Potential of handheld laser beam welding

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Abstract. Since 2023 at the latest, handheld laser beam welding systems (HLBW) gained interest by many companies. This is mainly due to two factors. Firstly, the cost of such a system has fallen considerably in recent years. Secondly, there is an economic pressure for the manufactures of welded products, partly due to the shortage of skilled workers. This publication addresses various aspects of HLBW, in particular the current state of the art and the potential applications. The higher throughput, less straightening work due to the lower heat input, and the use of less experienced personnel has to be mentioned here. However, welders still need to be qualified, especially to get informed about the hazards of laser radiation. In addition to welding, many systems for HLBW also include a cleaning function, some even a cutting function. The risks to be considered for both last mentioned are significantly greater, since on one hand, a touchdown or contact control is often omitted and on the other, the laser beam is conditioned for a longer working distance. For HLBW, the requirements of the process must be taken into account during the design phase already. This continues with edge preparation, e.g. pre-weld cleaning. HLBW is a supplement to traditional arc welding processes. Arc processes will be still used in the future as well, e.g. for small, complex geometries or in terms of accessibility. However, for longer welds, e.g. 1.5 m long 2 mm thick stainless steel sheets, HLBW sets currently the standard, especially with regard to the welding speed for manual welding.

Keywords: handheld laser beam welding, laser safety.

1. Introduction

In general, the term "manual laser welding" (Fig. 1) refers to systems in which the laser head is fixed and the motion between part and laser head is carried out by manually sliding or moving the work piece. It also refers to systems in which the laser head is mechanized/partially automated and the motion of the laser head or the work piece is controlled for example by joystick.

a) b)

Fig. 1. a) Typical manual welding laser and b) work area [photos taken at ifw Jena, January 2024]

HLBW (Fig. 2), on the other hand, is comparable to hand-guided arc welding processes. A handpiece/welding head/gun/laser torch is guided over the work piece, but the energy used to melt the material is coherent radiation and not an arc. The laser torch is in the welder's hand and is guided by the welder.

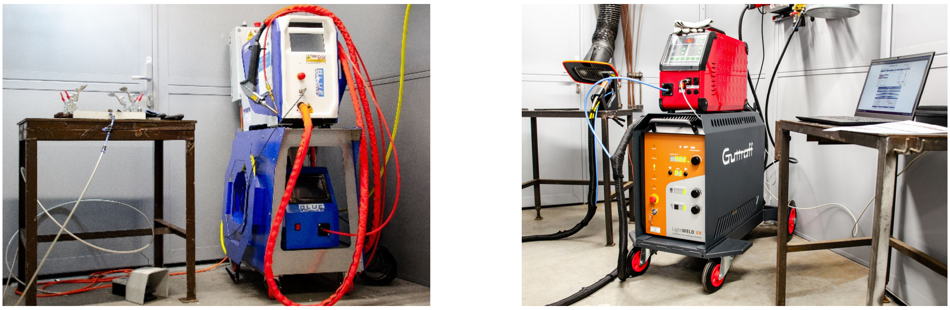

Fig. 2. Different HLBW systems [photos taken at ifw Jena, January and August 2024]

2. History and State of the Art

Historically, a first patent (DE2145921 – Device for material processing by means of a laser beam with a flexible light guide) for HLBW was registered in Germany in 1971, and first welding results were published by Nath in 1974 [1]. This was followed by further patents worldwide, including for various processing heads or laser torches, such as a gun shape, around 1980 (US 4237364 – Welding tools and method), for the integration of sensors or for different methods of filler material feed. However, the main obstacles against widespread use were the costs of the laser beam source and the sometimes unhandy as well as heavyweight laser torches.

Since the turn of the millennium, there have been repeated phases in which the topic of HLBW got into focus again, for example after the introduction of laser welding in automobile manufacturing and the desire for same process repair methods. One document, a final report on “Constructive safety devices for handheld lasers for material processing” was published as early as 2011 [2]. Processing heads that completely shielded the laser radiation from the environment existed. However, the disadvantages were the weight and size and the resulting difficulty in handling.

