Laser welding under reduced pressure

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The increasing market demand for the application of solid-state lasers in industrial welding processes requires a fundamental adjustment of the process technology and the system concept. An almost spatter-free high efficient process – laser welding under reduced pressure - has now found its way into series production. For weld applications with strict standards concerning the weld-seam and functional surfaces, this process provides cost-effectiveness and a technology optimization focused on the benefits of the solid-state laser beam characteristics.

Лазерно заваряване при редуцирано налягане (Филип Сиебер, Бьорн Хансен, Торстен Льовер, Александер Мааз). *Нарастващото търсене на пазара за прилагането на твърдотелни лазери в индустриални заваръчни процеси изисква фундаментална промяна на технологията на процеса и системната концепция. Почти без пръски високо ефективният процес - лазерно заваряване при понижено налягане - сега е намерил своя път в серийното производство. За заваръчни приложения със строги стандарти по отношение на заваръчния шев и функционалните повърхности, този процес осигурява ефективност на разходите и оптимизиране на технологията, като се фокусира върху ползите от характеристиките на заваряването с твърдотелни лазерни лъчи.*

Introduction

Laser beam welding under reduced pressure is a process first studied in the 1980s by Arata et. al.. In this time period CO_2-lasers were the only option – besides electron beam (EB) guns – to reach high weld depths. The limiting factor for CO_2-lasers is the high absorption rate of the CO_2 laser beam in the plasma plume. It was discovered that by transferring the welding process into lower pressure levels a significant increase of the weld depth can be reached. By decreasing the pressure the size of the plasma plume declines and thereby the absorption of the CO_2-laser [1].

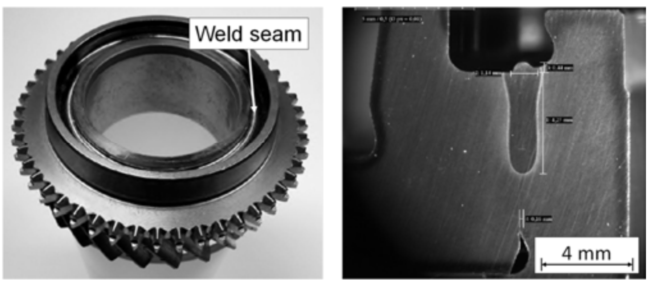

Fig. 1. Gear wheel with cross-section, weld depth 4 mm

In the current industry the number of CO_2-lasers is decreasing and are replaced by solid state lasers. In comparison to CO_2-lasers the new generation of solid state lasers have a higher energy efficiency in combination with a low beam parameter product (BPP) [2, 3]. The replacement is not always possible. In sensitive welding processes where the spatter formation is a key factor the application of solid state lasers is challenging. For example powertrain components such as gear wheels (Fig. 1) with weld depths of 4 – 5 mm have several functional areas where spatters are not tolerated because of the possibility of damaging these areas. Using solid state lasers in atmosphere is not suitable due to their high spatter formation. At ambient pressure solid state lasers tend to form many spatters originating from the higher absorption rate of solid state lasers compared to CO_2-lasers [4].

Besides welding of gear wheels with CO_2-lasers an essential fraction is welded with electron beam guns. EB welding produces welds with good weld quality, no defects, high aspect ratio and with less spatters. The recent approach of the laser beam to electron beam regarding the beam quality raises the question whether there is a difference between the welding process of a solid state laser and an EB gun. To get an answer to this question the remaining different parameter of the process pressure was equalized and the welding process with solid state lasers transferred to reduced pressures.

In the last years several papers regarding laser welding under reduced pressure or vacuum were published focusing on deep penetration welding (> 20 mm) with high power lasers up to 25 kW [5, 6]. In contrast this paper focuses on the welding with mid-range power lasers up to 6 kW under reduced pressure and its beneficial effects for industrial welding applications. Furthermore the increasing similarity between electron beam welding and laser beam welding is evaluated.

Welding equipment

The welding equipment for laser beam welding under reduced pressure combines a standard laser setup with the vacuum equipment of an EB machine. The basic setup is shown in Fig. 2. In addition a vacuum protection glass is needed to guide the laser beam into the vacuum chamber. If necessary, a replaceable laser protection glass can be installed between the vacuum glass and the work-piece protecting the vacuum glass from contamination. To sidetrack any particles produced by the vaporization of the material and to prevent any contamination of the glasses, a small gas jet can be led into the vacuum chamber. No shielding gas such as Ar or N_2 is required.

