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Laser beam welding in mobile vacuum

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Abstract

Laser beam welding is firmly established in industrial processing in a variety of forms. Most applications arise in the welding of thin sheets with sheet thicknesses up to 6 mm as a single process. For larger sheet thicknesses, the laser beam is used as a part of a hybrid process, e.g. in combination with an arc process. A large variety of materials from plastics to the typical use with steels to the applications with copper and refractory metals can be processed with the laser beam. Due to the continuous development of beam sources and optics, a wide range of possible applications ranging from microsystem technologies to heavy machine construction can be covered. However, in all processes of laser beam welding of thick plate sheets, deficits in the achievable weld depth and seam quality are found in contrast to electron beam welding. The new process variants of laser beam welding under low and medium vacuum (LaVa) and the resulting welding under mobile vacuum (MoVac) were designed and developed as a joining process at the Welding and Joining Institute ISF, RWTH Aachen University. The LaVa process closes the gap between the two beam welding processes and opens up new applications for laser beam welding. Especially the laser beam welding under mobile vacuum allows for the economical joining of thick walled components. The following article gives a short overview over the development of the LaVa process and its further development, the MoVac process.

Keywords: Laser Beam Welding; Vacuum

1. Introduction

Due to their process-specific properties, laser beam welding (LBW) and electron beam welding (EBW) cover different areas of application. Different methods are available for both processes, enabling the welding of a wide range of materials in different areas of applications, from heavy machine construction to

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microsystem technology. In the field of beam welding processes, constant efforts have been made to change or extend the possible spectrum of applications. These include, among other things, the further development of system engineering as well as the improvement of the mathematical models for process simulation and the prediction of welding results. With laser beam welding under vacuum, a process variant is investigated with which new fields of application can be developed, especially the welding of thick sheets. The required vacuum is, in many cases, a deterrent for users. When welding large components (e.g., longitudinally welded pipes), the cost increases exponentially with the chamber size. By generating a local vacuum, the economic viability of laser beam welding under vacuum can be improved and even more application areas can be made accessible.

2. State of the technology

2.1. Laser beam welding in atmosphere

The beam welding processes (laser beam welding and electron beam welding) are characterized by a high energy intensity at the workpiece surface, whereas the mechanisms of the beam-material-interaction differ significantly from one another. Both have the deep-weld effect in common, which is characterized by the formation of a vapor capillary. By means of the deep-weld effect, weld seams with a very high aspect ratio of the seam depth to the seam width can be achieved.

The electron beam is generated, shaped and focused inside of the beam generator. The emitted electrons gain up to 70 % of the speed of light and power densities on the workpiece of up to 107 W/cm2. When the electrons impact on the workpiece, the kinetic energy of the beam is converted into thermal energy. At low intensities, the losses during coupling are about 30 %. At an intensity threshold (about 10^6 W/cm^2 for steel), the material evaporates and a vapor capillary and thus the deep-weld effect are formed, see Fig. 1. With the formation of the vapor capillary, the losses due to electron scattering decrease to approximately 10 %. In addition, approximately 1 % of the energy is converted into x-ray radiation, Bobenek et al., 2001; Träger, 2002; Woeste, 2005.

The laser beam impacts the workpiece surface as a bundle of focused electromagnetic waves with a defined wavelength. At low intensities, only a very small ratio of the beam power is absorbed by the workpiece surface. Depending on the material, the reflection losses are between 70 (Fe) and 95 % (Al). Just as in the case of EBW, a vapor capillary is formed above an intensity threshold, see Fig. 1. Within this vapor capillary, multiple reflections of the laser radiation occur. Due to the repeated reflection and absorption of the laser radiation, the total losses decrease drastically to values <10 % with increasing depth of the vapor capillary.

