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Laser Beam Welding in Vacuum – Overview of Thick-Plate Steel Application and Beyond

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Abstract

Laser Beam Welding (LBW) and Electron Beam Welding (EBW) are both processes that are well established in industry. EBW has its main application fields in thick-plate joining as well as in manufacturing automotive drive train components in small indexing vacuum machines. LBW is widely used in thin-plate welding (6 mm and below) as a stand-alone process or as part of hybrid processes with arc welding variants. Despite the continuous development of laser beam sources regarding output power and beam quality, the LBW process remains behind the EBW process in terms of achievable weld-in depths and inner weld seam quality. The process variant of LBW in low to medium vacuum (LaVa) as investigated and developed by the Welding and Joining Institute (ISF) closes the gap between the two beam-welding processes and opens up new application fields for the Laser. This includes the joining of thick-walled structures beyond the possibilities of the common LBW process as well as the energy and quality optimized joining with small weld-in depths. The following paper will give a brief overview of the LaVa process, the results achieved on unalloyed steel and a comparison with EBW. Additionally, a brief glimpse of what is possible with LaVa beyond unalloyed steel is given.

Keywords: Laser Beam Welding, Thick-Plate, Vacuum

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1. Introduction

The beam welding processes Laser Beam Welding (LBW) and Electron Beam Welding (EBW) have many similarities despite the difference in the beam-material interaction. Both processes use focused, high intensity energy input to the work piece to instantly vaporize the base material and form a vapor capillary to allow a deep penetration welding. By moving this capillary along a butt weld bevel preparation, thick-walled work pieces can be joined. The resulting weld seams typically have a high aspect ratio between weld-in depth and width of bead.

The EBW process uses a beam of electrons generated from a heated cathode, accelerated by high voltage, formed and focused by an array of coils in a beam generator. The electrons of the beam hit the surface of the work piece with up to 70% of the speed of light and intensities reaching 10^7 W/cm². The kinetic energy of the electrons transforms to heat at the impact point. With low intensities, the losses due to reflection can reach up to 30 %. Beyond a critical intensity of ca. 10^6 W/cm², the base material instantaneously vaporizes and a vapor capillary forms and extends into the depth of the work piece and the deep penetration effect is formed. With a full-developed vapor capillary, the losses from scattered electrons reduce to values of about 10 % with approx. 1 % of beam power transferred to X-ray emission. Due to scatter-effects of electron and molecules from the surrounding atmosphere of the beam, the EBW has to take place in vacuum. Especially EBW of thick-plates and oxygen affine materials require vacuum pressures of 10^{-3} mbar and below.

The LBW process uses a focused beam of electromagnetic waves in form of light with a defined wavelength to transfer energy into the work piece. Generally, the wavelengths of modern laser beam sources used for material machining are in the near infrared area. Due to the low absorption rates of common construction materials, only a small fraction of the laser beam power is absorbed by the work piece with one beam-material interaction (i.e. heating or heat conduction welding). Based on the material the reflection rates are between 70 % (Iron/Steel) and 95 % (Aluminum). Analogue to EBW the LBW forms a vapor capillary when reaching a critical intensity on the work piece surface. Energy losses from reflection reduce to values below 10 %. Multi-Mode Solid-State Lasers allow focal diameters of 0.1 mm reaching intensities of more than 10^7 W/cm². Single Mode Fiber Laser offer a beam profile near to the ideal Gaussian distribution with focal diameters down to 0.03 mm. Despite generally available with lower output powers, these modern laser types allow intensities up to and beyond 10^8 W/cm². The common used LBW under atmospheric pressures uses shielding gas to protect the molten pool from oxidation and to reduce the spatter tendency of the process.

Despite the similarities, the LBW is not able to reach the performance of the EBW in terms of achievable weld-in depth and weld seam quality at comparable beam power levels. To overcome this handicap of LBW, much effort was dedicated in the development of laser beam welding in vacuum.

2. Laser Beam Welding in Vacuum

The impulse for developing laser beam welding in vacuum to a usable joining process is based on isolated research done in mid to late 1980s [1]. Target of these investigations was the reduction of the plasma plume inherent to CO_2-laser welding by reduction of the ambient pressure. As a mere side effect also an increase of achieved weld-in depths was noted but not further investigated.

