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## Welding with high-power lasers: trends and developments

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### Abstract

High-power laser beam welding became new stimuli within the last 10 years due to the availability of a new generation of high brightness multi kilowatt solid state lasers. In the welding research new approaches have been developed to establish reliable and praxis oriented welding processes meeting the demands of modern industrial applications during this time. The paper focuses on some of the current scientific and technological aspects in this research field like hybrid laser arc welding, simulation techniques, utilization of electromagnetic fields or reduced pressure environment for laser beam welding processes, which contributed to the further development of this technology or will play a crucial role in its further industrial implementation.

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### 1. Introduction

During the last decade high-power (> 10 kW, up to 100 kW) solid state lasers with a high brightness (< 15 mm mrad) came into the market, Nielsen (2015). Those lasers are very interesting for a variety of applications, not only on the shop floor, but especially also in the field, Thomy et al. (2006). There are well known applications in shipbuilding (e.g. Meyer, Fincantieri) Seyffahrt (2004), Staufer (2004), Gerritsen (2005), Olschok et al. (2007), Unt et al. (2015) from the early beginning on. Later results from Schneider et al. (2014) showed successful weldings of thick titanium sheets, also for marine applications.

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Further fields with intensive research activities are the longitudinal and orbital welding of pipelines or the welding of off-shore wind energy plants foundations. Typical materials welded are pipeline steels (X65, X80, X120) or very common S355 structural steel, Sokolov et al. (2011).

The interest in these lasers results from the high-power and brightness which facilitate the (single pass) welding of thick sections with minimal distortion, the wavelength which enables the beam delivery via a fibre, the high plug-efficiency, and a small footprint which makes an application in field conditions possible.

Nevertheless there are still some major challenges which have to be solved, which are listed here and will be discussed in the following major chapters: To work with a laser normally implies the need to have high-precision parts without any gaps or misalignments which is not possible in most applications. Therefore a lot of research was done in the field of laser hybrid welding. One major aspect here is the hot crack formation when welding thick plates in single-pass, Nielsen (2015). Another big challenge is the hydrostatic pressure which will lead to excessive root-dropping when welding single-pass welds in thicknesses of 15 mm or above. Some interesting works were done, looking into an electromagnetic weld support system, Avilov (2012, 2016), Bachmann (2012, 2013, 2014, 2016). During the last years there were also different research groups looking into laser beam welding under vacuum/reduced pressure, which can have significant advantages. Many of the experiments in the different fields were also accompanied by simulations.

## 2. Laser hybrid welding

In laser hybrid welding normally an arc welding process e.g. gas metal arc welding process (GMAW) is coupled with a laser in one process zone, but there are also hybrid processes combining laser and submerge arc welding (SAW), (Reisgen 2014, 2016b). The general idea is to combine the advantages of both processes, the deep penetration and high welding speeds from the laser with the good gap bridgeability and the opportunity of a filler metal of the GMAW process. Furthermore it is well known, that the arc is stabilizing the laser and vice versa, so that there is a much more stable hybrid process. A comprehensive review also on the industrial applications can be found e.g. in Ribic et al. (2009).

A main driver for laser hybrid welding processes is the application in the field of huge structures with heavy plates like ships, pipes, or off-shore constructions, where edge preparation and misalignment cannot be avoided. To reach deep penetration in combination with low heat input and low distortion the only other suitable welding process would be electron beam welding (EBW). Herewith, the necessary vacuum chamber is a major drawback. During the last decade several research groups worked with laser powers of up to 100 kW to reach single pass welds with high thicknesses, Katayama (2015). Vollertsen et al. (2010) published results of thick plates welding in PA (1G) position with a 17 kW laser power of 16 mm mild steel in square butt joint reaching 2.1 m/min welding speed. 20 mm were joined with edge preparation @ 19 kW laser power. Using a multipass technique Rethmeier et al. (2009) showed results of welding of 32 mm thick pipeline steel (X65) in 5 passes, Fig. 1. To weld even higher thicknesses with less passes, the use of laser SAW hybrid welding can be beneficial. When combining laser and SAW the distance between the two processes is crucial. With a 22 mm distance, synergy effects are reached which will be eliminated for higher distances Reisgen et al. (2016). With optimal parameters a 50 mm joint is possible when welding in double-sided single pass technique.

