced porosity can create trapped gas bubbles, and Elmer [26] and Khalid [27] have both noted the solubility of N compared with Ar in molten weld metal as a primary reason for the dramatic difference in quality resulting from shielding gas alone. Although definitive proof of this theory has not been published, the singular effect of shielding gas type on weld quality is clear.

(a)

(b)

Figure 22. Light micrographs showing HLBW of 347 SS demonstrating an absence of microstructural defects in (a) fillet weld overview and (b) increased magnification to show detail of weld metal microstructure [courtesy of Apollo Machine, Canada].

Welding 347 SS with filler metal has been performed successfully using HLBW. No solidification cracks were detected from metallographic analysis and production penetrant inspection as shown in Figure 22. The filler metal composition predicted a ferrite number (FN) of 8 based on the WRC 1992 constitution diagram, and a solidification mode of Ferrite – Austenite. The actual ferrite number of the weld measured using magnetic methods was approximately 1. David, Vitek and Hebble [28] observed that the ferrite content of laser welded austenitic stainless steels decreases with increasing welding speed or corresponding cooling rate, and concluded that constitution diagrams for austenitic stainless steels are not accurate for very rapid cooling that can occur with laser beam welding. Additionally, nitrogen is known to be an austenite stabilizing element, which may further reduce the resulting ferrite number of the deposited weld metal. Since the FN is low, but no solidification defects are observed, this may be an interesting avenue for further research to identify the specific mechanisms at play.

Martensitic Stainless Steels

Martensitic stainless steels typically have chromium contents ranging from 11-18 weight percent and harden similar to carbon and high-strength steel welds with the martensitic phase transformation. They are similarly susceptible to cold cracking issues (please see carbon and high-strength steel welds above). Preliminary experimentation using 410NiMo filler wire has shown good weldability with no defects observed in metallographic analysis.

Ferritic Stainless Steels

Ferritic stainless steels typically contain between 11-30 weight percent chromium. Although these steels are easily welded, compared to other stainless steels previously discussed, some ferritic stainless steels contain austenite stabilizers that may allow austenite to form during the welding thermal cycle. If this happens, martensite may form upon cooling and could decrease the ductility and impact energy absorbed values. David et. Al [28] found that for autogenous laser welding of ferritic SS, the rapid cooling rates completely suppressed the ferrite to austenite transformation, resulting in a fully ferritic microstructure.

Precipitation-Hardenable Stainless Steels

Precipitation-hardenable (PH) stainless steels are heat treatable resulting in relatively high strengths. These stainless steels may be martensitic types (such as 17-4 PH/UNS S17400 and PH 13-8 Mo/UNS S13800), semiaustenitc PH stainless steels such as PH 15-7 Mo/UNS S15700, or austenitic such as UNS S66286. The strengthening precipitate range in type and structure. Some of the PH stainless steels are susceptible to solidification cracking like the austenitic stainless steels, although they are typically less susceptible compared to the austenitic stainless steels.

HLBW of 17-4 PH produces weld metal of high strength in the as-welded condition. Experiments welding 3D printed 17-4 PH using matching filler metal composition failed in the weld metal at 1170 MPa (170 ksi). Direct aging to the H1150 condition following laser welding reduced strength while increasing ductility, and subsequent tensile testing resulted in failure in the base material opposed to weld metal failure for samples tested in the as-welded condition [Kamyabi et. al, submitted for publication].

Duplex Stainless Steels

These stainless steels are ferritic-austenitic stainless steels that provide a good combination of better corrosion resistance than many ferritic stainless steels and higher strength compared to austenitic stainless steels. These are likely weldable by HLBW, no data with these alloys are available related to HLBW.