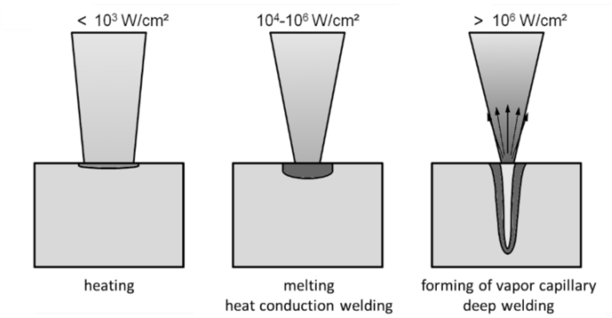

Fig. 1. Transition from heat conduction to deep welding

With multimode solid-state laser systems, focus diameters above 100 µm can be achieved. The corresponding intensities are above 107 W/cm2. With singlemode systems (emitted beam profile is very close to a Gaussian distribution) focus diameters of 30 µm at intensities of 108 W/cm2 can be achieved, Pletei, 2001; Matthes et al., 2002; Olschok, 2008; Chang, 2000.

Laser beam welding is usually used at atmospheric pressure with a shielding gas. With increasing beam power and correspondingly increased weld pool size, inert gas flow rates of 10-20 l/min are necessary. The gas flow does not only serve to protect the melt pool and the solidifying seam, but also to reduce the influence on the laser beam above the workpiece, by displacing the emerging metal vapor and other process emission from the capillary, see Fig. 2.

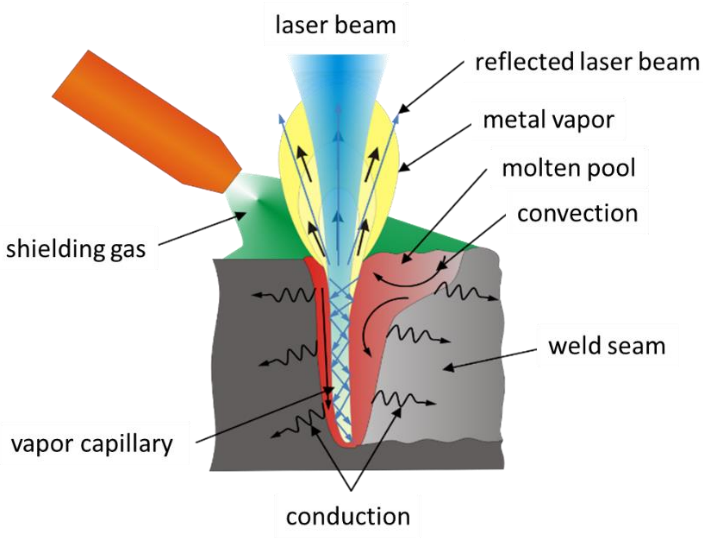

Fig. 2. Joining zone in laser beam deep welding

2.2. Laser beam welding under vacuum

The impetus for the development of laser beam welding und vacuum into a joining process is based on occasional research papers from the 1980s. These papers examined the extent to which the reduction of the ambient pressure allows for the suppression of the harmful plasma torch above the vapor capillary when welding with a CO2-Laser. This effect has been demonstrated and in addition an increase in the achievable weld depth has been observed, Arata et al., 1985; Verwaerde et al., 1995.

The first own investigations with a modern solid-state laser system (singlemode fiber laser) in a vacuum showed both, a reduction of the plasma torch above the capillary and a significantly increased welding depth with comparable parameters. While a process at the boundary between heat conduction welding and deep welding can only be achieved at atmospheric pressure, a reduction of the ambient pressure to 10 hPa resulted in the formation of a pronounced vapor capillary and a four times higher welding depth, see Fig. 3, Longerich, 2011.

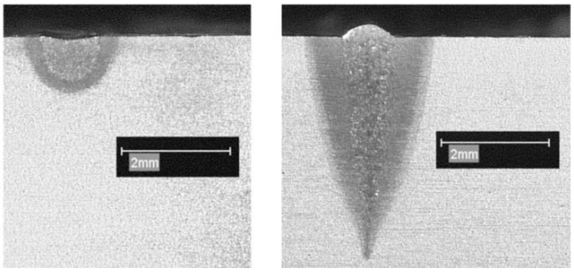

Fig. 3. Change in welding seam geometry atmospheric pressure (left), 10 hPa (right), 600 W

The reasons for the significant influence of the reduced ambient pressure on the welding process are manifold, whereas the most obvious change in the reduction of the plasma torch only plays a minor role.

