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Potential of Laser Beam Welding under Vacuum

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Abstract

The first studies on the effects of reduced pressure on a laser beam deep welding process were carried out in the 1980s using the CO_2-laser of the time. Beside the suppression of plasma plume buildup, also a correlation between working pressure and welding depth achieved could already be established. With the availability of solid-state lasers with high beam quality and power, also these new lasers were occasionally brought to a reduced pressure atmosphere. Most of these investigations are largely phenomenological, dealing with the effects of different pressures and beam powers. In addition, the process was developed into a usable joining process for various applications. In this lecture, the physical conditions of laser beam welding under vacuum are presented. The potentials of this process are derived and welding results on different materials such as steel, aluminum, titanium and copper are presented.

Keywords: Laser Beam Welding, Vacuum; Dissimilar Welds, Titanium, Nickel

1. Introduction

Joining tasks that require connection welds on parts with large wall thicknesses are often realized by multi-layer arc welding processes with all connected drawbacks like high demand in filler material, increased chances of interlayer flaws and long welding times. Seldom, mainly with high value parts, also the electron beam welding EBW was and is a process that is used for thick plate application. Electron beam welding can achieve high penetration depths due to high available powers and high intensities to form a deep penetration welding process. For a long time, laser beam power sources typically used in welding lacked comparable power levels and the ability to be focused to comparable intensities.

With the advent of fiber and disc lasers, the available laser power grew and vast improvements in beam quality despite multi-kW powers have become available. With now comparable figures for beam power and intensity, it was obvious to make a direct comparison between the two beam welding methods with comparable parameters.

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To have common base, a typical setup for thick plate welding and welding parameters based on the established electron beam welding process were chosen [1]. Despite identical power and comparable beam intensities as well as comparable parameters, the weld seam geometry differ significantly. LBW welds show a clearly pronounced nail head and less than half of the weld-in depth of the EBW counterparts, Figure 1. Of course, there are differences in beam-material interaction, but initial measurements of the areas of the weld metal show comparable results, which leads to the conclusion that the amount of energy deposited in the material is also comparable.

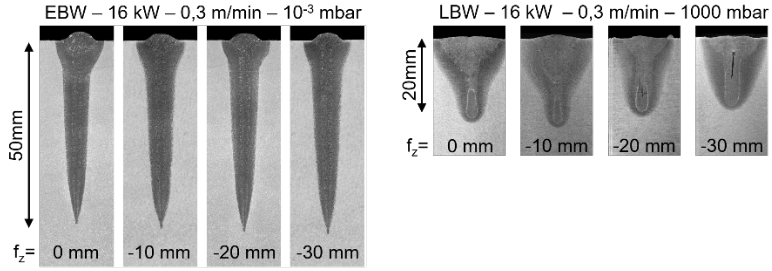


Fig. 1. Comparison of EBW and LBW at equal process parameters [1]

One distinct process related difference between the two beam processes is the vacuum that is required with EBW to suppress beam widening due to scattering of electrons at atmospheres molecules. To do a real comparison between the two beam welding processes, the LBW had to be brought inside a vacuum chamber using comparable process parameters. The literature shows that the idea of using the laser in reduced pressure atmosphere or vacuum is not a new one. Initial research was done in the mid to late 1980s [2,3]. At that time, the target of the investigations was to reduce or completely suppress the plasma plume inherent to CO2 laser beam welding. This target was reached and, as side effect, also an increase of weld-in depth was noted but not further investigated.

2. Laser Beam Welding under Vacuum – Realization and Effects

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 just 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, Figure 2 [4].

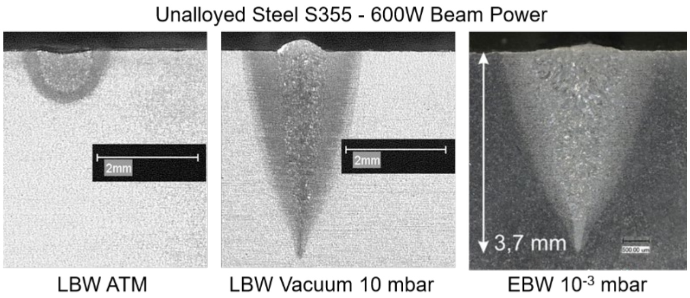


Fig. 2. Initial results Laser beam welding under vacuum with 600 W beam power [4]

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 is clearly visible in the vapor pressure curve of iron, the main element of steels, Figure 3.