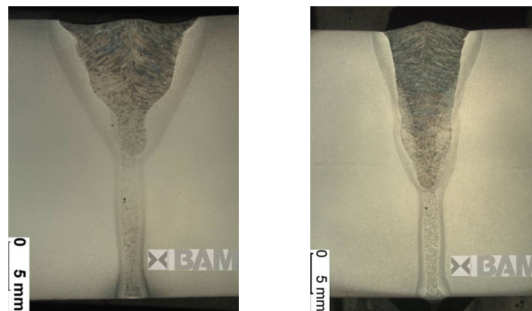


Fig. 1. 28 mm 2 layers (left) and 32 mm 5 layers (right) multi-pass welds.

During laser GMAW hybrid welding the possible edge misalignment was 2 mm with gaps of up to 0.3 mm, Rethmeier et al. (2009). Similar results were presented by Turichin et al. (2015), where a good weld, but with undercuts was still produced with a gap width between 0.6 mm and 0.9 mm. An interesting approach for 25 mm thick square groove butt joints was presented by Wahba et al. (2016), who used a backing and besides that cut-wire particles to bridge a gap of 2.5 mm.

Further work by Gook et al. (2014) showed the potential of the laser hybrid welding process for a reliable production of longitudinal welds of high strength pipe steels X80 and X120. In this case a GMAW tack weld was substituted by a laser hybrid weld, reaching all necessary charpy values, even for temperatures of  $-60^{\circ}\text{C}$ .

One very prominent application is an assembling of pipelines. Therefore a (half-) orbital welding process is necessary to join the linepipes with thicknesses of one to several inches. This application is of a high economical interest, as one aims to substitute a slow multipass MMAW or GMAW process by a single-pass laser hybrid welding process. A major challenge is the application of the laser hybrid process in all positions. Results from Gook et al. (2010a, 2010b) and Gumenyuk and Rethmeier (2013) show that this is principally possible for pipes of up to 16 mm in thickness, when using a laser power of around 17 kW and a welding speed of 2.2 m/min in the falling positions, Fig. 2. The high welding speed is necessary to avoid a dropping of the weld seam especially in the overhead position. Furthermore a root backing gas is very useful to guarantee a good formation of the root.

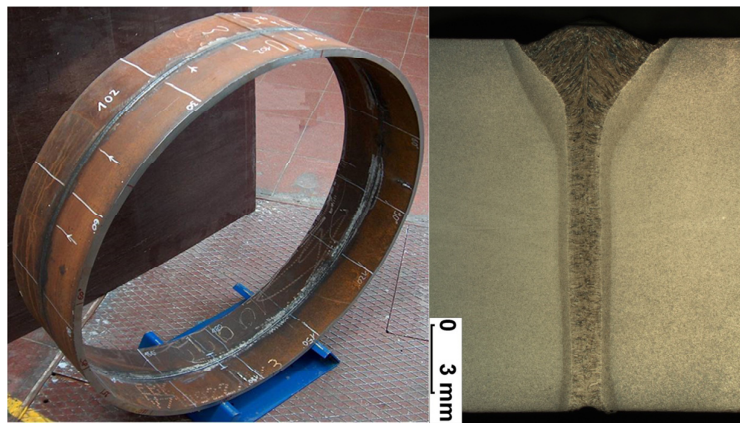


Fig. 2. (a) Laserhybrid welded pipe 36", X65, thickness 16 mm; (b) Macrosection welded in PA position @ 17 kW laserpower and 2.2 m/min.