The main reason for the observed changes in the welding process at different ambient pressures is due to a pressure dependence of the evaporation temperatures and a strong pressure independence of the melting temperatures of the materials. The pressure dependence of the evaporation temperature is exemplified by the vapor pressure curves of the most important components of unalloyed steels, iron and manganese, Fig. 4.

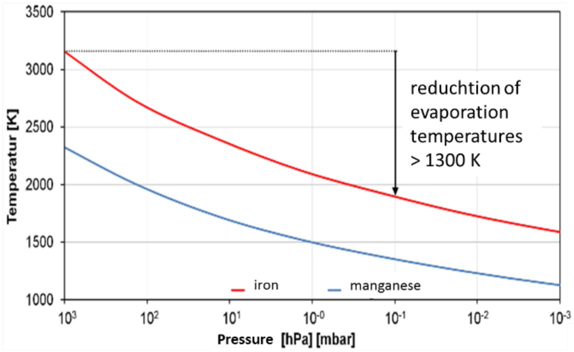

Fig. 4. Vapor pressure curve of iron, manganese

The reduction of the working pressure inside of the vacuum chamber from atmospheric pressure down to 10^{-1} hPa results in a significant reduction of the evaporation temperature of the alloy constituents. In the case described, the reduction of the boiling point of iron is above 1300°K.

This reduction affects several properties of the weld. As a first effect, less energy is required to transfer material to the gas phase, which improves the economic viability and lowers the thermal stress on the workpiece. Additionally, the investigations show that the intensity threshold for the transition between heat conduction welding and deep welding is lowered, see Fig. 3. The third effect of the reduction of the boiling point is associated with the strong pressure independence of the melting point. The lower temperature at the phase boundary between the vapor capillary and the surface of the covering in combination with the unchanged melting point presumably leads to a reduction in the thickness of the covering around the vapor capillary. Due to the reduced melt volume, the vapor capillary is more stable and the weld seam is significantly less pronounced and generally has parallel seam flanks, Fig. 5.

Fig. 5 shows the comparison between a laser beam weld at 10^{-1} hPa (left) and atmospheric pressure (right) with a beam power of 16 kW and a welding speed of 1 m/min. The changes in welding depth and seam geometry are evident. Studies have shown that the effect of increased weld depth is furthered with decreased welding speed.

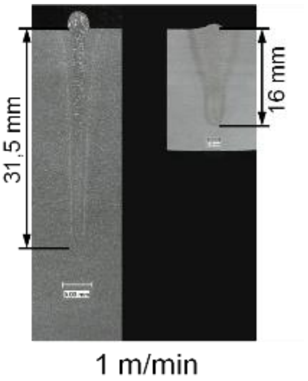

Figure 5. Comparison ATM and 10-1 hPa at 16 kW

3. Laser beam welding under mobile vacuum (MoVac)

The majority of the previous research on laser beam welding in vacuum was carried out in a pressure range of 10^{-1} hPa. Our own investigations and earlier research suggest a negligible increase in welding depth with a further increase of the vacuum pressure. With regard to a possible optimization of the ratio between welding depth, seam quality and operating expense of vacuum generation, a first series of tests was carried out at higher pressures of 50, 100 and 200 hPa.

The tests show that, even with these low vacuum requirements, good seam qualities, with a significantly increased welding depth compared to laser beam welding at atmospheric pressure, can be achieved. The pressure range from 50 to 100 hPa appears to be particularly suitable. In this pressure range, good seam quality can be achieved with 75 – 80 % of the welding depth at 10^{-1} hPa, Fig. 6, Jakobs, 2015.