At the ISF, first investigations were made with a modern single-mode laser power source with 600 W output power in 2009 [2]. Welding trials with a modified remote welding optic at an EBW chamber also showed a significant reduction of the visible vapor-plume above the keyhole. With elsewise constant parameters the achieved weld-in depth was quadrupled from a process on the border between heat conduction and deep penetration welding at ambient pressure to fully developed deep penetration welding at mere 10 mbar vacuum pressure. Cross-sections from these weld seams also showed a striking similarity to EBW seams reproduced with comparable beam and welding parameters but a pressure of 10^{-3} mbar [2].

While the reduction of the visible plasma plume may be the most apparent result of bringing the LBW process into vacuum, the main factor for the increase in weld-in depth is the change of the boiling point of the molten base material. Since there is very scarce information on commonly used construction materials, this effect can be shown by the vapor pressure curve of iron, the main element of steels, see Fig. 1.

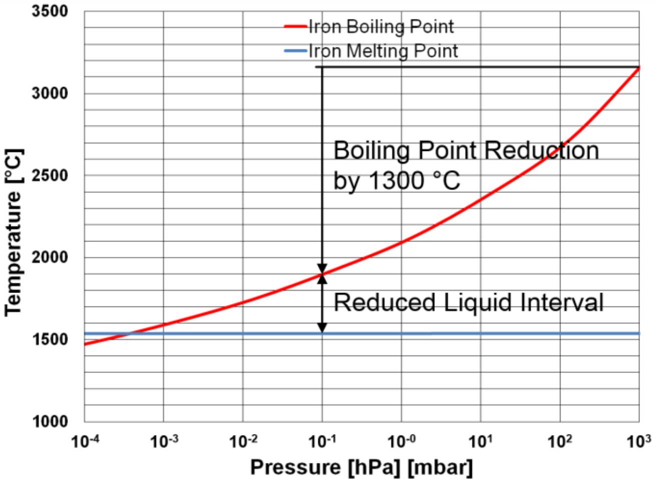


Fig. 1. Impact of pressure reduction on boiling and melting point of iron

With a simple reduction of the working pressure to 10^{-1} mbar, the vaporization temperature of molten iron is reduced by approx. 1300 °C. This reduction leads to several effects. First, the amount of energy needed to transfer the molten material to vapor, which is necessary to form and stabilize a keyhole, is significantly reduced. Second, even the very first trials performed by ISF using 600 W laser power suggest that the critical intensity to form a keyhole is reduced by the lower vaporization temperature. The third effect is connected to the fact that, while the boiling point is strongly affected by the reduced pressure, the melting point of the material is nearly unchanged. This suggests that the temperature at the boundary layer between the vapor capillary and the surrounding shroud of molten material is lower in vacuum than in ambient pressure. Given the largely pressure independent value of heat conductivity and melting point of common construction materials, it seems safe to postulate that the thickness of the shroud of molten material around the vapor capillary is lower in reduced pressure. Therefore, the reduced ratio of molten material and inner surface of the vapor capillary increases the stability of the keyhole and produces deep, narrow inner weld seam geometries.

Based on these first results, the further development of laser beam welding in vacuum from a basic research topic to an industrially usable joining process was decided. To allow application-oriented development of the new process variant, a dedicated vacuum chamber for laser beam welding in vacuum with tailor-made optical system and new developed coupling window protection was planned and realized. The setup allows welding trials with laser powers up to 16 kW at vacuum pressures down to 5×10^{-2} mbar. Target of the welding system is the further investigation and development of the process variant for thick plate application. Therefore, the movement axles and the clamping mechanism is designed to handle plates with thicknesses up to 120 mm and weights up to 150 kg with an operational range of 300 mm x 300 mm. The optical system features a focal length of 930 mm and a low aspect ratio of 1:2. This setup is enhanced by the possibility to add a beam oscillation with frequencies up to 1 kHz (sinus, triangle and square wave) and oscillation widths of up to 6 mm. The cylindrical setup of the 600 l vacuum chamber, resting on frame with turning mechanism allows welding trials in a wide range of welding positions from PA/1G over PB/2F to PC/2G. Additionally, the welding positions PF/3G uphill and PG/3G downhill are possible.