Because of the similarity to EB machines the first experiments were done on modified EB cycle machines. Pro-beam was able to use its years of experience in vacuum technique to transfer the laser welding process into the low pressure region. In cooperation with the ifs of the university of Brunswick and Trumpf the necessary equipment was developed. For welding disk lasers from Trumpf were used with a BPP of 8 mm mrad and a maximal laser power of 6 kW (cw).

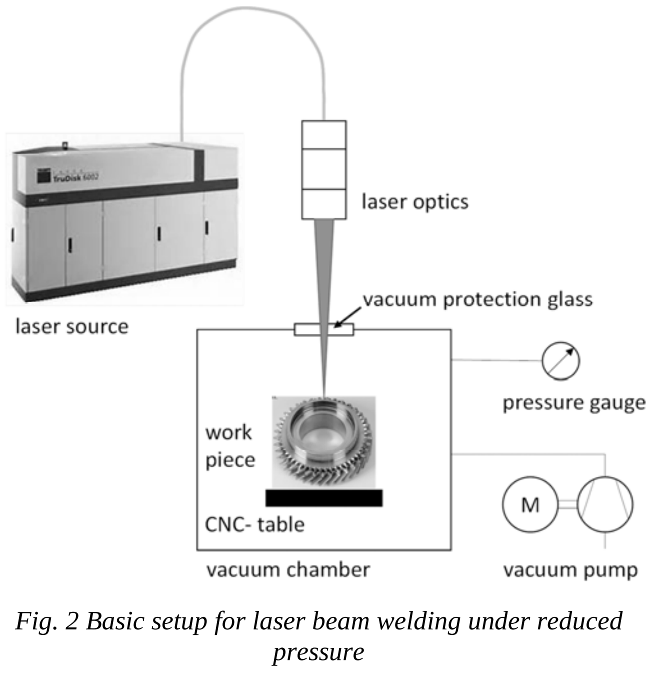

Fig. 2 Basic setup for laser beam welding under reduced pressure

In comparison to EB machines vane pumps are sufficient to reach the required pressure levels and therefore no expensive vacuum equipment is needed. Moreover during laser welding no radiation is generated which saves the shielding of the vacuum chamber.

Effects on the welding process

Laser beam welding under reduced pressure differs considerably from welding in atmosphere. Typically keyhole welding with solid state lasers at ambient pressure is accompanied by many spatters, smoke and a big plasma plume. Reducing the process pressure influences these effects considerably (see Fig. 3, 4).

In Fig. 3 the decreasing plasma plume is imaged. It is noticeable that the plasma plume reduces its size by lowering the process pressure. Beginning at 1000 mbar where a big plasma plume is present, it vanishes until it is barely visible.

This reduction of the plasma plume can be explained by the increase of the mean free path of particles under low pressure. At ambient pressure the mean free path of particles is short [7]. This short mean free path causes collisions between the vaporized metal particles streaming out of the keyhole and air molecules near the weld pool surface. As a result a high particle concentration forms over the keyhole and an intense interaction between these particles and the laser beam takes place leading to the plasma plume [6, 8].

Under low pressure the particles have a longer mean free path and travel a longer distance before they collide with another atom or molecule [7]. Therefore the particle concentration on top of the keyhole is low. A reduced interaction occurs and no plasma plume is visible (see Fig. 3) [6, 8].

Furthermore a lesser movement of the plasma plume under reduced pressure was observed indicating less fluctuation of the keyhole. At ambient pressure the plasma plume exhibits intense fluctuations during welding caused by instabilities of the keyhole. Transferred to low pressure these fluctuations diminish and the plasma plume keeps a constant size and shape. Consequentially a more stable keyhole has formed without any severe fluctuations of the keyhole wall.