Nickel-Based Alloys

Nickel-based alloys are typically used in applications for higher-temperature and corrosion service environments, that require exposure to high temperatures and corrosive environments. Laser processing is typically used with these alloys. If one of these alloys is weldable by other processes, such as HLBW by arc welding, then it usually can be laser welded by semi-automatic or HLBW. Liquation cracking has been found to occur in the HAZ of laser welds in some nickel-based alloys. Many of these alloys may contain alloying additions of boron and zirconium which could cause intergranular HAZ cracking. Nickel and nickel copper alloys are also typically weldable, but tramp elements such as sulfur and phosphorous may cause solidification cracking similar to that discussed in austenitic stainless steels above. Some of these alloys are susceptible to strain-age cracking, where stresses cannot be accommodated during aging after welding. This coupled with the contraction that occurs because of the precipitation of the gamma prime phase.

Inconel 625 is used widely across a number of industries and is considered to be readily weldable. HLBW of IN 625 has demonstrated excellent results, both in applications of joining IN 625 using matching filler metal, as well as using IN 625 as a repair or overlay material on other alloys, such as age-hardened IN 718.

Figure 23. Single side welding of IN 625 tube with matching filler wire produced using HLBW [courtesy of Apollo Machine, Canada].

Aluminum and Aluminum Alloys

Laser welding of aluminum and its alloys may have issues with laser welding because of the following:

- The low absorptivity of laser energy with aluminum
- The high thermal diffusivity of aluminum
-
- High vapor pressure elements found in aluminum alloys (e.g., Zn and Mg) could lead to porosity in welds
- Vaporization of the high vapor pressure elements may cause issues with mechanical properties

A number of aluminum grades are weldable and should be weldable with HLBW either with or without filler metals. These grades include the 1000 series of aluminum and certain alloys in the 2000 series and 5000 series. Aluminum alloys are prone to porosity in the welds caused either by hydrogen contamination or from the high vapor pressure alloying elements. Solidification cracking may also be an issue when welding certain aluminum alloys with the handheld laser process. Alloys in the 2000, 6000, and 7000 series are susceptible to solidification cracking and filler metals are typically used to prevent this.

Welding of Aluminum grade 6061 – T6 is challenging, and often results in softening of the HAZ due to dissolution and/or over aging of precipitates designed to provide strength. Due to the concentrated heat input of HLBW, 6061 has been successfully welded using ER5356 filler wire with minimal distortion and without cracking as shown in the image below. Direct aging of 6061 weldments has shown potential for further increases in weld metal strength, while maintaining acceptable bending properties to meet weld qualification test requirements. For example, as standard heat treatment for 6061 of 1 hour at 400°F resulted in a 30% increase in tensile strength of the weld metal, without measureable distortion on a 3mm thick plate.

Figure 24. Thin walled fabrication using 6061-T6 aluminum welded using HLBW with ER5356 filler wire [courtesy of Apollo Machine, Canada].

Titanium and Titanium Alloys

Titanium and its alloys are important in industries where corrosion resistance and light weight are needed. These metals react with oxygen, hydrogen, nitrogen to form brittle compounds, so care must be taken when choosing the inert cover gas and nozzle during welding to avoid the formation of these brittle compounds. Some titanium alloys are susceptible to HAZ cracking, although most of these metals are easily laser weldable in a clean atmosphere.

Nitrogen should not be used as a cover gas for titanium and it's alloys due to the risk of formation of brittle Ti-N phases.

Refractory Metals and Alloys

Refractory metals such as molybdenum, niobium, tantalum and tungsten are laser weldable. Some of these metals, such as tungsten, are prone to weld cracking because of the ductile-to-brittle transition found in body-centered cubic metals. Similar to titanium, a clean atmosphere is needed to avoid cracking from the formation of brittle compounds which may form from hydrogen and oxygen.

Dissimilar Metal Welds

Similar to machine laser welding, HLBW is suitable for dissimilar metal joining. Common dissimilar welds that should be weldable with HLBW include joining different grades of stainless steels. When joining other grades, such as titanium to stainless steel, cracking typically results because of the formation of various brittle intermetallic compounds. As such, care must be taken when making dissimilar metal welds with handheld laser processing.

When welding dissimilar materials using HLBW, laser parameter selection is of critical importance. Due to the capability of most HLBW systems to achieve deep penetration welds, excessive mixing of dissimilar metals followed by rapid solidification and cooling can result in liquation cracking, porosity and other defects that may or may not be apparent on the surface of the weld bead.

