Mobile Vacuum in Pocket Format

Mobile local low-pressure cap for high power laser beam welding of thick materials

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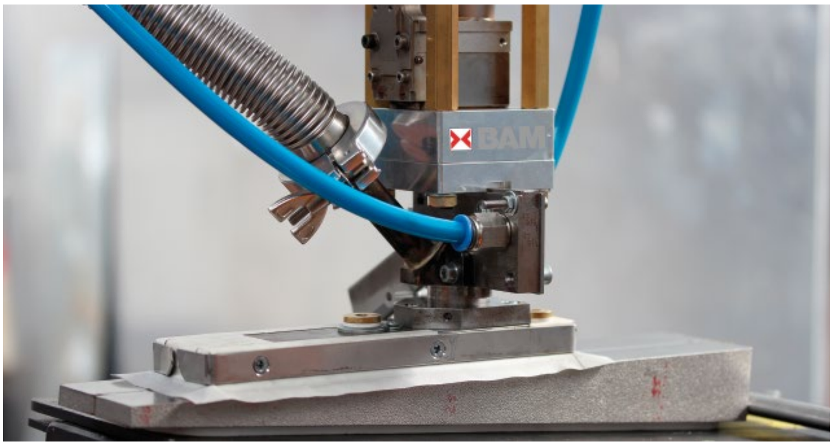
The presented apparatus enables laser beam welding of thick materials under local reduced pressure conditions, thus improving the quality of welds and reducing the laser beam power necessary for complete penetration welding. The vacuum cap presented in this article uses a local reduced ambient pressure environment in a tight zone around the welding area and, in contrast to a conventional vacuum chamber, it is movable in the welding direction. The mobile installation is very compact and reaches pressure values of around 200 mbar. The reduced pressure in the vacuum cap is sufficient to generate 50 % higher penetration depth in comparison to welding under ambient pressure conditions. The low pressure around the keyhole reduces the vapour-plasma plume and therefore prevents a defocusing and scattering of the laser radiation. This allows to raise the amount of laser beam power entering the keyhole as well as the effective power density.



Laser beam welding and the influence of the vapour-plasma plume

The steady development of high power laser systems in the multi kilowatt range constantly enables new application fields for the laser beam welding of thick metal sheets. The raise of the thickness of the welded metal sheets cannot be scaled linearly with an increase of the laser beam power. It was previously shown [1] that the penetration depth during laser beam welding of mild steel increases up to a threshold value; then, at a certain maximum power, it reaches saturation. The change of the laser beam power from 1 to 3 kW with the same welding speed and focus position generates a rise of the welding depth from 0.7 to 3.5 mm, a five times higher penetration depth. However, the welding depth is hardly changed by an increasing of the laser beam power to 5 kW and achieves only 3.8 mm. This correspondes to only 10 % higher penetration depth in comparison to the welding with 3 kW laser beam power. The reason is the vapour-plasma plume with a propagation direction along the laser beam axis, which develops during the evaporation of the liquid metal, see Fig. 1.

The vapour-plasma plume absorbs the laser beam power by a very small percentage. However, the condensed phase of the vapour-plasma plume consists of particles with a size of 30 to 200 nm [2], which act as a scattering medium for the laser beam radiation. Additionally, a deflection of the laser beam occurs due to the density gradient in the particle cloud. Both described phenomena lead to the fluctuations of the laser beam power and therefore to a decrease of the power density on the workpiece surface, the important parameter for the deep penetration welding of thick sheets. A typical power density for keyhole formation is above 10^6 W/cm^2. An elongated keyhole allows the laser radiation to deeply penetrate the workpiece. The easiest way for the rise of the power density is an augmentation of the laser beam power. Thereby, more material evaporates and the vapour-plasma plume becomes wider. The abovementioned effects and their negative influences gain more importance as well. A possible method to reduce these factors is welding in vacuum. In a particle-empty room, the va-

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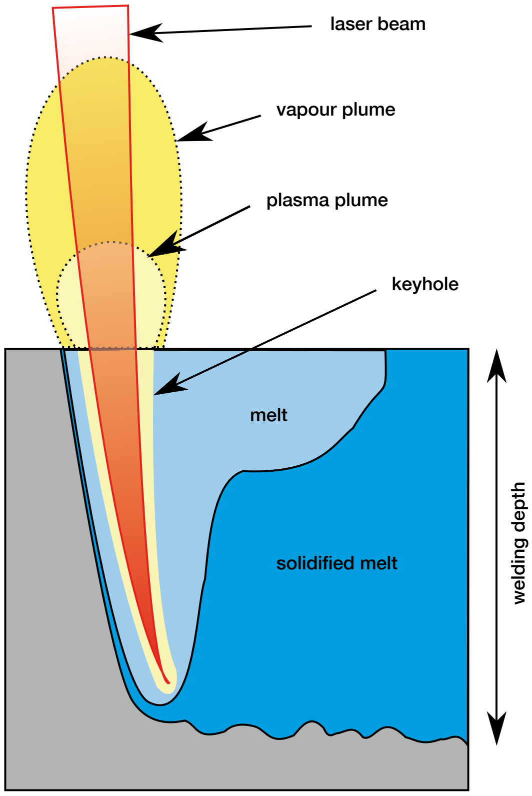