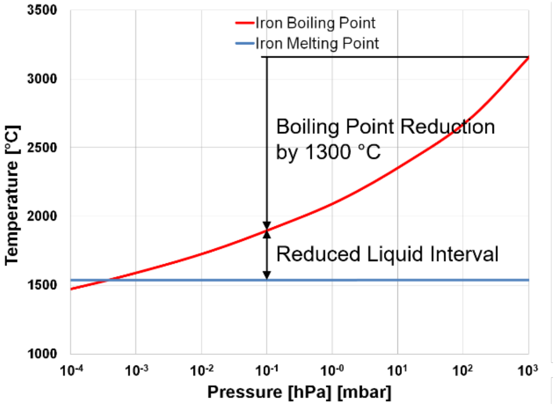


Fig. 3. Melting and boiling temperature of iron in relation to pressure reduction

The reduction of the vaporization temperature with the reduction of pressure also allows the conclusion, that the amount of energy necessary to transfer the base material to metal vapor that forms the capillary of the deep penetration welding, is significantly reduced. In addition, the temperature inside the capillary, at the boundary between metal vapor and molten material, is also significantly lower in reduced pressure. At the same time, the heat conductivity and melting point of common used metals are nearly independent on the ambient pressure. As a result the lower temperature gradient between the boundaries of metal vapor to molten material (vaporization temperature) and molten material to solid baser material (melting temperature) leads to reduced thickness of the shroud of molten material around the capillary. 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.

3. Potentials in thick plate Applications

Based on these results gained and the apparent gap of the common laser beam welding and the electron beam welding in terms of achievable weld-in depth and overall seam quality, the ISF started to develop laser beam welding under vacuum to enhance the process boundaries of conventional LBW. The first machines developed in the ISF were especially designed to allow thick plate welding with a similar focal length and focal diameter as the typical electron beam welding machine to allow a close as possible comparison between the processes in thick plate application. The custom build setup consists of a 600 l chamber, axis and clamping capable of handling work pieces up to 150 kg and a vacuum system able to evacuate and regulate the vacuum in the pressure range of 0.1 to 200 mbar. The optical setup includes an iteration of optic protection system [Patent] developed by ISF and a custom build laser optic with 932 mm focal distance and 550 µm focal diameter. The optic is rated for a maximum laser power of 20 k and is equipped with an oscillating mirror capable of a linear oscillation, Figure 4. In line with the target to reach maximum weld-in depth, the machine is powered by a Trumpf disc laser with 16 kW beam power. With this setup, the ISF was the first to research the laser beam under vacuum as real welding process in thick plate steel and duplex-steel welding in the scope of a funded research project [5].