It was at the beginning of the 2020s, when the costs for 1 kW laser beam sources dropped to a level, which allowed the process to be more widely used. Furthermore, the laser torches were be miniaturized (today down to 500 g).

Parallel to the system cost drop and increased interest of companies into HLBW, the research activities about this laser process started growing. In 2020 Proskuryakov reported the application of HLWB for welding of aluminum [3]. It is to be mentioned, that even in this year, the experiments were carried out manually as well as automated (laser torch attached to a CNC gantry). About the development and application of a HLBW system published Xin a paper in the same year [4]. Beside application and resulting properties, e.g. about parameter influences [5], effects of different shielding gases [6, 7] or HLBW of titanium [8], system development is another area of research, like a smart laser torch [9]. Holmström did an evaluation of different aspects on HLBW, including economics and welding fumes [10]. Further publications concentrating on laser safety aspects were provided by Owczarek [11] and Pöllän [12] in 2024.

3. Systems setup

The systems currently offered consist of the following components: laser beam source with integrated control unit, optical fiber (“hose package”), laser torch and optional wire feeder. Depending on the supplier, the complete systems are portable or installed on a trolley. HLBW systems are mostly equipped with a fiber laser beam source that can have an output power of up to 4 kW. The laser beam source is a major cost factor in HLBW systems. Until a few years ago, the price of 1 kW of laser beam power was well into the six-figure range, but today beam sources

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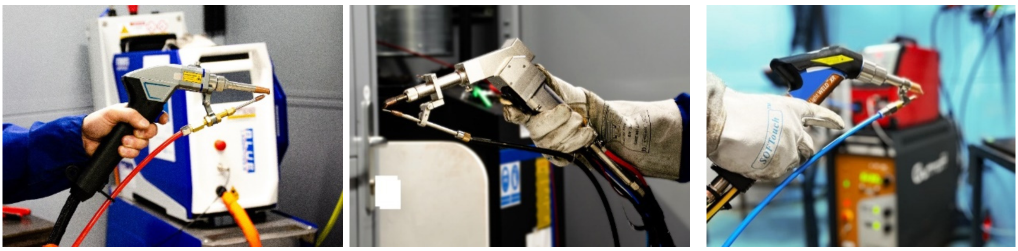
with 1 kW are already available on the market in the four-figure range. This means that complete systems can be purchased starting at around €10,000.

Both multimode and single mode laser beam sources versions are offered, with the latter typically providing a smaller minimum focus diameter and so a higher maximum penetration depth. Depending on the maximum power and the type of the beam source as well as the material to be welded, penetration depths up to 10 mm are possible. The cooling of the beam sources also differs. Both water- and air-cooled systems are offered. The decisive factor is the duty cycle at the set power. The systems differ here, regardless of the cooling version.

Depending on the system, the focus diameter (possible both via spacer tube and electronic control) and the welding nozzles, which serve as guide in addition to establishing contact for the safety circuit, can also be varied. Process parameters affect, among other things, the welding speed, the welding depth, the seam width and the penetration on the flanks.



a) b) c)

Fig. 3. a) Laser torches with single-axis and b) two-axis beam oscillation and c) with active plasma monitoring [photos taken at ifw Jena, January and August 2024]

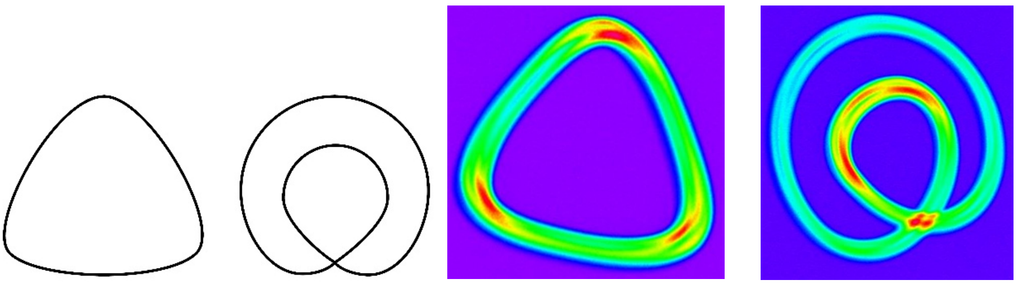
The hose package includes media lines (gas, sometimes cooling water), control lines and the optical fiber, which guides the laser radiation to the laser torch. The laser torches vary in design, particularly with regard to the oscillation of the laser beam. There are single-axis (perpendicular to the feed direction) or two-axis (perpendicular and in the feed direction) versions (Fig. 3) available. The design variant also affects the weight and dimensions.