In an extreme example of dissimilar metal welds, HLBW has been used to successfully weld a hot isostatically pressed (HIP) block of tungsten carbide and Kovar to a ground engaging tool casting for a mining application.

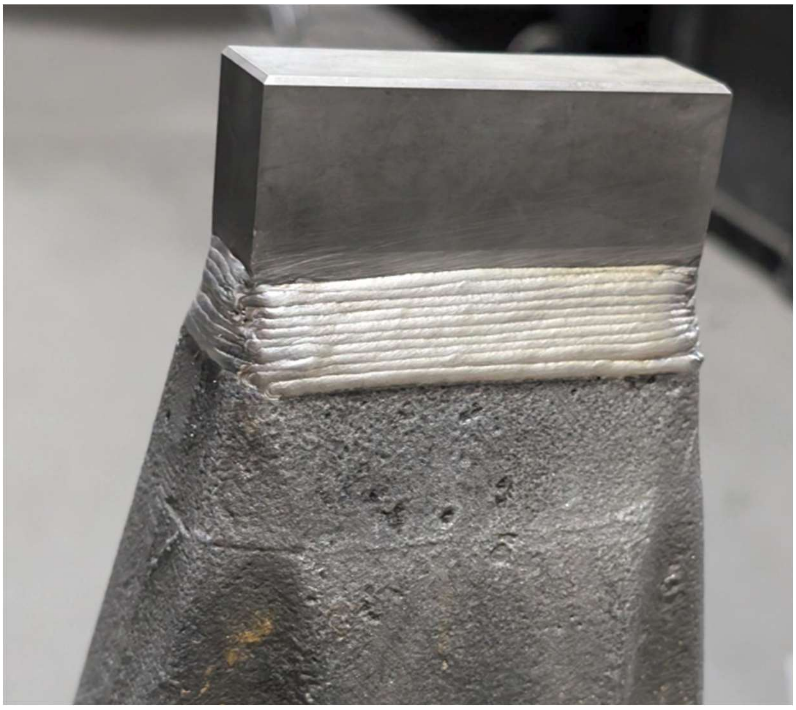


Figure 25. Dissimilar metal weld completed using HLBW with Tungsten carbide (Top) welded to a wear casting for a mining application [courtesy of Apollo Machine, Canada].

Consumables/Filler Metals

In the case of cold cracking susceptible alloys, the filler metals should be stored in an appropriate container to avoid hydrogen cracking issues after welding. Most HLBW systems use bare wire, which helps to limit the absorption of moisture, which is a common source of hydrogen in welding consumables.

Shielding Gas/Plume Control

Care should be taken when welding titanium and other gas-sensitive refractory metals, these are regarded as laser-weldable but often require specialized shielding gas setups. The gas must be high-purity argon or helium, and an additional trailing shield gas nozzle is often used to prevent nitrogen and oxygen embrittlement of the cooling weld bead. Such specialized trailing shield gas nozzles are impractical to fit to handheld devices and cannot be used in most applications. When welding titanium or other metals prone to gas interactions, care should be taken that shield gas coverage is sufficient for both the melt pool and the cooling weld bead.

Weld preparation

Some HLBW systems also double as laser cleaning systems. Laser cleaning is an effective method of joint preparation for some metals but should not be relied upon exclusively. Incomplete removal of aluminum oxide films, for example, can lead to weld anomalies when welding aluminum alloys. It has also been reported that certain laser cleaning parameters on certain metals can lead to localized surface melting which embeds impurities. Testing should be performed before replacing a previous cleaning and oxide-removal process with laser cleaning to ensure that the laser cleaning process is sufficiently robust and equivalently effective at removing the oxide film.

Summary

HLBW is an exciting and promising process that is relatively new for the welding and joining community. This document was borne out of necessity to ensure that this process is performed in a safe manner overall. In addition, several other considerations are presented which include education, qualification, and metallurgical considerations. This document should be used as a guideline for using HLBW in a safe manner with a variety of weld joints and materials. It is anticipated that this document will be updated periodically with further considerations that are yet to be found as the use of HLBW will continue to expand.

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