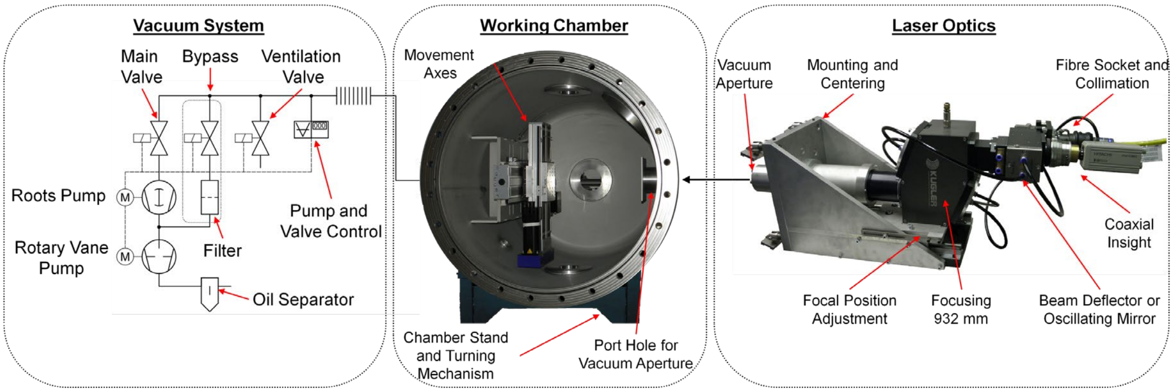


Fig. 4. Welding setup for thick plate laser beam welding under vacuum

During extensive welding series with laser powers at 8 kW and 16 kW, the setup and especially the optic protection system proofed very stable and needed very little maintenance. During the test series also the comparison against conventional LBW and EBW was picked up, Figure 5

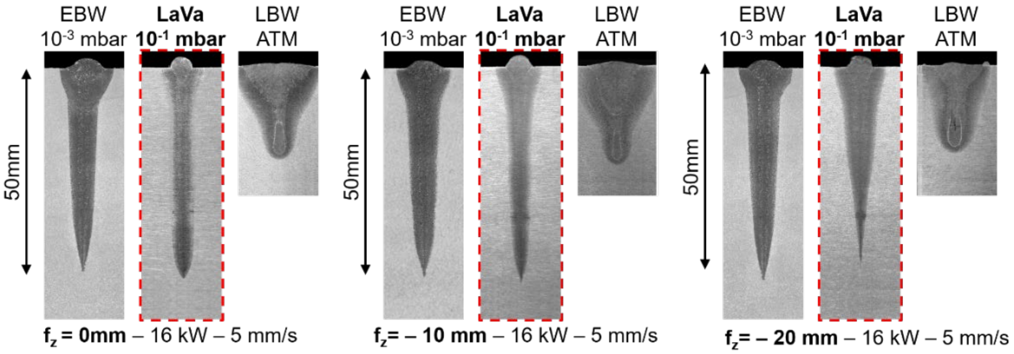


Fig. 5. Comparison at 16 kW at unalloyed Steel at different focal positions

The comparison clearly shows the impact of the pressure reduction from normal ambient pressure to 10^{-1} mbar with the laser process at a beam power of 16 kW different focal positions. At vacuum pressure, the laser weld geometry is well comparable to EBW weld seams with narrow inner geometry and nearly parallel flanks. Compared to conventional LBW, the achieved weld-in depth has more than doubled at least. The main difference to EBW is that the laser process under vacuum is more sensitive to the focal position used. To assess the potentials of laser beam welding under vacuum for thick plate application, a wide range of parameters in both position 1G and 2G, based on the process knowledge of EBW, have been investigated, Table 1

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

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}

Welding quality was assessed by VT of bead and cross-sections. X-ray inspection was done on selected samples to confirm the low to non-existent pore formation of the process. The achieved weld-in depth and other geometrical values were measured at several cross-section per parameter set. Inner weld seam geometry and possible flaws were documented. Acceptance criteria was quality level C according DIN EN ISO 13919-1. Nevertheless welding results from large parameter fields reached quality level B.

The assessment of outer an inner weld seam features and quality in position 1G show a very good applicability. Using a laser power of 8 kW actually the whole parameter range delivered more than acceptable weld seam quality with weld-in depths up to 33 mm. The welding trials with high laser power (16 kW) show also a wide range of usable parameters with weld-in depths up to 55 mm. Parameter sets with welding speeds beyond 1.25 m/min show a tendency to form shrinkage cavities or cracks in upper weld seam area [1].

In the more important PC/2G welding position for thick plate application the usable parameter ranges tend to be slightly smaller. Nevertheless, 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, Figure 6.