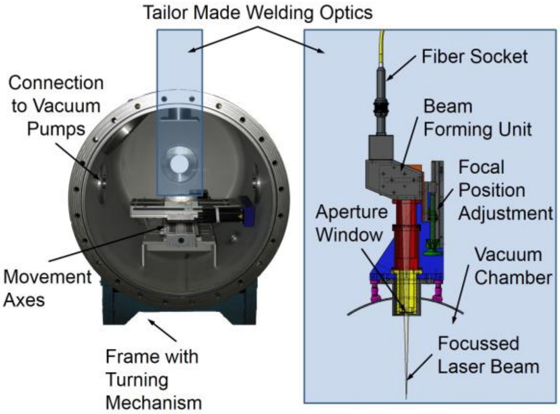


Fig. 2. Welding chamber setup for laser beam welding in thick plate application

Since the deep penetration welding process with a laser beam in vacuum generates metal vapor, special attention was dedicated to develop a safe protection system for the optical components that are exposed to these process emission. With the use of a beam-forming unit outside the vacuum chamber, there is only the aperture window as interface between atmospheric pressure and vacuum that needs protection. Never the less even slight pollution of the aperture window can lead to process instabilities and destruction of the window. To develop the laser beam welding to an industrially usable joining process, a protection system is necessary that allows numerous welds without the need to cleaning or replacing the protected parts. The actual system is the result of continued evolution and is able to protect the aperture window for a multitude of welding trials with high laser power. To give an example, the welding trials of the following chapter (n>130) were done with only one aperture window without the need of cleaning or replacing. This machine setup allowed the first fundamental research of the laser beam welding in thick plate application using both welding positions PA/1G and PC/2G.

2.1. Usable parameter ranges for laser beam welding in vacuum

Up until now the research in the topic of laser beam welding was mainly restricted to phenomenological results in the welding position PA/1G. With the target of developing process parameters for thick plate application, the altered gravity influence on the molten pool in welding position PC/2G has proved beneficial for electron beam welding. Currently, there are no known research results for this welding position. To define the usable parameter ranges for laser beam welding in vacuum for both welding positions, a welding trial matrix was developed. The welding trials were performed as weld-ins on S355. With the matrix designed to cover thick plate application, the maximum laser power of 16 kW was used. In addition, the test series was repeated with 8 kW to assess welding performance in a laser power range more common in today's industrial use. The ranges of focal position relative to the work-piece surface and welding speed were selected based on experience in electron beam welding, see Table 1.

Parameter	Unit	Value/Range
Laser Power P_L	kW	8 and 16
Focal Position f_Z	mm	0 / -5 / -10 / -15 / -20 / -25 / -30 / -35
Welding Speed v_W	m/min	0.2 / 0.3 / 0.4 / 0.5 / 0.75 / 1.0 / 1.25
Vacuum Pressure p_{vac}	mbar	10^{-1}

Table 1. Parameter ranges investigated in welding position PA/1G and PC/2G

Welding quality was assessed by visual examination of bead and cross-sections. Acceptance criteria das quality level B according DIN EN ISO 13919-1. These specifications were enhanced by additional criteria such as parallelism of weld seam flanks and minimal widening of the inner weld seam geometry over the weld-in depth. The welding position PC/2G show a very good applicability. With surface or surface-near focal positions, the whole range of welding speeds deliver acceptable weld seam quality and weld-in depths up to 64 mm, see Fig. 3 [3].