Another major challenge which occurs during laser hybrid welding of thick plates is the appearance of hot cracks. Those hot cracks are influenced by the alloy composition, the temperature field due to the welding process and the mechanical constraint of the welding construction, Cross (2005). They can even appear when the alloy composition is not critical. Gebhardt et al. (2012) showed results of welded tubes in low S and P high strength steels, where the main influencing factor could be seen in the joint penetration. Full penetrating welds showed no hot cracking whereas partial penetrating welds showed cracks. This effect was also studied with the help of FEM-simulations, Gebhardt et al. (2013). The results showed high stresses in regions, where solidification cracks were found in the experiments, with higher levels in the partial penetration model. When looking into the effect of the process parameter Gebhardt et al. (2014) could identify, that there are highly significant influences of wire feeding speed and laser beam power, while the welding velocity had no measurable impact.

Within the last years and the rising topic of sustainability, life cycle assessments could proof that laser hybrid welding is a very sustainable process compared to for example GMAW and manual metal arc welding (MMAW), Sprösser et al. (2015), Chang et al. (2015).

### 3. Process diagnostics and simulation

To understand the basic phenomena in laser and laser hybrid welding some researchers use besides high-speed videos, also X-ray transmission real-time observation systems, Katayama et al. (2002, 2007), Pan et al. (2016). With the help of those systems very impressive insights into the process are possible. In the case of the X-ray transmission real-time observation systems one has to bear in mind the very thin specimen, which might also have an influence on the process itself. Nevertheless, the phenomena during welding and especially the pore formation can be studied very well.

Another approach when welding with high power lasers is to look into the effect of the vapour plume, Katayama et al. (2010), which is significantly different from the effects well known from high power CO<sub>2</sub> lasers, where it is a barrier for really deep penetration welding > 20 mm. Shcheglov et al. (2011) calculated the mean square band of the power oscillations of radiation entering the deep penetration channel inlet to range between 87% and 95% of the initial fiber laser power, Fig. 3 a (measured up to 20 kW). This means, that not more than 13% of the laser power are lost. They found out that the vapour plume consists of two parts. The lower part has about 5 mm height and is formed by the laser-induced weakly ionized plasma jet consisting of the metal vapor from the keyhole. It has no influence on the fiber laser radiation and the welding process. The upper part reaches up to 50 mm height and is formed by the emission of small condensed particles (Fig. 3 b). The integral attenuation of the high-power fiber laser beam was calculated when it propagated through the whole plume height with about 12%, Shcheglov et al. (2013). The effect of metal vapor condensation must be taken into consideration when developing laser welding technology with deep melt-through, in particular, in processes without shielding gases like remote laser welding, Uspenskiy et al. (2013).

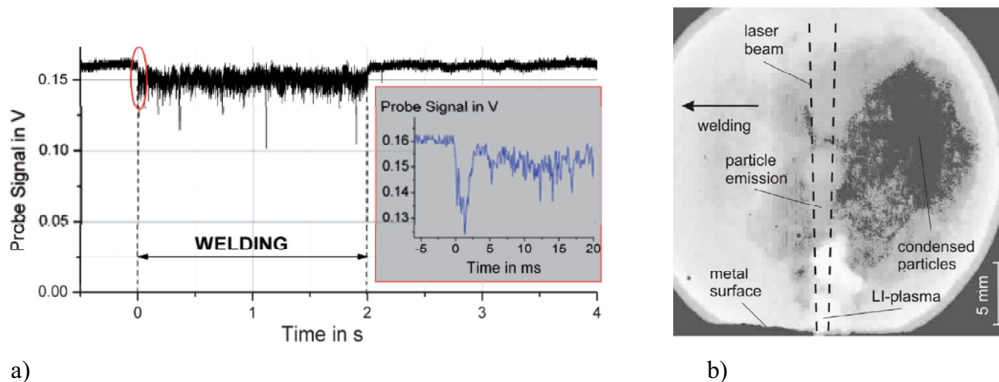


Fig. 3. (a) Typical form of the probe beam transmission signal during welding; (b) video observation of the condensed particle cloud during the welding process.