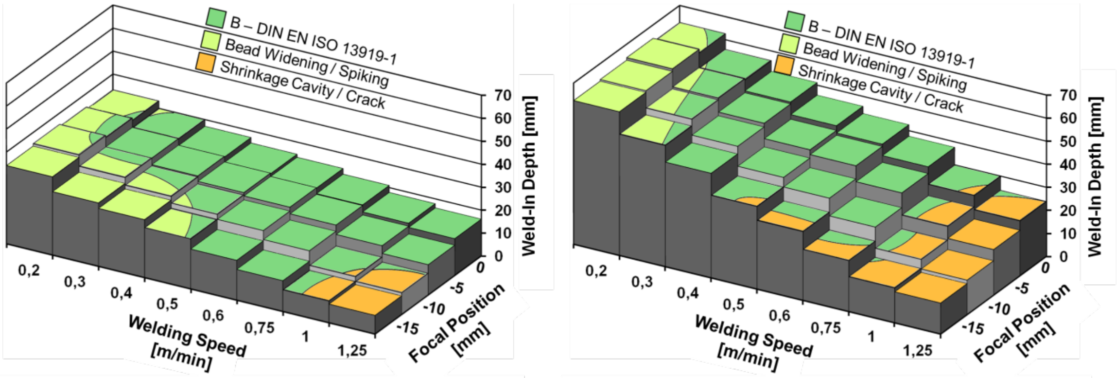


Fig. 6. Overview of usable parameter ranges of laser beam welding under vacuum in position 2G

These results show a general usability of the process variant for reaching weld performance on par with EBW. The results can be transferred to full penetration weld seams as well. So connection weld seams with free bead and root formation at 50 mm S355 and S690QL have been performed, Figure 7 left.

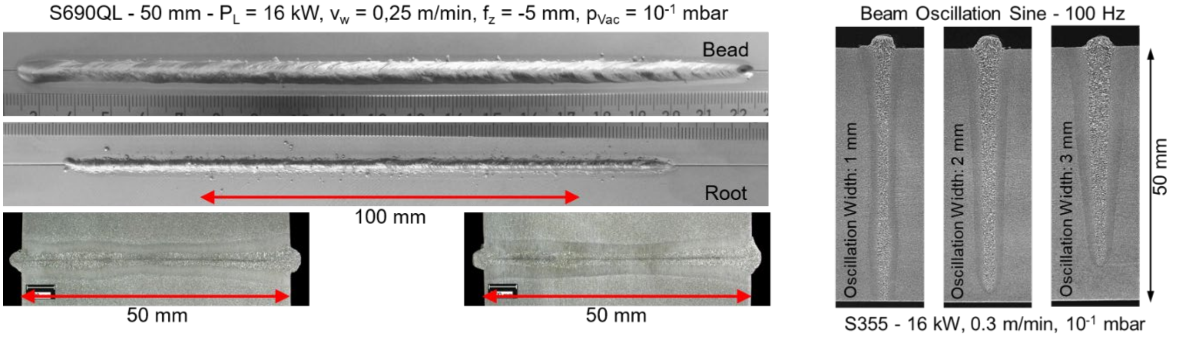


Fig. 7. Left: Application as full penetration connection weld 50 mm – Right: Possibilities of beam oscillation

With the adaption of beam oscillation, the laser beam welding under vacuum is further enhanced. Inner weld seam geometries can be optimized and tailored to the application at hand.

4. Potentials in NF Metals

Aside from the feasibility of laser beam welding under vacuum at steel from unalloyed and high-strength to high-alloyed variants, the process is also well suited for application on nonferrous metals. The effect of the reduced pressure and the possibility to weld in an oxygen-reduced atmosphere, due to the use of a minimal inert gas flow to protect the laser aperture, enhances the application range of the traditional laser beam welding.

4.1. Nickel-based Alloy

In the course of research work and industrial projects, the feasibility of laser beam welding under vacuum has been proven several times, especially on alloys at risk of micro hot cracks. Beside the process development done in bilateral industrial projects, ISF made a comparison of arc based welding processes and laser beam welding under vacuum at Alloy 617. Scope of the funded research project was an energy reduced connection weld at plate thicknesses up to 40 mm. The target was to reduce the deposited energy of the arc process so far, that neither weld metal, fusion zone or heat affected zone show micro hot cracks [6, 7]. In the scope of the project welding processes with TIG, energy reduced GMAW and an especially developed energy reduced SAW process with additional cooling wire were developed and tested against the laser vacuum process.