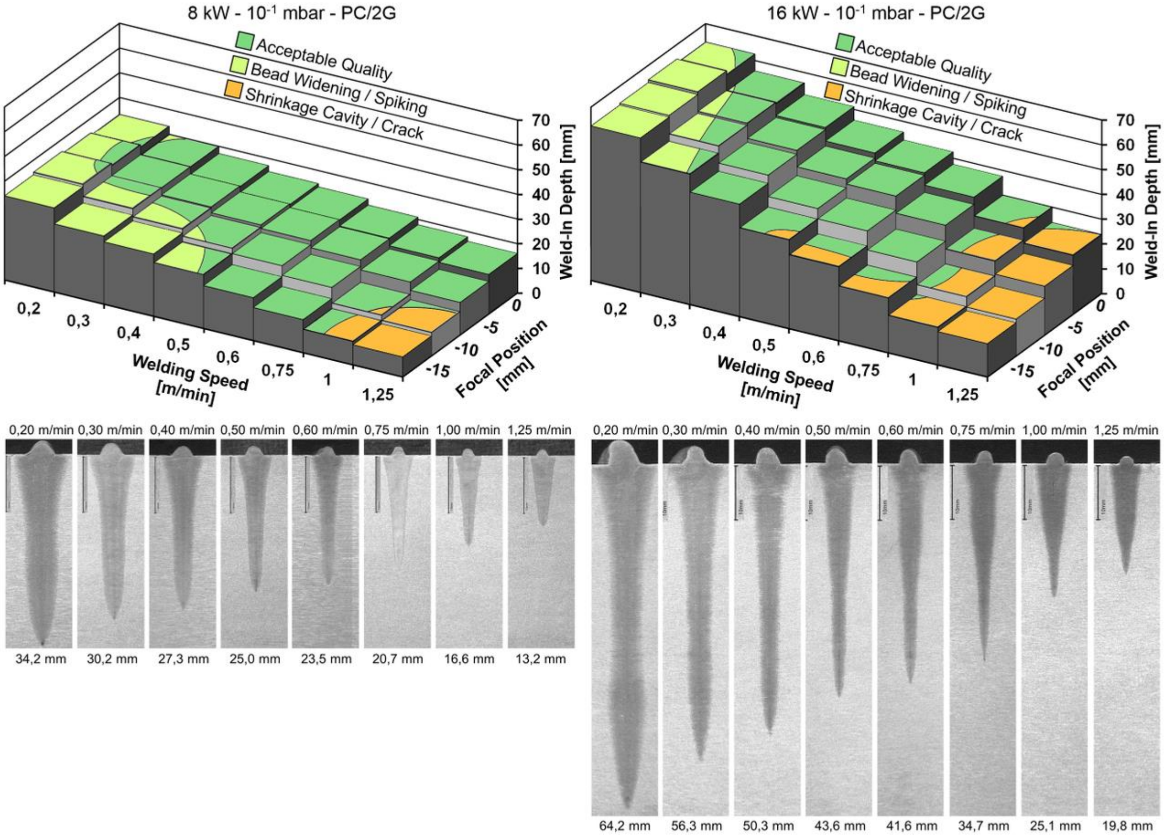


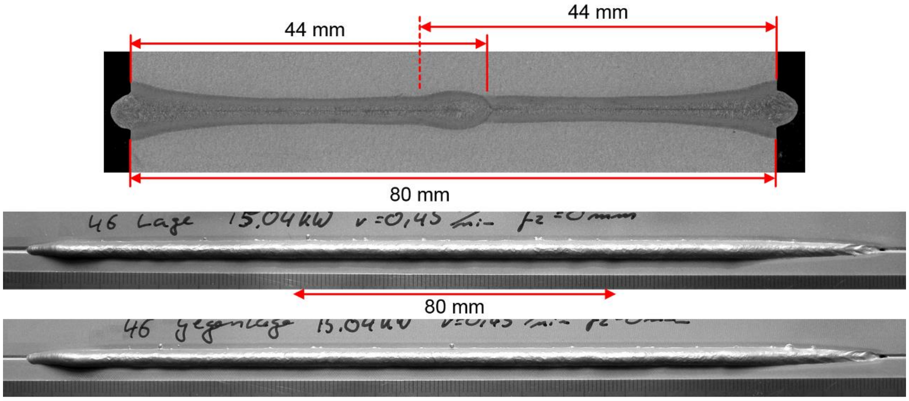
Fig. 3. Overview of usable Parameter Ranges and Cross-Sections (f_Z= -5 mm) in PC/2G – 8 kW (left) and 16 kW (right)

The evaluation of the test series offers several results. As singular welding trials showed before, the laser beam welding in vacuum benefits strongly from low welding speeds. While keeping an acceptable inner and outer weld seam geometry and quality, the achievable weld-in depth grows with reduction of welding speed. During the visual inspection of several hundred cross-sections there were only very few and small pores found. X-ray analysis on selected weld seam confirm this result. Interestingly, focal position that proved best suited for the new process variant, is on or slightly below the surface of the work piece.

Advantageously, the knowledge base compiled by these test series allows to approximate linearly between the net points of the experiment matrix. The achievable weld-in depth scales quite well with the used laser power, and also the product of weld-in depth and welding speed is approximately constant for welding speeds between 0.3 and 0.75 m/min. Based on the knowledge gained, the finding and optimization of parameter sets for given joining tasks on unalloyed and low alloyed steels is significantly reduced.

2.2. Connection Welding – Unalloyed Steel – Position PC/2G

For direct application of the parameter fields for laser beam welding in vacuum, the double-sided, single pass technique was used on plates with a wall thickness of 80 mm (S690QL). Given the fact that both of the welding runs necessary to achieve a full penetration weld are in fact weld-ins, the parameters from the knowledge base were directly usable, see Fig. 4.