In many cases nowadays advanced modelling techniques are applied to understand and to optimize the laser hybrid welding process. Therefore different simulation techniques are applied. One aspect is the simulation/reconstruction of the welding temperature field. Karkhin et al. (2011) simulated the inverse heat conduction problems with extended analytical heat source models. In comparison to known techniques the new introduced parabolic energy distribution allows to model complex seam shapes, such as laser hybrid welds in thick plates, by usage of only a single heat source. The parameters of the heat source models are unknown a priori and have to be evaluated by solving an inverse heat conduction problem. The main advantage can be seen in the drastically reduced time (one direct simulation takes about 1 s) for data input and solution. In another paper Pittner et al. (2015) showed exemplarily for a laser-GMAW hybrid welding experiment that the experimental temperature field could be reconstructed on the basis of width values of the fusion line in the macro section, top weldpool length and a single extracted temperature value of the thermal cycle during the cooling phase. The agreements between experiments and simulation were excellent. Other working groups concentrate on process modelling to understand the effects during welding and to optimize their processes, Otto et al. (2011), Cho et al. (2012). Zhang et al. (2014) simulated full penetration laser welding of thick steel plates with high power high brightness laser numerically. The transient

evolution of the molten pool and the keyhole in the quasi steady stage of laser full penetration welding has an obviously periodic character. The transient flow field of the molten pool is the outcome of the dynamic competition between recoil pressure and surface tension. A typical cycle of molten pool fluctuation was determined to be about 8 ms. Sohail et al. (2014) discussed the characteristics of weld pool behavior in laser welding with various power inputs for disk and fiber laser welding between 6 kW and 18 kW laser power. Higher laser powers lead to bigger vortex flow patterns. This work was extended by Sohail et al. (2015) for the fiber laser welding at different welding positions. Na et al. (2015) found out, that in full penetration cases, a necked weld pool shape was observed and that the welding position seems to have a minor influence on the bead formation. However, the welding position has an influence on the weld pool shapes.

#### 4. Electromagnetic weld support system

Modern high power laser beam systems enable efficient and fast joining of thick components for various applications, e.g. pressure vessels, pipelines, and power plant parts. Their full exploitable potential becomes obvious in full penetration welding. Welding distortions and porosity due to keyhole tip instabilities are reduced at a low heat input and a fast processing speed when compared to conventional welding techniques for thick section joints. A limiting factor in most welding positions and especially in PA position for full penetration welding of thick plates is the gravitational force acting on the molten material. This leads to high values of the hydrostatic pressure in the melt that can, above a critical threshold, no longer be in balance with the surface tension forces. This effect can provoke a non-acceptable decrease of the weld cross-sectional area, kerfs or even a severe drop-out of liquid metal.

Further issues which can cause a mechanical post-treatment of the welded plates are due to the formation of spatters in the upper region of the welded components and a rough or wavy surface finish. They may arise from the highly dynamic behavior of the molten material, e.g. due to keyhole fluctuations and evaporation of material, but also from the Marangoni effect being present at the free surfaces of the weld bead.

A promising opportunity to eliminate the impact of the described effects on the weld pool behavior is the application of contact-less external magnetic fields which was thoroughly investigated in the last years experimentally but also numerically. The material processing with electromagnetic forces was already applied to a variety of engineering processes Asai (2000). In metal casting, an electromagnetic stirring can influence the grain structure at the solidification front Moffatt (1991) and also the resulting microstructure Barman et al. (2009), but positive effects with different purposes were also published, amongst others related to crystal growth Dennis et al. (2002) and surface alloying Velde et al. (2001). Further investigations report on the surface quality and also the dilution of filler materials in welding processes Zhao et al. (2007), Gatzert et al. (2011). An overview on different electromagnetic applications in arc and laser beam welding can be also found in Vollertsen et al. (2006).

In case of applied oscillating magnetic fields, eddy currents are induced within the electromagnetic skin depth of the material, which are orientated parallel to the welding direction. The generated time-averaged Lorentz forces are directed along the gradient of the magnetic field away from the magnet system. Thus, possible applications of such a magnet system are manifold, e.g. a balancing of the hydrostatic pressure when the magnet was mounted below the welding zone, Avilov et al. (2012), Bachmann et al. (2012), and Bachmann et al. (2013a) for aluminum alloys, Jones et al. (2003), Avilov et al. (2008), Avilov et al. (2009), and Bachmann et al. (2014a,b,c) for austenitic stainless steels, and Avilov et al. (2016) and Bachmann et al. (2016b) for steels with ferromagnetic properties. Thus, the use of conventional backing bars which imply the need for a mechanical removal after welding can be avoided. Further applications pursue a smoothening of the surface and a degassing of the melt when the magnet was applied above the weld pool, Schneider et al. (2013) and Bachmann et al. (2014b). Thereby, the former is physically based on the variation of the induced Lorentz force depending on the vertical distance of the melt to the magnet. The latter effect refers to the orders of magnitude different electrical conductivities of liquid metal and gas bubbles in the weld pool.