If welding is to be carried out with additional material, among other things to increase the gap bridging capacity, a wire feeder is required. Again, the designs differ in terms of continuous or pulsed wire feed and wire retraction as well as in user interface (Fig. 4). If it is necessary to achieve a given design throat thickness or leg length for fillet welds, sometimes two or more wire feeders are in use.

Fig. 4. Different wire feeder for HLBW system [photos taken at ifw Jena, February 2025]

A wide range of parameters can be set on the systems, but once again there are differences between diverse suppliers. In addition to the laser power and operating mode (continuous (cw) or pulsed mode), the beam oscillation frequency and width respectively shape and size for two-axis beam oscillation. In addition to circles (widely used for laser spot welding), more complex shapes are also possible for the beam oscillation figure in order to tailor the heat input (Fig. 5).

As the HLBW systems differ in essential characteristics, process parameters cannot be transferred, for example from a system with a multimode laser beam source and a focus diameter of 150 µm to a device with a single mode laser and a focus diameter of 50 µm. This is not even possible for systems with similar properties, as the energy distribution in the focus can also be different (e.g. sharp Gaussian distribution vs. closer to top hat profile) [13].



a) b) c)

Fig. 5. Beam oscillation figures for two-axis beam oscillation: a) principal sketches and b), c) measured energy distribution (right) [images created at ifw Jena, January 2024]

4. Laser safety considerations

The HLBW devices are assigned as laser class IV ("open laser system"). Therefore, special attention must be paid to the laser safety regulations, especially during operation. In order to operate a HLBW system, a laser safety officer must be appointed within the company. Companies that already use a laser systems, for example for cutting, already know these requirements. However, newcomers are often unaware of this, which provides risks. From system level and welder to laser controlled area (LCA) the most important requirement are descripted in the following.

Most HLBW systems offer multi-level monitoring. The first stage is a contact monitoring: the laser beam is only released if there is an electrical contact between the laser torch and the work piece ("ground cable" between the work piece and the system). The second stage is a release button on the laser torch with "laser on" signaling. For safe use, the systems have to have a third stage in order to meet the requirements, for example with regard to the Laser Protection Ordinance (Occupational Health and Safety Ordinance on Artificial Optical Radiation). This can be an additional foot operated switch or plasma monitoring.

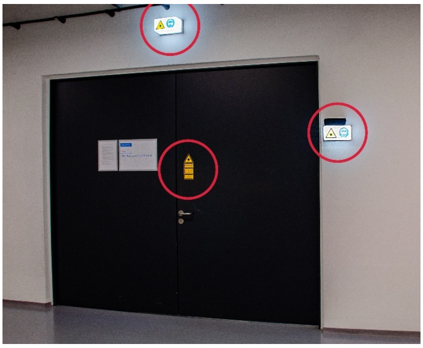
Fig. 6. Different helmets for HLBW [photo taken at ifw Jena, August 2024]

Similar to arc welding, the welder must wear personal protective equipment. The clothing used for arc welding can be used. However, due to the reflection of the scattered laser radiation and the material-related generation of UV radiation ("UV radiation during hand laser material processing"

(DGUV-FP439 [14]), care must be taken to ensure that the welder's skin is covered (gloves, e.g. according [15]). To protect the face and eyes, a welding helmet approved for laser use with integrated laser safety glazing (Fig. 6) or a combination of helmet a laser safety eyewear must be worn. If the welder uses both processes for joining, HLBW and arc welding (e.g. TIG/GTAW), the use of a hybrid helmet, providing protection for both processes, is highly recommended (in order to avoid to wear a helmet with protection for the wrong process). HLBW also produces fumes, that must be extracted [16] or a respiratory protection system must be worn as well.