S690QL - 80 mm - P_L = 15 kW, v_W = 0.45 m/min, f_Z = 0 mm, p_{vac} = 10^{-1} mbar (Argon)

Fig. 4. Connection weld on 80 mm thick plates of S690QL in double-sided, single-pass technique

The result was a very stable process with free bead formation and minimal spatter tendency. The cross-sections taken from the weld seam show an achieved weld-in depth of 44 mm and thus an overlap of 8 mm. The inner geometry is acceptable with parallel flanks.

Based on the knowledge base that lists achievable weld-in depth of up to 64 mm in position PC/2G, another welding trial with maximum laser beam power of 16 kW and a reduced welding speed of 0.25 m/min was performed on two plates S690QL with 110 mm wall thickness, see Fig. 5. Despite the increased volume of molten material, the bead still forms without tendency to sack due to the gravity influence. The increased energy per unit length leads to insignificant spattering. The inner geometry shows some tendency to local widening, but it still can be considered acceptable. For both welding runs, a weld-in depth of approx. 59 mm is achieved giving an overlap of 8 mm.

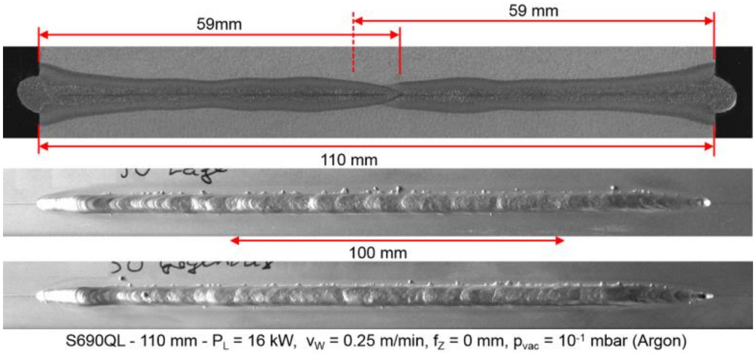


Fig. 5. Connection weld on 110 mm thick plates of S690QL in double-sided, single-pass technique

Remarkable with these trials in double-sided technique is the stability of the process. Despite quite short laser power ramps at the start and the end of the process, neither cross-section nor longitudinal cuts show significant inner flaws. The weld-in depth is stable and shows only small fluctuations, see Fig. 6.

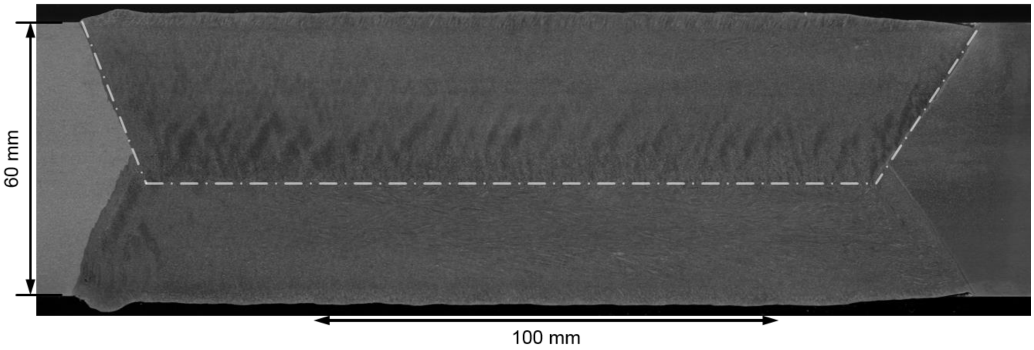


Fig. 6. Connection weld S690QL, 60 mm, double-sided, single pass technique – longitudinal cut with highlighted second welding run

Connection welding with full penetration (single-sided, single pass) requires a special interpretation of the parameter knowledge base. Because the keyhole is open to the backside, a fraction of the laser beam power used passes through the work piece. This results in a much higher energy per unit length required for acceptable weld seam in comparison to just reaching the same weld-in depth. Based on this knowledge, welding parameters were developed for the single-sided, single pass joining of 50 mm thick plates (S690QL), see Fig. 7.