The arc processes needed an extensive bevel preparation and a multitude of weld runs, the laser beam process was able to perform a single, full penetration weld seam on a plain butt weld preparation, Figure 8.

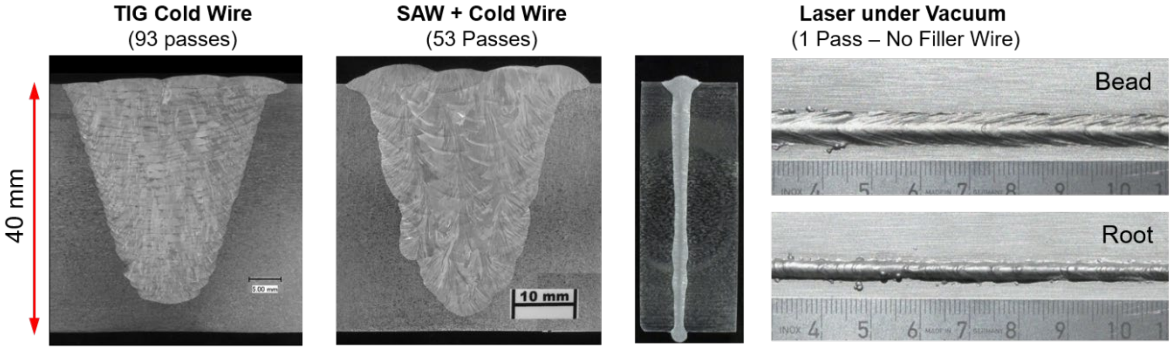
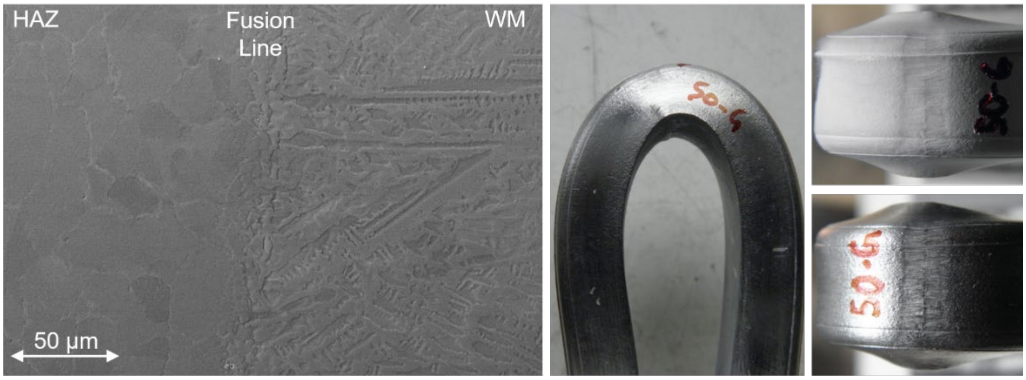


Fig. 8. 40 mm Alloy617 – TIG (l.) – SAW (m.) – Laser under Vacuum – 16 kW, 0.35 m/min, 0.1 mbar

Set against the optimum arc process (SAW with cooling wire) the number of necessary weld runs were reduced from 53 to 1, the pure welding time per meter, without cooling times for reasonable interlayer temperatures was reduced by more than 90%. Additionally the laser beam welding process under vacuum needed no filler wire.

Neither X-ray examination, scanning electron microscopy nor bend tests showed the slightest sign of micro cracking with the laser process whatsoever, Figure 9. Comparison analysis of the base and weld metal (EDX) showed no noticeable alloying element burn-off [1]. The combination of large penetration depth with reduced capillary temperatures, concentrated heat input and protection by an inert reduced pressure atmosphere allow high quality welds with significant economic benefits. Beside the thick plate application, very similar results were achieved on nickel alloys down to a wall thickness range of less than one millimeter.