Fig. 1 Schematic illustration of the keyhole with the propagation of the vapour-plasma plume.

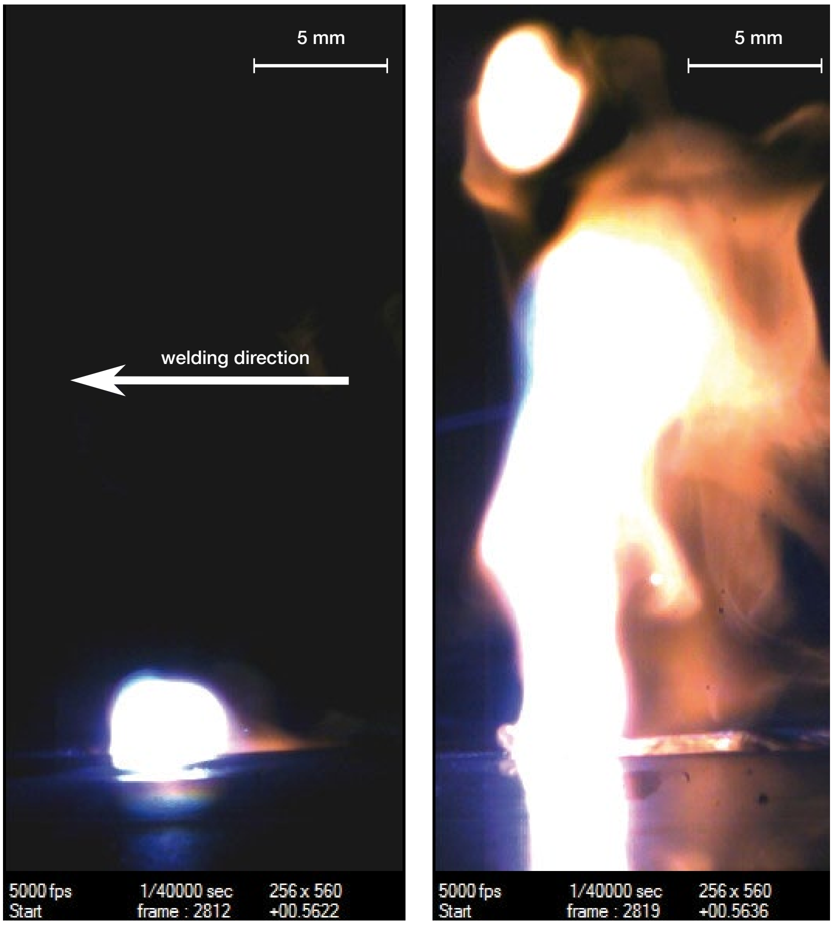

Fig. 2 High-speed image of the plasma plume (left) and the vapour-plasma plume (right).

pour-plasma plume is suppressed, but for this, a pressure lower than 0.1 mbar is needed. Earlier investigations had already indicated that a reduced pressure of around 200 mbar partly suppressed the vapour-plasma plume. This makes it possible to increase the penetration depth by approximately 50 %. The structure of the vapour-plasma plume has been described earlier [2, 3]. Its lower part consists of partially ionized metal vapour – having a temperature slightly above the boiling point. The partially condensed metal vapour plume with a temperature below the boiling point is located adjacent to it. The area of the vapour plume above the plasma plume is significantly higher having lower brightness and diffuse borders, see Fig. 2 on the right side. The reduced ambient pressure is sufficient to suppress a vapour plume. The plasma plume remains unchanged, being small with high brightness and showing sharp edges, see the left side of Fig. 2 [3].

The effect of the vacuum

Conventional techniques use vacuum chambers to generate a reduced pressure environment around the parts to be welded. The dimensions of the vacuum chamber put restrictions on the dimensions of the welded parts. Increasing of the chamber size also increases the evacuated volume and the associated pumping time. A further disadvantage of using a vacuum chamber lies in the restricted application of the laser welding process to a fixed stationary installation. Alternatively, the mobile vacuum technique could be applied to resolve some of these disadvantages [4]. Thereby, a local vacuum surrounding the weld pool is produced being movable in the welding direction.