(1) $$p_V = p_C + p_d + p_{st} + p_0$$

p_V	-	Pressure of the vaporized metal
p_C	-	Capillary pressure
p_d	-	Hydrodynamic pressure

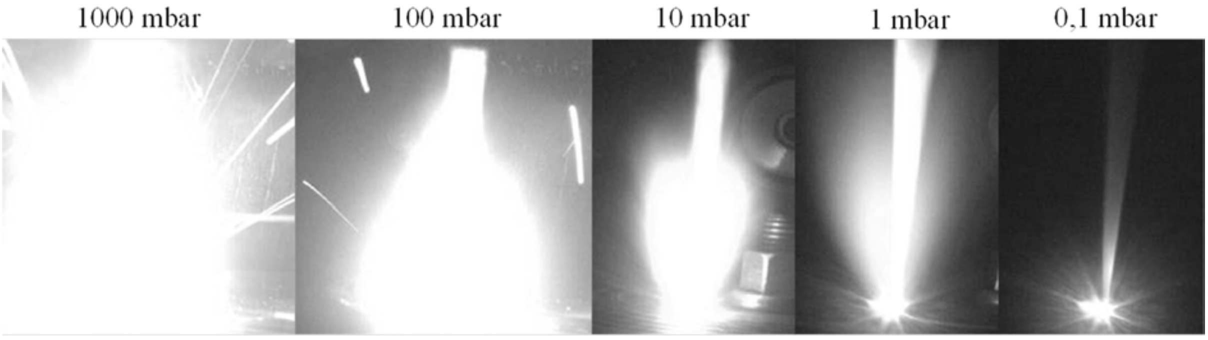

Fig. 3. Plasma plume at different pressure levels (laser power = 3 kW, welding speed = 50 mm s^{-1}, spot size = 300 µm)

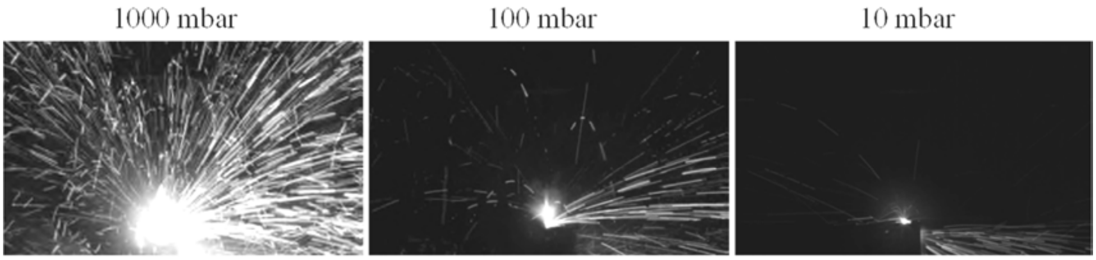

Fig. 4. Spatter formation at different pressure levels (source: ifs TU Brunswick)

p_{st} - Hydrostatic pressure

p_0 - Ambient pressure.

This effect is caused by the influence on the pressure relations described in equation (1). Equation (1) shows that the inner pressure of the keyhole p_V has to be equal to the pressure of the sum of capillary, hydrodynamic, hydrostatic and the ambient pressure to keep a keyhole open [9]. The inner pressure of the keyhole is generated by the vaporization of the metal. If the ambient pressure declines, less pressure of vaporized metal will be required to keep the keyhole open. Concluding a more stable keyhole will form by transferring the laser welding process into lower pressure levels.

Another phenomenon generated by the stabilization of the keyhole is a reduced spatter formation. At 1000 mbar a high spatter formation is present (see Fig. 4). By reducing the process pressure the spatter formation declines which can be seen in Fig. 4 at 10 mbar exhibiting barley any spatters.

Spatters originate generally from the keyhole edge. During keyhole laser welding an upward movement of the molten metal is present resulting from friction between the vapor jet and keyhole wall (Fig. 5). This movement of the molten melt leads to a buildup on the edge of the keyhole. In combination with the vapor jet, these two components put force on the liquid buildup at the keyhole edge. Due to fluctuations of the keyhole at atmospheric pressure some molten metal of the buildup will randomly get into vapor channel. Under the influence of a force caused by the vaporized metal a part of the buildup will get separated from the melt pool and form a spatter [4, 10]. At reduced pressure the fluctuations of the melt pool are decreased and therefore the spatter formation is reduced.