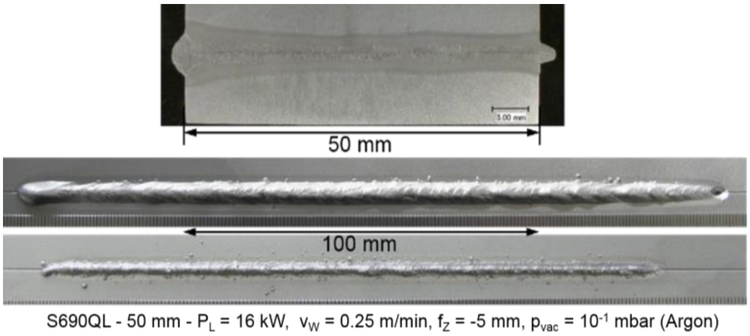


Fig. 7. Connection weld S690QL, 50 mm, single-sided, single-pass technique

The welding process with full penetration shows an insignificant spatter tendency toward the surface. Naturally, the open keyhole to the backside of the plate leads to a process-related spattering, that cannot be avoided. The bead and root formation as well as the inner weld seam geometry is acceptable with only slight tendency to local widening.

2.3. Comparison with Electron Beam Welding

The results from the parameter field definition and the test series regarding connection welds on unalloyed steel show that the LaVa process is well suited as joining process in the thick plate application. In comparison with the common LBW process under atmospheric pressure the weld-in depth scale well with the slower welding speeds without introducing excessive spattering or inner weld seam defects. Comparing laser beam welding in medium vacuum pressure at 10^{-1} mbar to EBW at 10^{-3} mbar at same or comparable welding parameters reveals that both processes deliver similar weld seam geometries, see Fig. 8.

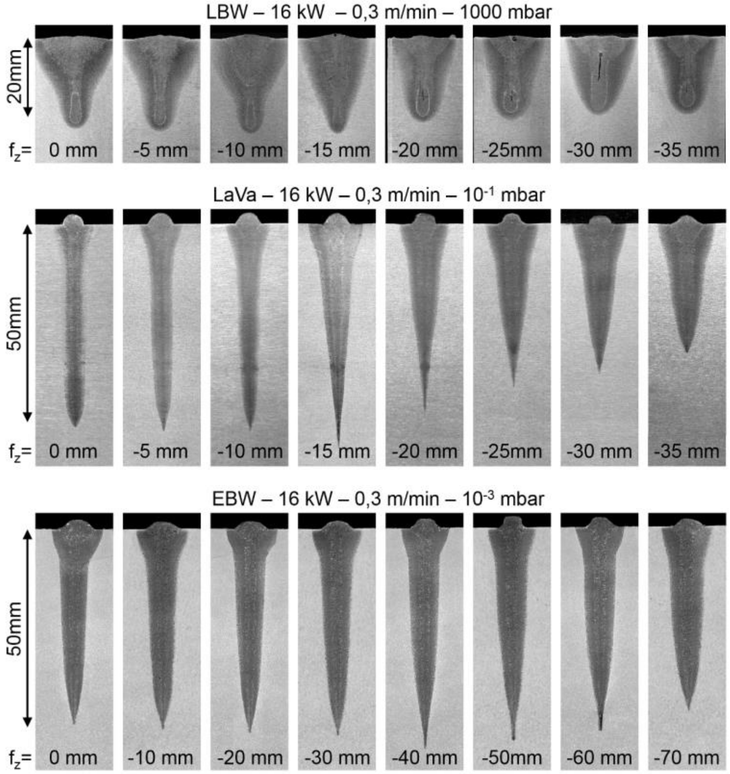


Fig. 8. Comparison of LBW – LaVa – EBW at equal beam power and welding speed with different focal positions

The main difference is that the LaVa process produces weld seams with acceptable inner geometry and optimal weld-in depth with surface or surface near focal positions. For the EBW process, focal positions deeper inside the work piece deliver the optimum in terms of inner geometry and weld-in depth. Because the raw diameter of the used EBW generator is around 10 mm compared to the collimated laser beam diameter of 60 mm, the EBW tolerated a larger range of focal positions, see Fig. 8.

2.4. Beyond unalloyed Steel

Beyond the extensive investigations on the LaVa process on unalloyed mild Steels, there have been test series on various other construction materials, see Fig. 9. Parameters for connection welds on 30 mm high strength S1100QL were directly derived. Due to similarity, the adaption of welding parameter to low alloyed steels is as well trivial. First connection welds on 20 mm thick plates of 10CrMo9-10 were realized successfully within the first shot. With increasing content of alloying elements, the differences in heat conductivity, melting point and melt viscosity influence the welding parameters. Nevertheless parameters for connection welds on 20 mm austenitic steel 1.4404 and 30 mm nitrogen alloyed duplex steel 1.4362 have been found, see Fig. 9.