A further component of the electric currents forms due to the movement of electrically conducting particles perpendicular to the applied magnetic field according to the generalized Ohm's law. The corresponding Lorentz force consists of a component that is directed against the original melt velocity thus acting as a braking force, which is called Hartmann effect. Hence, the impact of Marangoni forces can be decreased and the dynamics in the weld pool in terms of peak velocities attenuates, Bachmann et al. (2013b) and Bachmann et al. (2016a). A reduction of weld pool dimensions and a flow damping when applying a stationary magnetic field was also reported

Gatzen et al. (2010). A schematic illustration of the electromagnetic weld pool support system as well as the electromagnetic deceleration of the melt can be seen in Fig. 4.

A very sensitive issue for the inductive weld pool support is the distribution of the electromagnetic properties in and around the fusion zone, namely the electrical conductivity which is usually much lower in liquid state compared to the values of solid material at room temperature, and particularly the relative magnetic permeability. Thus, the principal investigations were conducted for aluminum alloys (Avilov et al. (2012), Bachmann et al. (2012), and Bachmann et al. (2013a)) and austenitic stainless steels (Bachmann et al. (2014a,b,c)) without or if any weak non-ferromagnetic behavior. In case of duplex or ferritic stainless steels, the relation between magnetic field and flux density becomes non-linear with a strong electromagnetic hysteresis loop that causes additional power losses thus converting the applied electromagnetic power not only in electromagnetic induced pressure but also in heat losses supplementary to Ohmic losses. In the case of welding, things become even more complicated as the material loses its ferromagnetic properties when being heated above the Curie temperature, so that there coexist regions with and without magnetic hysteresis behavior.

Nevertheless, the electromagnetic weld support system could be established for all aforementioned materials.

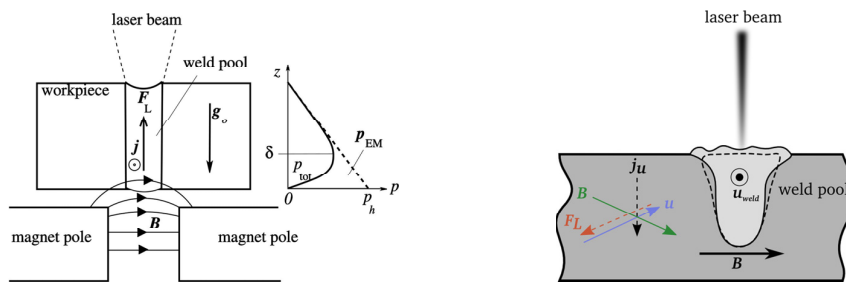


Fig. 4. Schemas of the inductive weld pool support (left) and the Hartmann effect (right) in high power laser beam welding, taken from Bachmann et al. (2014b).

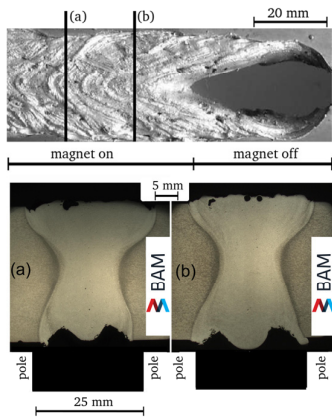


Fig. 5. Full penetration welding of 30 mm thick AlMg3 with and without electromagnetic support taken from Avilov et al. (2012). Welding speed was 0.3 m/min with 15 kW laser power. The oscillation frequency was 450 Hz and the applied magnetic flux density was around 100 mT. The corresponding electromagnetic power was around 200 W (rms).