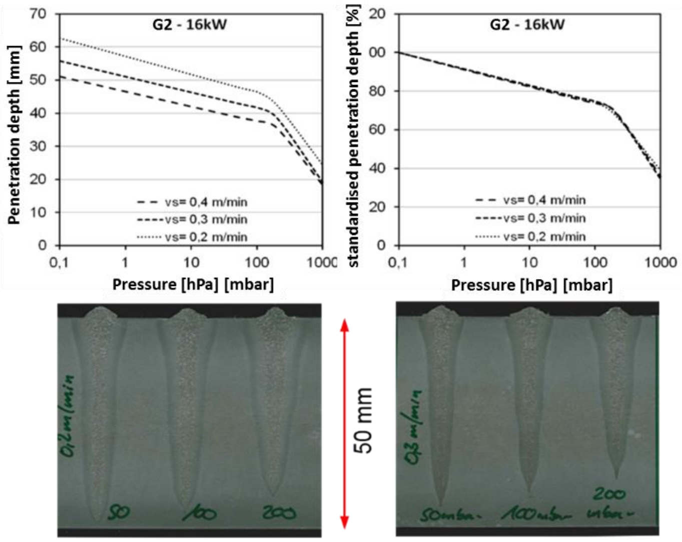

Fig. 6. Influence of pressure LaVa

One of the most significant disadvantages with regard to the economic viability of the LBW vacuum process is the fact that usually the workpiece has to be placed inside of a vacuum chamber. This inevitably leads to restrictions on the size of the workpiece. Additionally, the evacuation causes dwell times. In electron beam welding, cycle, lock or double chamber systems are regularly used to reduce these dwell times. However, these are not universally applicable and are most suited for large quantities. In order to improve the economic viability, flexibility and possibilities of the LBW, the aim was to develop a LBW process with a mobile/local vacuum. Fig. 7 shows the experimental setup of the mobile vacuum system developed at the ISF, which was integrated into the working station of a 16 kW disk laser system.

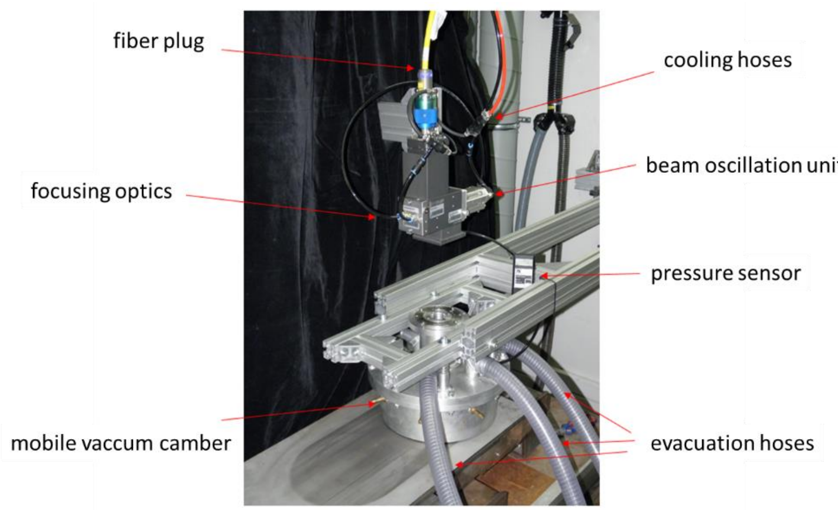

Fig. 7. Experimental setup of the mobile vacuum system for laser beam welding

The mobile vacuum chamber is divided into two pressure stages. Both pressure stages are surrounded by a seal contacting the workpiece. The focusing system is separated from the vacuum chamber to prevent a displacement of the focus position during the welding process. The laser beam is focused through a protective glass at the top of the vacuum chamber, see Fig. 8.