SEM - Magnification 1000x

Bending Test with Dye Penetration Test

Fig. 9. 40 mm Alloy617 – Left: SEM Image of HAZ to WM – Right: Sample of Bend Test including PT

4.2. Titanium-Alloy

Titanium and its alloys need an optimal shielding against oxidation during welding, not only in the actual process zone but also trailing the molten pool. For high quality requirements, normally TIG is used in a complete inert gas atmosphere, thus requiring large amounts of shielding gas. EBW is a good alternative to weld titanium due to the required vacuum atmosphere. However, even there the state of the art demands an improved vacuum quality of 10^{-4} mbar or better to limit residual oxygen. Given the combination of a vacuum atmosphere in addition to the use of an inert gas, typically argon, for optics protection against metal vapor, the laser vacuum welding process practically combines the advantages of EBW and arc welding.

During research work on thick plate welding, also welding trials on 40 mm Ti6Al4V have been performed in single sided full penetration welding [1]. The results show that the laser beam welding under vacuum even with a pressure of 0.1 mbar gives acceptable results while using argon as protection gas for the optical system. Even with a gas flow of less than 1 l/min the resulting bead and root showed no sign of coloring, Figure 10, left. The relative low thermal conductivity of the alloy results in an inner weld seam geometry that features parallel flanks with a minimal widening toward the surface, Figure 10, left. With the full 16 kW laser power, it was possible to achieve full penetration welds with welding speeds between 0.3 to 0.5 m/min and hence different energy inputs with only little change to the resulting weld geometry.

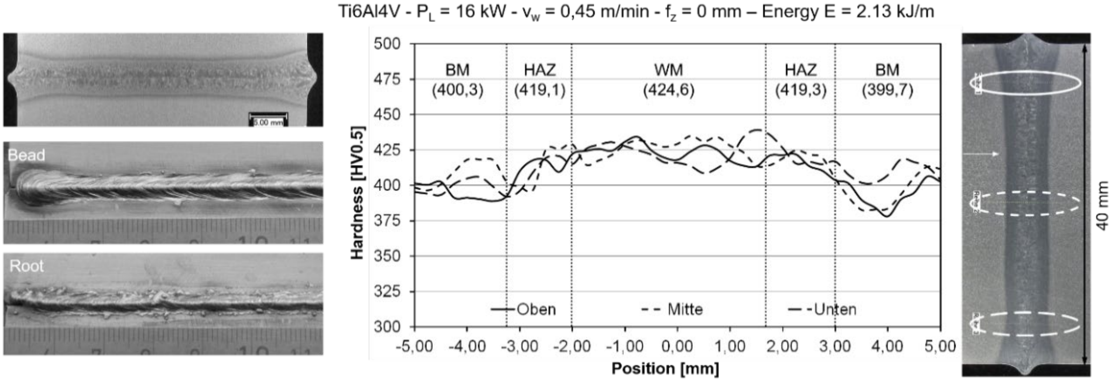


Fig. 10. Titanium Ti6Al4V 40 mm – Left: Cross-Section, Bead and Root – Right: Hardness Measurement

Hardness profiles were taken from base metal to base metal in three different positions, Figure 10, right. The average hardness of the unaffected base material is ca. 400 HV. The HAZ feature an average hardness of 419 HV and the weld metal averages at 424 HV with a local peak of 439 HV. Taking in account that the Vickers test with low loads tends to be sensitive to local micro-hardness, the measured values are well below hardness increases that happen by oxidation [8]. The hardness measurements and the absence of oxidation indicators on bead and root allow the conclusion that shielding against oxygen by the combination of the low vacuum and inert gas for optics protection is more than sufficient.

The task of welding parts of various titanium alloys with laser vacuum is also in high demand by different industries. The following Figure 11 shows a typical laser vacuum weld on Ti6Al4V, performed by laser vacuum welding in merely 5 mbar using 1 l/min argon gas flow to the optics protection system.