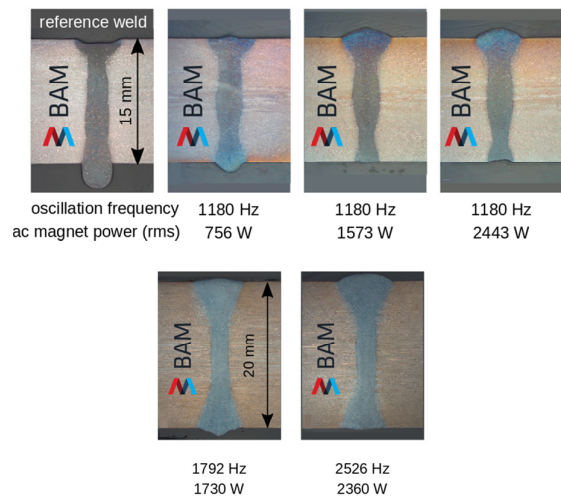


Fig. 6. Full penetration welding of up to 20 mm thick duplex stainless steel AISI 2205, taken from Bachmann et al. (2016b). Welding speed was 0.5 m/min with 8.5 kW and 13.9 kW laser power, respectively.

Exemplary full penetration welding test results without and with applied Lorentz forces as well as weld cross sections can be seen in Fig. 5. Without electromagnetic forces, the melt drops out of the weld seam completely, whereas a compensation of the hydrostatic pressure in the column of liquid material was successful with moderate electromagnetic power levels. The non-uniformity of the lower surface was due to the variation of the oscillating

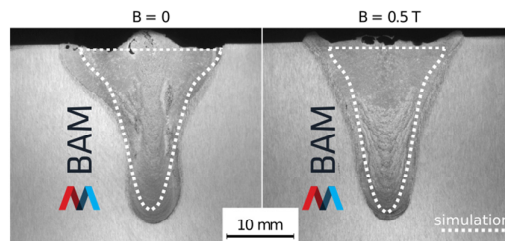


Fig. 7. Hartmann effect in laser beam welding of AlMg3. The welding speed was 0.5 m/min and the laser power was 16 kW taken from Bachmann et al. (2016a).

magnetic field in the vicinity of the magnet edges which results in stirring effects there. This effect does not occur when using a larger magnet pole distance (Avilov et al. (2012) and Bachmann et al. (2012)). Similar very promising results were found for austenitic stainless steel (Bachmann et al. (2014a,b,c)) as well as duplex stainless steel, see Fig. 6 (Avilov et al. (2016), Bachmann et al. (2016b)). The possibility to use the Hartmann effect in high power deep penetration laser beam welding to improve the surface quality and to homogenize the weld geometry was also demonstrated in Bachmann et al. (2016a). Two permanent magnets with a magnetic flux density of around 500 mT were mounted to the lateral sides of a 40 mm wide AlMg3 welding piece. The braking effect of the Lorentz forces which are self-induced by the movement of the liquid material perpendicular to the applied magnetic field is clearly visible in Fig. 7. The weld surface with applied stationary magnetic fields becomes flat and the side walls of the weld seam are more parallel compared to the reference case. As before, in all presented cases, the experimental results were extensively and successfully backed by numerical simulations.

## 5. Laserbeam welding under vacuum/reduced pressure

Another very interesting trend during the last few years is to weld with laser beams under vacuum or reduced pressure, although first publications can be found in the 1980s, Arata et al. (1985), and 1990s, Verwaerde et al. (1995). Arata reached 40 mm penetration with 11 kW laser power (CO<sub>2</sub>-laser) and already proposed vacuum laser welding with an aerodynamic window for practical applications.