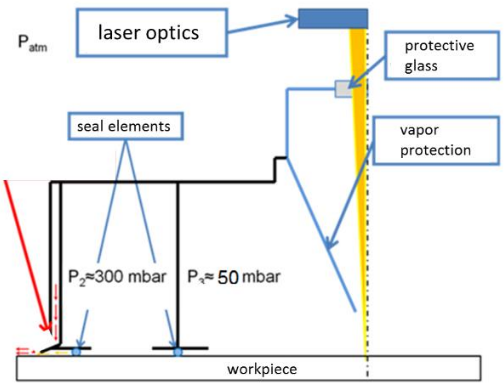

Fig. 8. Schematic setup of the mobile vacuum chamber

With this system, welding was carried out at about 50 hPa and with speeds of 0.2 to 1.25 m/min. Fig. 9 shows two cross-sections of welds with 8 and 16 kW laser beam power on the left. All experiments were largely spatter-free. Pores could not be seen in any of the evaluated cross-sections or radiographs.

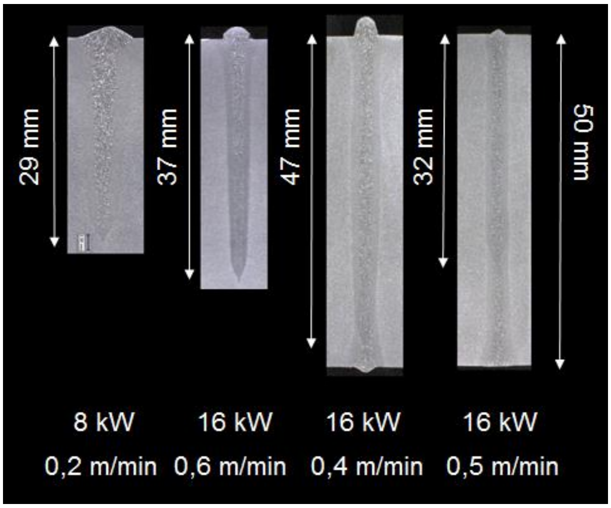

Fig. 9. Micrograph through bead-on-plate weld (left) connection weld (right), MoVac, 50 hPa

Fig. 9 shows on the right side the micrographs of two joint welds with zero gap. At the first welding, the root was previously closed with another process (e.g. LBW at atmosphere or TIG), and then the remainder of the weld was welded using the MoVac method. The rightmost weld is a welded by the double sided single pass welding method while, for the first pass, atmospheric pressure prevails at the backside. In order to avoid a leakage flow through the zero gap during the layer welding, an aluminum adhesive tape was attached on the root side. This tape was removed before joining the back weld pass. Sheets up to a thickness of 50 mm were joined without defects.

It has been demonstrated that the process variant of laser beam welding under mobile vacuum is very suitable for welds on thick-walled constructions. However, if there is root penetration, pressure compensation between the ambient pressure (at the root) and the process pressure (at the welding point) occurs via the keyhole. This generally leads to blowing out of the molten pool and to a significant disturbance of the process. A part of the melt can hit the shielding glass and contaminate it, which usually results in shift of the focus position. As a result, a penetration weld must be absolutely prevented in this setup. In order to enable a penetration weld, a secondary vacuum system has to be placed at the backside of the seam. The coupling of the two vacuum chambers and the use of a shared system of vacuum pumps ensured equal pressure on both sides of the weld. In the welding position G1, penetration welds with free root formation up to a sheet thickness of 20 mm could be achieved with an unalloyed steel, see Fig. 10.

In the case of larger sheet thickness, an extensive weld concavity, due to the hydrostatic pressure of the molten pool, was observed.

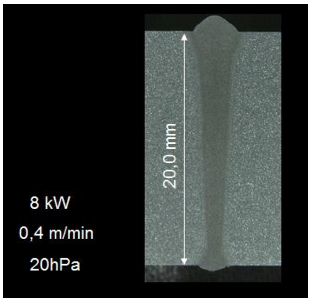

Fig. 10. Micrograph through weld, MoVac, 20 hPa

The joint welds were performed with a zero gap. Even the smallest gap width can cause a high leakage current which prevents the working pressure in the vacuum chamber to be reached. Therefore, a process was developed at the ISF Aachen to join weld metal sheets with gaps of up to 0.5 mm with a mobile vacuum. Prior to the use of the mobile vacuum system, the joining gap is welded shut in a continuous manner with laser beam welding at atmospheric pressure. The MoVac process can then be carried out as in the case of components with a zero gap, see Fig. 11. In order to ensure a continuous connection of the two components, the laser beam has been oscillated by about 3 mm transversely to the welding direction.