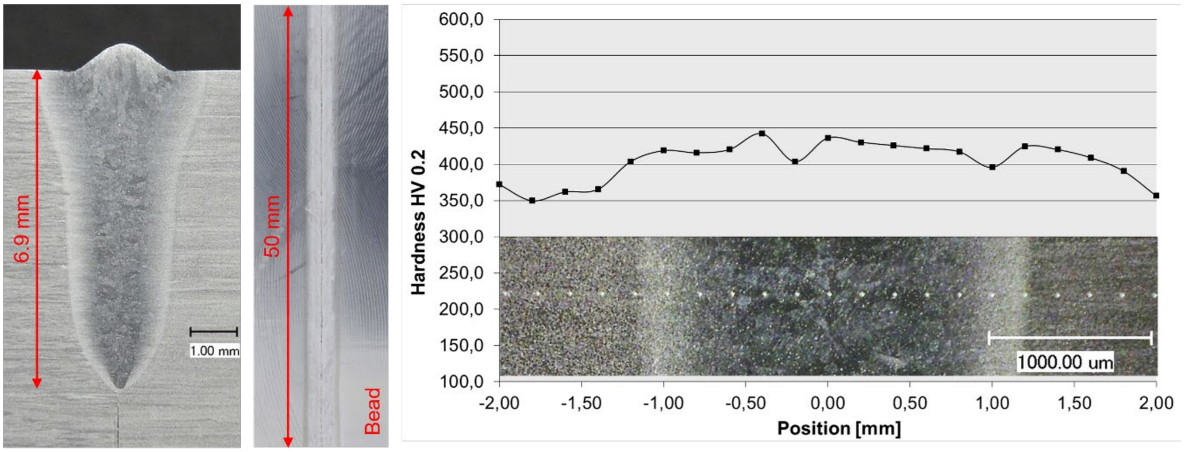


Fig. 11. Titanium Ti6Al4V Bead on plate: 1800 W, 0.75 m/min, 5 mbar – achieved weld-in depth of 6.9 mm

Even with 50 times higher vacuum pressure of 5 mbar, both bead surface as well as hardness measurement show no sign of oxidation.

5. Potentials in dissimilar joints

Mixed material joints can pose several problems when it comes to thermal joining processes. There are different physical material characteristics like melting temperature as well as vaporization temperature, thermal conductivity and coefficient of expansion as well as microstructure transformations that can differ enormously and cause internal stresses up to the point of structural instability and failure of the joint even without additional load. In addition, most mixed material joints form a number of intermetallic phases that, if not accordingly controlled, will influence the weld metal and fusion line to the point that the joint cannot cope with the external stresses and even may break due to the internal stresses induced by the welding process.

Using the laser beam welding under vacuum, especially in combination with small focal diameters like modern disc or fiber laser as well as single mode lasers, can open up possibilities and result in joints that can bear better mechanical properties as the traditional LBW and EBW. To limit the formation of unwanted intermetallic phases, two main tools can be applied. The first one is the control of the amount of each material melted and intermixed in the weld metal. Here the use of sharp focal diameters with less than 100 µm in combination with an accurate positioning of the laser beam to the dissimilar joint configuration helps to reproducibly control the amount and mixture of the molten material. The second one is to limit the energy input and limit the diffusion ability and the growth of intermetallic phases. The reduced pressure on the process leads to lower temperatures inside the capillary, slim inner weld seam geometry with straight flanks and an overall reduced energy input compared to laser beam welding. The following example highlights a few material combinations successfully joined with laser beam welding under vacuum.

5.1. Steel – Stainless Steel

One advantage of the laser beam welding under vacuum in comparison with EBW in mixed material welding is the is the insensitivity to the thermoelectric effect and general magnetic fields. Forming a molten pool between two dissimilar materials means forming a thermo-electrical current source, which in turn form a local magnetic field [9]. The electrons of beam in EBW are deviated in the field and a sound weld seam without lack of fusion (especially with large penetration depths) is hard to achieve. The laser beam welding under vacuum, which can achieve comparable weld-in depths, is not affected by the process-immanent magnetic field thus delivering sound welds without the need of compensation magnetic deviations, Figure 12.