Such a mobile vacuum cap is shown in Fig. 3. The patent pending construction is capable of reducing the pressure to 200 mbar around the keyhole and has dimensions not larger than a shoebox (20 cm × 15 cm × 8 cm). A rotary vacuum pump evacuates the cavity (not presented) and sucks the residual air via the connection on the right side (Fig. 3, blue arrow). Both zones, the vacuum and the ambient pressure, are separated with an aerodynamic window as a pressure stage. This aerodynamic window consists of a Laval nozzle with a supersonic airflow which is directed in an arched path and runs out in a diffuser. The pressure supply for the aerodynamic window is equipped with the usual compressed air connection as in almost every manufacturing plant. Here, pressures from 5 to 10 bar are necessary. The area with the arched path is designed according to the irrotational vortex principle and produces concentric streamlines around a whirl center. With growing distance from the whirl center, the velocity in the streamline decreases but the pressure increases. The cavity pressure in the whirl center is lower than the more distant streamlines at the ambient pressure side. Therefore a pressure separation is possible and an additional optical medium like quartz glass as a pressure stage is not necessary.

The disadvantage of a quartz glass is the deposition of metal vapour and spatters on its surface. As a consequence, the laser beam couples into the glass and destroys it. This cannot happen with an aerodynamic window because any contaminants leaving the welding zone are blown away by the air jet. As the air flow velocity in the aerodynamic window locally reaches the speed of sound,

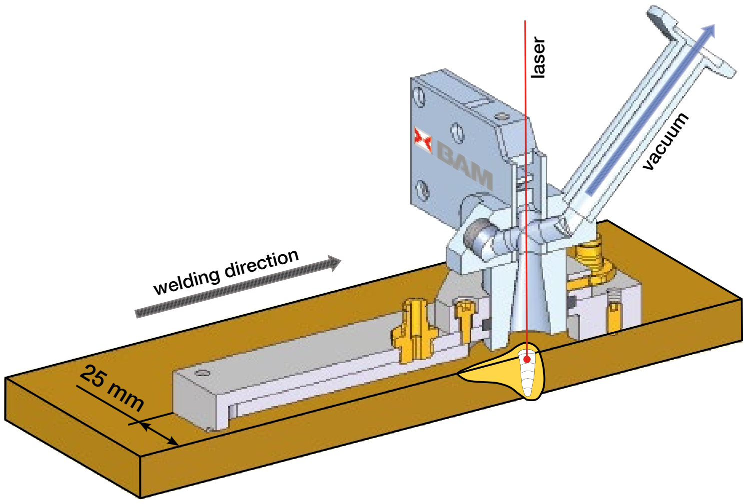

Fig. 3 Section drawing of the vacuum cap with weld pool.

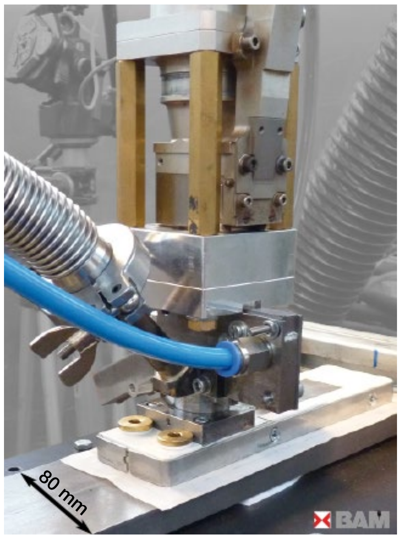

Fig. 4 Experimental setup with a steel plate of 15 mm thickness.

the application of an additional cross jet becomes dispensable. Furthermore towards the vacuum zone around the weld pool, the construction has a subsequent trailing cap which protects the cooling down weld bead against ambient influence. This trailing cap is connected with the cavity in the front side and has the same pressure like this. The length and geometry of the trailing cap can be adapted to the welding conditions (weld seam form, welding speed, etc.).

In case of full penetration welding, the root and top side of the workpiece need to have the same pressure values, otherwise this results in suction of the molten material and destruction of the vacuum cap or the vacuum pump. In the experiments, a box with an elongated cut was used which was positioned along the butt weld and evacuated along with the vacuum cap at the top surface. For practical applications, a mobile solution is needed that allows moving the box along with the vacuum cap. For pipeline constructions, two circular plates inside the pipe around the welding position would solve that issue. These two plates are airtight connected with the inside pipe and the interspace being evacuated. After the welding process, both plates can be disconnected and shifted to the next joining area.