The overall idea is to eliminate/reduce the plume which reduces the welding penetration and to reach penetrations with a laser which are otherwise only possible by electron beam welding. Katayama et al. (2011) reached penetrations in type 304 steel of more than 70 mm @ 26 kW power, 0.3 m/min velocity, and a pressure of 0.1 kPa. The overall interaction between laser beam and plume became smaller with decreased pressure. Using this approach, deeply penetrated laser weld beads of more than 40 mm in depth could be produced @ 100 kW and 2 m/min at atmospheric pressure and a sound weld bead could be made in a stainless steel plate of 70 mm in thickness with two passes from both surface sides. Moreover, it was confirmed that laser weld beads of about 100 mm to 125 mm in depth were formed under the welding conditions of the high laser power of 50 kW to 70 kW, the low speed of 0.3 m/min and the low vacuum of 1 kPa, Katayama (2015). Reisinger et al. (2016a) showed that with their laser beam welding under vacuum (LaVa) process a significant increase in process stability at low welding speeds can be obtained which leads to a high weld seam quality and high penetration depths. In S355 and S690QL they reached penetrations of 50 mm with 16 kW @ 0.3 m/min and 0.1 hPa. They present very impressive penetration and parameter fields for welding speeds between 0.2 m/min and 1.5 m/min. Possible applications were also shown for high alloyed steels, nickel-base alloys, duplex stainless steels, titanium and copper. A huge advantage of the laser beam technology is, that fine vacuum conditions are not necessary, very impressive results were achieved at a pressure of about 0.1 hPa, which reduces the overall costs and opens also applications outside a vacuum chamber. Therefore another interesting solution was presented by Schneider et al. (2015a,b,c). They present an apparatus for

mobile welding which allows to produce a pressure of 200 mbar around the interaction zone. Due to the low pressure, the vapour plume formation is depleted and the welding depth is around 50% higher compared to welds produced at ambient pressure. The construction is compact and independent of the size of the component to be welded. For the usage of the vacuum cap, only a vacuum pump and compressed air supply are needed. The aerodynamic window as already proposed by Arata et al. (1985) makes it possible to substitute a conventional cross-jet and eliminates the necessity of using optical components for the pressure stage (see. Fig. 8)

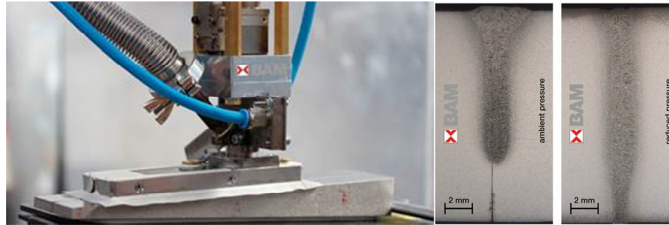


Fig. 8. (a) Mobile vacuum device and for laser beam welding under reduced pressure; (b) Macrosection of 15 mm steel, laser beam power 7 kW, welding speed 0.75 m/min.

## 6. Summary and Conclusions

As follows from the present analysis, the high power laser beam welding technology has made a large progress in the last decade and was established in different industrial applications. One of the most prospective technologies for heavy components assembling could be seen in hybrid laser arc welding. This type of the welding process has numerous advantages associated to using of filler material in comparison to an autogenous laser process, among them the higher tolerances to the gap and misalignment and a higher process stability are the most important ones. Especially for pipeline steels these could be an important factor promoting its industrial implementation in years to come.

A big progress has been achieved in gaining better understanding of the welding phenomena during high power laser welding by using both experimental and simulation techniques. Application of modern high speed video observation, in situ x-ray screening and different process diagnostic methods elucidated the mechanisms of heat conversion in the keyhole and heat and mass flow in the liquid metal as well as beam interaction with evaporation products determining welding process dynamics and in long run the quality of the weld joint. The different simulation techniques like FEM, CFD and analytical computational methods provide additional possibilities for analysis of the welding phenomena.

New approaches have significantly contributed to extending the process boundaries far beyond the known limits. Thus application of electromagnetic fields for melt pool control during laser beam welding of thick plates helped to solve the problem of hydrostatic pressure induced liquid metal drop-out not only for non-ferromagnetic materials but also for ferritic-austenitic and ferritic steels. With help of specialized systems allowing to create a reduced pressure environment around the welding process zone it became possible to significantly increase the penetration depth and to realize stable welding processes at lower welding speeds, as compared to those typically used for high power laser welding processes at atmosphere.

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