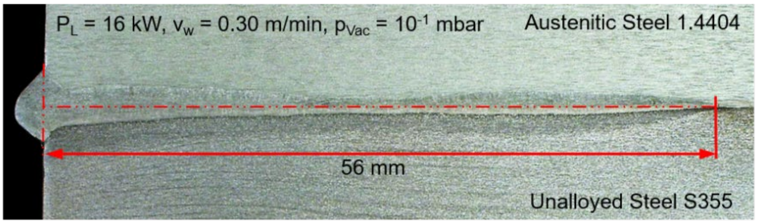


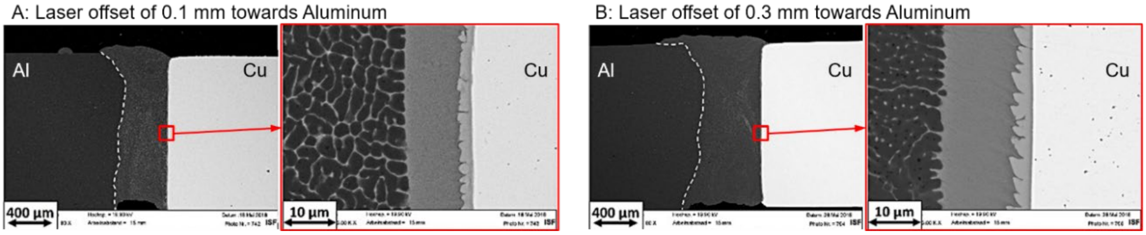
Fig. 12. Example for non-existing deviation by thermos-electric effect with laser welding under vacuum

Despite the weld-in depth of 56 mm and the absence of beam oscillation to improve the inner weld seam geometry, the laser beam weld between the unalloyed and the alloyed, stainless steel shows no sign of curvature and lack of fusion which would be expected when welding the same configuration with EBW.

5.2. Aluminum-Copper

A typical mixed material joint with growing importance is the connection of aluminum to copper. Especially in the field of electro-mobility, these joints are needed for inter-cell connections of lithium accumulators. The second usage are connections of electric conductors due to the fact that aluminum offers only slightly inferior electrical properties compared to copper at much lower cost and especially weight, [10]. Mechanical joints are prone to contact oxidation as well increasing resistance due to relaxation causing loss of connection force. In general, welded connections show better resistance values but have to cope with the formation of intermetallic phases and thus limited mechanical stability. The use of laser beam welding under vacuum with a single-mode laser shows very promising results in investigations performed in a funded project in ISF [11]. The combination of the advantages of the process variant, the use of a ca. 70 µm focal diameter and the exact positioning by magnified coaxial camera insight allows to reproducibly weld Al-Cu connections with controlled mix ratios and reduced thicknesses of intermetallic phases, Figure 13.

The resulting connections have very good electrical resistance values quite independent of the laser positioning and process parameter. Tensile tests show a clear dependency between beam position and thus growth of intermetallic phases. First results yield maximum tensile strength up to 90 MPa with elongations of 1.5%.


A: Laser offset of 0.1 mm towards Aluminum

B: Laser offset of 0.3 mm towards Aluminum

Fig. 13. Al-Cu LBW under vacuum: 1.2 kW, 1.5 m/min, 100 mbar – Different laser positions

6. Summary

It has been shown that the laser beam welding under vacuum achieves outstanding results in terms of weld-in depth per beam power ration and weld seam quality for a wide range of materials. Coming from thick plate application on steel materials, the process has proven its advantages also in the range of automotive power train [12] and also in industrial projects at joining tasks that required highest quality welds at low weld-in depth. The exemplary comparison of welding 40 mm nickel alloy 617 show that the limited heat input of the process can be used to weld alloys that have the risk of hot cracking while vastly reducing welding times completely without filler wire. The results on titanium alloys up to thick plate application show that the combination of the process advantages in combination with the inert reduced pressure atmosphere allow high quality welds with reduced shielding gas cost. The examples of dissimilar welds show that on the one hand the process allows thick plate applications that were only possible with EBW without risking lack of fusion due to thermoelectric effect. On the other hand, the use of high intensity lasers with reduced focal diameters allows combining the process advantages with pinpoint accuracy and the possibility to limit the amount of weld metal, the mixture and the growth of intermetallic phases.

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