Welding with the mobile vacuum

The experimental setup from the laboratory is shown in Fig. 4. The vacuum cap was fixed with clamping bolts and a distance plate at the laser beam optic. Therefore, the construction has a constant focus distance, but this was variable with plates of different thicknesses.

Fig. 4 shows welding experiments of 15 mm thick steel plates with a fibre laser. The laser beam power was 7 kW and the welding speed 0.75 m/min. During the welding experiments, the vacuum cap had a pressure of 200 mbar. A cross-section of the weld seam welded at 200 mbar and one at ambient pressure is shown in Fig. 5. The reference on the left side clearly shows the nail head form. Due to the vapour plume, the laser beam widened and produced a wide weld seam profile in the upper part which leads to less laser beam

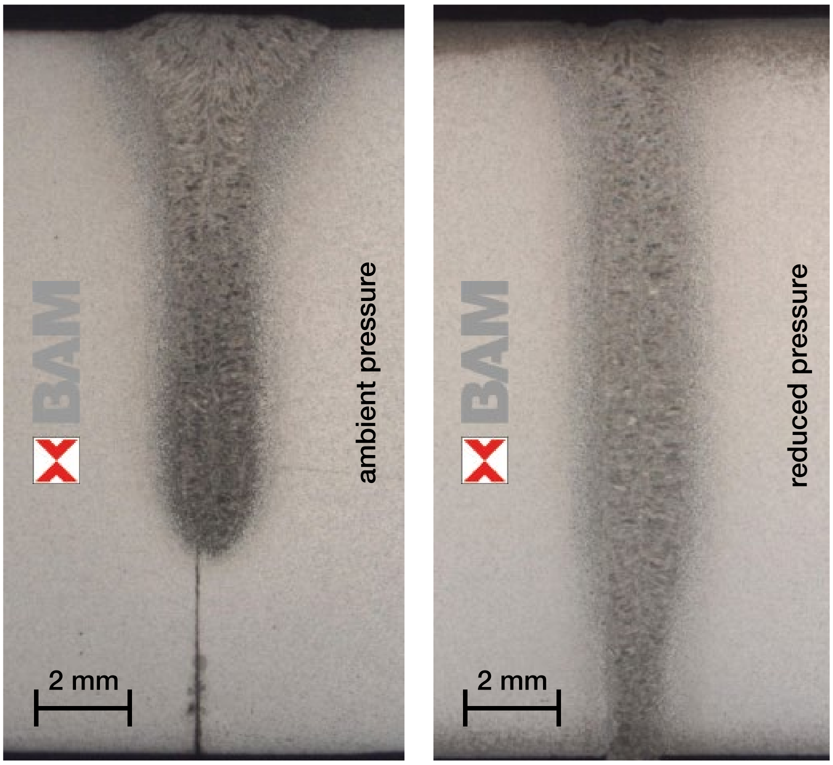

Fig. 5 Macrosection of 15 mm steel, laser beam power 7 kW, welding speed 0.75 m/min.

power absorbed in the lower part. Thus, the welding depth was restricted due to the lack of laser beam power available in the lower region of the keyhole. The welding depth under ambient pressure was around 10 mm. In comparison to the cross-section of the weld seam which was welded at 200 mbar, it is obvious that the profile is clearly slimmer and the laser beam fully penetrates the 15 mm thick workpiece. The nail head form is missing which indicates that enough laser beam power for a full penetration welding process was available. This positive effect is in particular observed at low welding velocities where the keyhole is directed vertical to the laser beam axis [5].

Conclusion

The presented apparatus for mobile welding applicable allows to produce a pressure of 200 mbar around the interaction zone. Due to this low pressure, the vapour plume formation is depleted and the welding depth is around 50 % higher compared to welds produced at ambient pressure. Furthermore, the trailing cap of the back side of the cavity protected the weld seam during the cooling down stage against the influence of the ambient gases. The construction is compact and independent of the component part dimensions. For the usage of the vacuum cap, only a vacuum pump and compressed air supply are needed. The aerodynamic window makes it possible to substitute a conventional cross-jet and eliminate the necessity of using optical components for the pressure stage.

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Authors

André Schneider, after working as a service technician in the automobile industry for several years, studied mechanical engineering at the Berlin Institute of Technology with specialization in construction. During his study period, he worked with the Federal Institute for Materials Research and Testing (BAM) and made his diploma thesis there. In 2012, he obtained his diploma. Afterwards, he worked as a PhD student at the BAM with the topic of laser beam welding under locally reduced pressure.

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