Beyond iron based material, there have been successful welding trials on nickel base alloy 617 with plate thickness of 38 mm, see Fig. 9. Especially with this material, the currently investigated use of laser beam oscillation during welding is expected to be advantageous in term of inner weld seam geometry.

A quite surprise were the welding trials on titanium alloy Ti6Al4V plates with thicknesses up to 40 mm, see Fig. 9. The low heat conductivity of the material allows the use of less laser power while increasing welding speeds compared to steel materials. Despite the high affinity of titanium to oxidation, first element analysis of the weld metal and hardness measurements show now sign of oxidation despite working in vacuum pressures of 10^{-1} mbar. Further research work in this topic is planned.

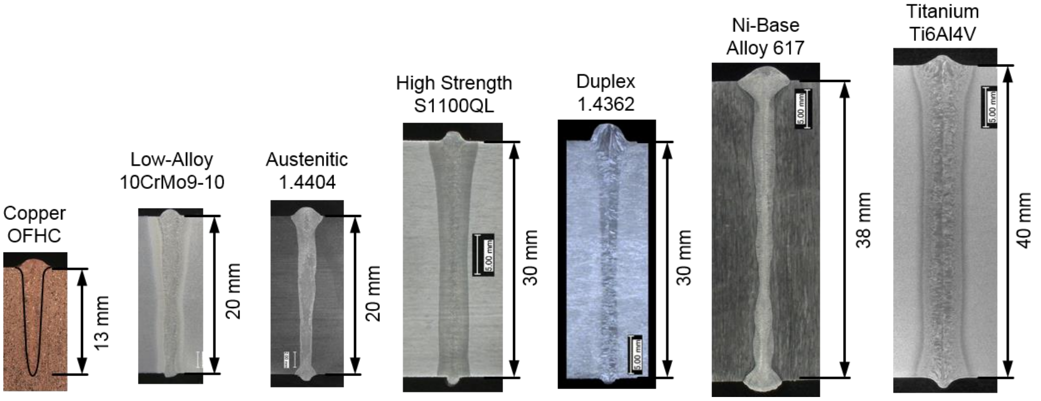


Fig. 9. Samples of welding trials beyond unalloyed mild steels

The laser beam welding in vacuum also improves the weld-ability of pure copper, see Fig. 9. The Material poses quite a number of problems to the laser beam welding process. It possesses a high thermal conductivity combined with a high reflectivity in the typical wavelength ranges of lasers used for welding. The virtually non-existent melting range because typical oxygen-free copper is effectively a pure chemical element is also problematic. These factors complicate the welding of copper with the conventional LBW process. Welding with lower welding speeds result in more or less periodical molten pool ejection. With high welding speeds, the process stabilizes, but the achievable weld-in depth is very low. Combining the infrared welding laser with a green laser (higher absorption rate) stabilizes the welding process but welding plate thicknesses of more than 1 mm is still difficult.

First test series of OFHC copper with the LaVa process at $2x10^{-1}$ mbar at welding speeds of up to 1.2 m/min showed impressive results in terms of achieved weld-in depth (up to 13 mm) and process stability. These welding trials led to new government founded research project on the topic of welding copper and its alloys with plate thicknesses of more than 3 mm.

3. Summary and Outlook

The laser beam welding in vacuum in the thick plate range achieves comparable results to the electron beam welding process at similar beam powers. In comparison to EBW, LaVa requires vacuum pressures 100 to 1000 times higher. This allows the use of less and cheaper vacuum pumps and/or faster evacuation times. With the use of a 16 kW disc laser it is possible to reproducibly perform single-sided connection welds on 50 mm thick plates of unalloyed steel. In double-sided technique, acceptable connection welds on up to 110 mm thick plates have been realized so far.

Up to now the main research work done in the field of laser beam welding in vacuum in the ISF focusses on unalloyed steels. Nevertheless, the test series on low- and high-alloyed steels, nickel base alloy, titanium alloys and copper are very promising. The next test series will focus on nitrogen alloyed duplex and lean duplex steel in plate thicknesses up to 30 mm. In parallel, a two-year government project on welding copper with the laser beam in vacuum will be conducted.

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