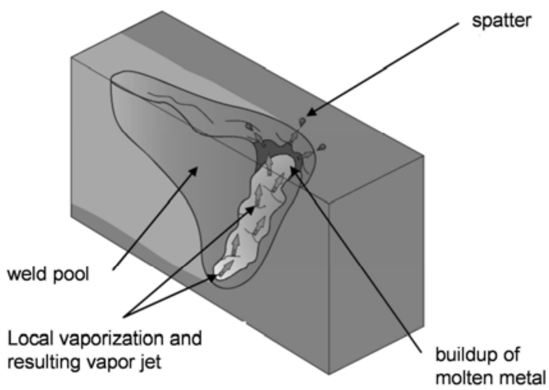

Fig. 5. Mechanism of spatter formation [10]

Effects on the weld

In addition to the effects on the welding process, the reduced pressure influences also the weld depth. Fig. 6 visualizes that from 1000 mbar to 100 mbar the weld depth raises by 35% in case of welding with a laser power of 3 kW and a welding speed of 5 m min^{-1}. A further decrease of the pressure than 100 mbar shows now influence on the weld depth for this parameter combination.

As previously mentioned, in atmosphere the particle density of the vaporized metal particles over keyhole is high. Therefore a severe interaction between laser beam and the particles takes place causing a loss of laser power for welding. This loss results in a lower weld depth. By decreasing the pressure the particle density on top of the keyhole declines and the interaction diminishes resulting in an increasing weld depth [6].

Observations obtained by Katayama et. al. show similar effects. Further investigations of him indicate that the inflection point where no increase of the weld depth occurs is depending on the weld depth in relation to the pressure level. The experiments point out that an increasing weld depth caused by low welding speed and high laser power shift the inflection point to lower process pressures [6]. With regard to the previous explanation by increasing the weld depth the fraction of vaporized material grows and therefore the particle density over the keyhole. This density decreases with lowering the pressure leading to a higher weld depth compared to ambient pressure.

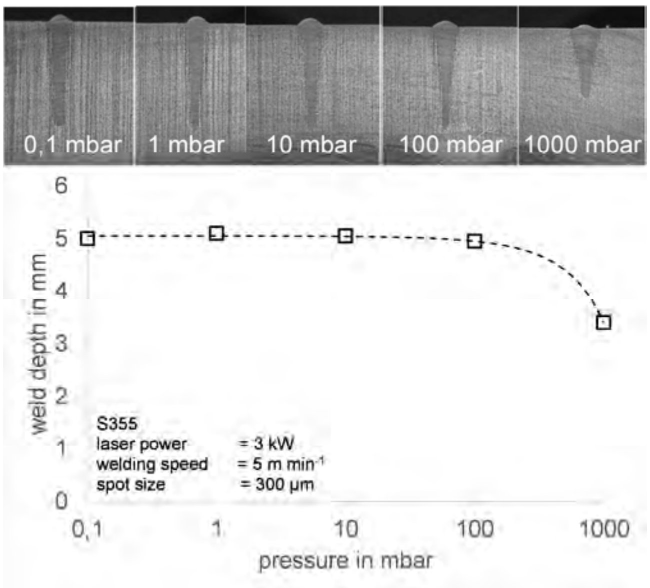

Fig. 6. Influence of the process pressure on the weld depth

Besides the laser power and the welding speed the focus position effects the weld depth too. Experiments with high laser power and low welding speed show that different weld depths and weld forms will be gained depending on the focus position (Fig. 7) [6]. The adequate parameter combination makes it possible to reach weld depths over 20 mm using only a laser power of 6 kW.

The maximal weld depth will be reached by placing the focus into the work piece (Fig. 7). If the focus is placed near the surface the weld depth will decrease. These effects are caused by the beam caustic. A position of the focus below the maximal weld depth results in a low weld depth but in a wider weld. At this position the power density on the surface is too low to reach a deep weld. The energy input increases the width of the weld because of the wide beam diameter on the surface resulting from the defocused laser beam.