A distinction has to be made between the protection of the welder and the protection of third parties. If other people are close to the welding area, they have to wear the same protection against the mentioned hazards as the welder.

The work area must be secured against unauthorized access in order to protect third parties from unprotected exposure to laser radiation (LCA) [17]. Ideally, the systems should be used in closed rooms or enclosures with ceilings. If in the work area parts were transported by crane, walls with a minimum height are required. Depending on height of room and crane clearance, the walls of cabins open at the top should be at least 2.8 m high. In addition, regardless of the design with or without a ceiling, further hardware equipment is mandatory: firstly, a "laser on" signal outside the work area, e.g. in front or beside the door. This serves as a warning against entering an area with an active class IV laser system (Fig. 7). Secondly, a so-called interlock control is required. As soon as the door to the work area is opened, the laser radiation must be switched off. Furthermore, laser safety goggles must be kept outside the work area ready to hand for emergencies.



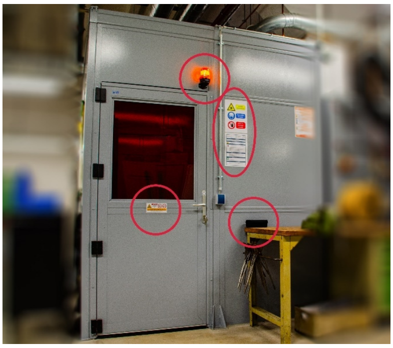


Fig. 7. Information about laser systems in use and signals
for “laser on” outside the LCA [photos taken at ifw Jena, August 2024]

5. Advantages and limitations

HLBW offers a variety of advantages compared to arc processes. Amongst others, the most important are the increased welding speed, the lower heat input and simplified training as well as operation. Depending on the seam geometry and length, the welding speed is at least 2 times higher, typically in the range of 3 to 5 times. This also means an alteration for experienced welders. The travel speed can be up to 2 m/min and higher, but it is tough for welder to keep this over a longer period. Compared to arc process, the energy input is significant lower (around 3 timer lower compared to TIG welding), but not as low as for automated laser welding since the weld seam is wider for HLBW. Based on this, there is no or less distortion and so no or only reduced straightening works necessary. This results in a decreased post weld effort.

HLBW requires less welder skills compared to TIG welding, as there is no need for precise electrode control. The training time for new welders is shorter and learning curve steeper since experience and skills were substituted by technical solutions, e.g. beam oscillation is carried out automatically in the laser torch and the wire feed rate sets the travel speed. For example, after a week of training in TIG welding, a student was able to join two work pieces together on the last day, but after only few hours of practice, he was able to produce testable weld seams with HLBW. The position of the laser torch and motion with the speed specified by the wire feed are important. The HLBW process is almost invisible to the welder; the oscillation to capture the flanks takes place automatically in the laser torch. The findings are consistent with those of others, including for example Caprio [18]. For this study, beginners competed against professionals in a comparison. Ultimately, all results are comparable, both in the dimensions of the welded joints and in terms of strength. Only the melt pool / weld seam width variation was smaller for the professionals.

Beside the advantages, there are limitations for HLBW as well. The first to mention are the laser safety requirements. Beside a HLBW systems, which applies to the given safety rules, a LSO is necessary as well as LCA, e.g. an enclosed work area with access control. Since the process is carried out by hand, there is less control of welding speed compared to fully automated laser welding. Today, the process understanding is not fully understood as it is for arc welding or automated laser welding processes. The set travel speed overlaid by beam oscillation lead the weld seam appearance, which is different to already known ones, especially with regard to longitudinal view of micro graphs [19]. The application of HLBW by experienced welders requires in most cases longer training compared to “newbies”. Welders with decades of welding experience do not produce better results. On one hand, the process behaves "differently" in terms of sensory perception (particularly sight and hearing), and on the other hand, setting the travel speed by the wire feed is unusual for most trained welders. Last to mention as disadvantage is the challenge given by some materials – because of their reflectivity properties. Especially Al- and Cu-materials need welding systems with higher requirements, e.g. single mode laser sources and higher power.