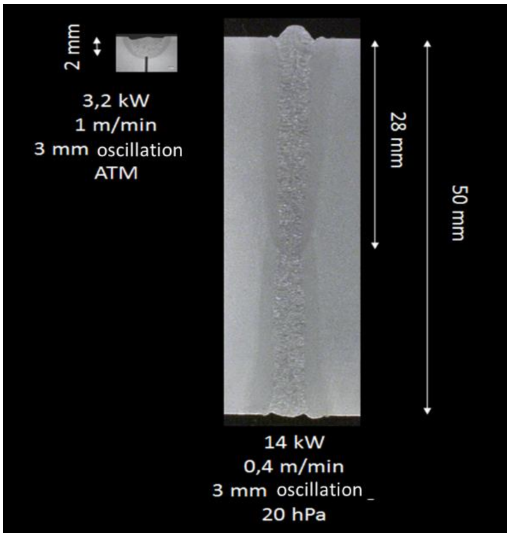

Fig. 11. Micrograph sealing weld (left) and joining weld (right), MoVak, 20 hPa

First tests on the aluminum alloy EN AW-5083 show that laser beam welding under mobile vacuum is also suitable for this material, see Fig. 11. In addition to the large weld depth increase, a considerable minimization of spatter, pores and further seam defects could also be observed when welding aluminum under mobile vacuum.

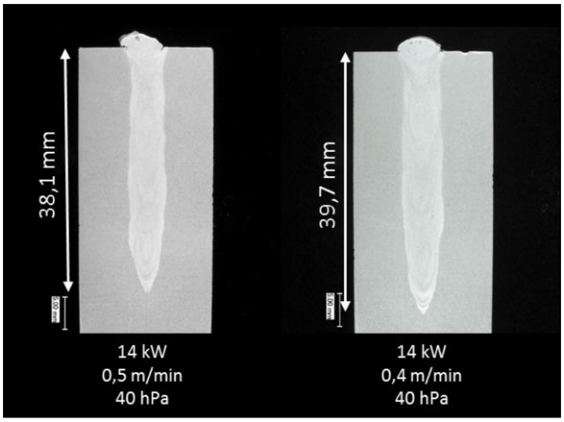

Figure 11. Micrograph butt weld aluminium, MoVac, 15 hPa

The aim of future research is now to test this system for application-related tasks with the laser beam, to optimize it and to define the limits of the process. Additionally, the feasibility of the mobile vacuum system for electron beam welding shall be investigated in order to increase the economic viability and application fields for the electron beam.

4. Conclusion

The investigations presented here show the enormous potential of laser beam welding under vacuum. With the new method variant, it is possible to achieve the seam quality and weld depth of electron beam welded seams with comparable welding parameters. In addition, laser beam welding in vacuum still has some process-related advantages compared to EBW:

For optimum use, the process requires vacuum pressures in the range of 10^{-1} hPa. These pressures can be produced technically by vacuum pumps, which are used as pre-pumps in electron beam welding systems. The pressure level also allows a much faster evacuation of large-volume working chambers.

If the working pressure of the process is increased further towards 50 hPa, this allows for higher leakage flows and thus enables the realization of small mobile vacuum chambers which can be guided over the workpiece with the welding process.

Another advantage of the laser beam welding in the vacuum compared to electron beam welding is the insensitivity of the beam to magnetic fields. This clearly facilitates the reliable joining of large components, which are usually laborious to demagnetize completely.

The advantages compared to laser beam welding in the atmosphere are the significantly increased single-weld depth, the low spatter formation and the significantly improved weld seam quality.
All in all, laser beam welding under vacuum (especially laser beam welding under mobile vacuum) has great potential to optimize processes in the industry.

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