6. Weld properties and applications

The achievable penetration depth depends amongst others on the material type, the power and the type of laser beam source. Due to the smaller focus diameter of single mode laser beam sources (30-60 μm) compared to multimode versions (typically 100-150 μm), penetrations depths that are 1.5 to 2 times higher can be achieved. Currently, 8 mm is listed as penetration depth for steel, which can be realized by several systems. With a 2 kW multimode laser beam source, a welding depth of 4 mm can be reliably obtained in steel, with a single mode system with same power around 8 mm. One-sided full connections in a T-joint can be realized, but a flat angle of attack must be selected for this and the laser torch guided in an unusual angle compared to arc processes (Fig. 8).

Fig. 8. Different T-joints done by HLBW [photos taken at ifw Jena, January 2024]

The gap bridging ability is similar or slightly lower compared to TIG welding for standard joints. Areas with a wide gap can be particularly problematic for HLBW. But more experienced HLBW welder can even fill gaps of 5 mm. But the HLBW approach for is different, here is the multipass principle often used.

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If the process parameters are set right, welds can be produced that meet the highest requirements. If this is not the case, however, deficiencies in the form of pores can occur inside. These cannot be seen from the outside. That is why the use of X-ray evaluation is highly recommended during parameter development (see pores in Fig. 8 and 9).

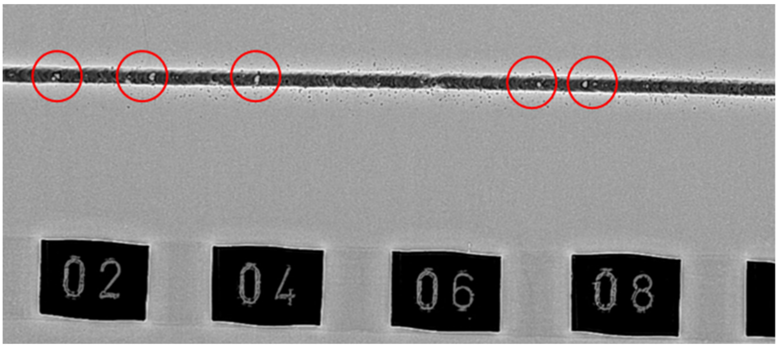


Fig. 9. X-ray image of a HLBW joint showing porosity [photo taken at ifw Jena, January 2024]

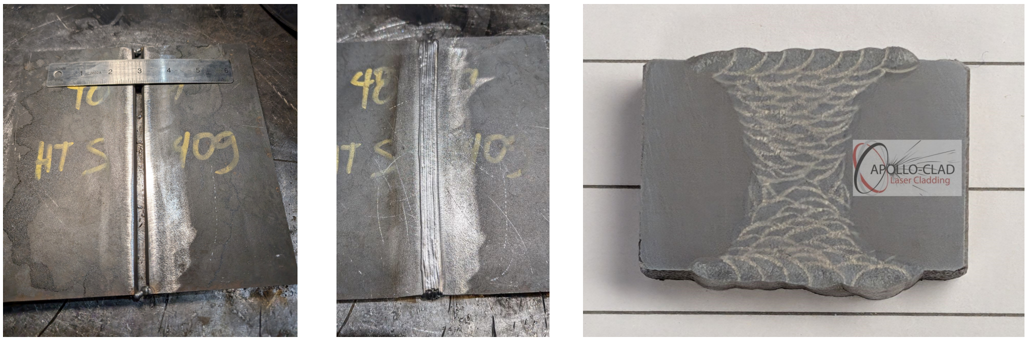
The advantages of the higher welding speed are particularly evident for longer seams of 20 cm or more. To compare performance, a stainless steel component, a funnel for winery, was welded, with TIG welding being used for one half and HLBW for the other half (Fig. 10).

With HLBW, a higher welding speed of up to 140 cm/min was achieved compared to TIG welding on 1.4301 stainless steel with a thickness of 2 mm. Companies that already use the HLBW process report a 30 % to 50 % higher throughput (chrome-nickel steel welding in the thin sheet area). The increase in production rate depends mainly on length of weld seams. The rise is attributed to the higher welding speed on the one hand and the lower straightening effort on the other.

Fig. 10. HLBW welding of the stainless funnel made for winery [photo taken at ifw Jena, September 2023]

Today HLBW is applied in various areas. A few years ago, the first application were in the field of stainless steel and in the thin sheet thickness area (up to 2 mm) only. For arc welding, stainless steels needs experienced skills, but for HLBW it is one of the easiest materials to weld. Based in this, the first applications were in the stainless area, e.g. kitchen, switching cabinets and others components made of this material. With increasing power and decreasing focus size (transition from multimode to single mode laser beam sources), high reflective materials got into interest as well. Today most of materials, traditionally welded with arcs, are joint by HLBW at least in research environment. In addition to the materials, there was further application growth in terms of material thickness. With appropriate selection of welding parameters and laser welder skills, open root welding without backing can be successfully performed. Fig. 11 shows a welding procedure qualification test coupon, 12 mm thick with an open root of 5 mm before and after

HLBW as well as a cross section. Another example for large parts is a base plate of a biogas plant made of stainless steel. In total 350 m weld seams were done in I-configuration with nearly no distortion and passed all penetration and x-ray NDT evaluation [20]. Besides seam welding, HLBW can be used for tack welding as well and further for spot welding [9]. Applications for spot welding include connections between individual battery cells or other electrical contacts.



a) b) c)

Fig. 11. Open root HLBW: a) prior to welding, b) after welding c) etched cross section of weld shown in b [courtesy of Apollo Machine, Canada]

7. Welder qualification

A welding test is recommended and further required if HLWB should be used in regulated industries. This manual welding test can be carried out based on ASME Boiler and Pressure Vessel Code Section IX [21] or ISO 9606 series of standards [22]. As special, it has to be mentioned that the process (521 for fiber laser beam source, 523 for diode laser beam source) was carried out manually. No further set of rules is necessary, only an update of the existing standard. The aim, however, therefore is to integrate HLBW into the standards as an own process. Initial activities have been started at ISO level for this purpose. In the ASME Code, section IX, HLBW is included since the 2023 edition.

Educational institutions and material testing centers are already able to offer courses and examinations in the area of HLBW as well as WPS qualification. In addition to the manual skill testing (required to weld samples), the examination also includes a theoretical knowledge test (written exam). This is especially important because there is often no knowledge of laser radiation and its potential hazards. This knowledge must be trained to welders and tested.

8. Conclusions

HLBW offers a wide range of potentials, 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 for this process. This is necessary to inform the welder about the hazards of laser radiation and required in regulated industries. Furthermore, the application of the process requires an appointed laser safety officer (LSO) in the company and a work area designed in accordance with laser protection requirements (Laser Controlled Area - LCA). In addition to the welding process, many systems for HLBW also include cleaning and cutting features. The risks to be considered here are considerably greater, since on the one hand, a touchdown or contact control is often omitted and on the other hand, the beam is conditioned for a larger working distance.

In order to utilize the full potential for HLBW, process requirements must be taken into account during the design and preparation (e.g. cleaning). HLBW is a supplement to conventional arc welding processes, although arc processes still have their place, for example with small, complex geometries or in terms of accessibility. However, if longer parts, for example 1.5 m long, have to be welded and these were prepared accordingly, HLBW is currently the new standard, especially with regard to welding speed for manual processes.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

Simon Jahn: conceptualization, writing, supervision. Martin Schmitz: investigation, funding acquisition. Matthias Pieper: data curation. Robert Prowaznik: investigation. Johannes Lange: visualization.

Conflict of interest

The authors declare that they have no conflict of interest.

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