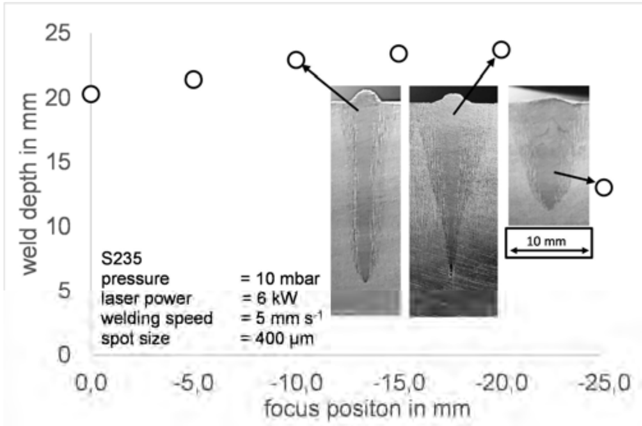

Fig. 7. Influence of the focus position on the weld depth

Automation

Laser welding is a typical process for automated manufacturing because of its good reproducibility, no contact to the work piece, short cycle times, fast welding speeds etc. The same can be achieved by welding in low pressure because no high vacuum is needed. By welding at 10 mbar all of the previous described benefits are already present and the cycle time can be kept short.

In the context of automation, the contamination effects resulting from the vaporized metal particles are to mention. The welding process takes place in a vacuum chamber posing a closed environment. Therefore the metal particles are enclosed inside. After the vaporized particles cool down they form a fine dust layer especially when welding at ambient pressure. The rate of contamination depends on the process pressure.

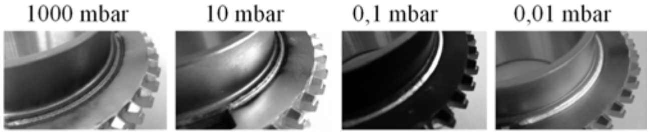

Fig. 8 Work piece contamination at different pressure levels

In Fig. 8 gear wheels welded at different process pressures are imaged. The pictures show that from 1000 mbar to 10 mbar the dust layer on the work piece decreases, recognizable by the brighter shade of the gear wheel. At 0.1 mbar the color of the dust layer turns black. These layers are easy to clean. Depending on the welding setup and parameter the chamber contamination caused by the dust must be taken into account when planning an automation of the welding process.

When welding under 0.01 mbar no dust layer will form and the work piece will be clean. The vaporized metal is coating the vacuum chamber as it occurs when welding with an EB gun. Regarding the contamination, at pressure levels under 0.01 mbar the laser welding process is similar to an EB process.

The benefits of the laser welding process under reduced pressure led to the development of a fully automated welding line (Fig. 9) by pro-beam producing gear wheels for the automobile industry without any post-treatment necessary. The developed mass production plant consists of a modular structure with all production processes included. The parts are automatically loaded, mechanically joined, welded and controlled.

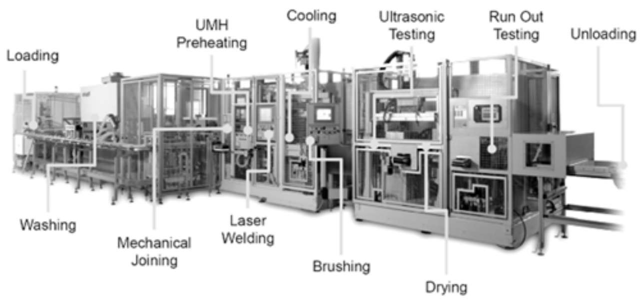

Fig. 9. Automated laser welding plant GEARline made by pro-beam.

Comparison to electron beam welding

The effects caused by transferring laser beam welding into reduced pressure distinguish the process significantly from laser welding in atmosphere. On the other hand the laser welding process under reduced pressure equals increasingly an EB process. This is the outcome of the enhancement of the BPP of lasers making it equal to electron beams. In the end, the approach of the beam technologies leads to similar process properties in case of welding in reduced pressure or vacuum like:

- Reduction of the spatter formation;
- High weld depths possible;
- No/ reduced plasma plume;
- Coating of the vacuum chamber at pressures under 0.01 mbar.

The remaining difference is the lower positioning speed of laser beam in comparison to an electron beam. An electron beam is nearly inertia free and very fast positioned by using magnetic fields. High positioning speeds enable process technologies like beam oscillation, pre- and post heating, multi pool welding etc. [11].

Laser beams are positioned via scanner systems using Galvano mirrors to deflect the beam. Due to their mechanical drivetrain their positioning speed is limited. Scanners applied in research can reach high positioning speeds but are still slower in comparison to EB guns. To reach high positioning speeds small mirrors are used which make them susceptible to thermic damage and limits the usable laser power. In comparison to EB welding the power does not interfere with the positioning speed and enables the previous mentioned process technologies. Nevertheless modern laser scanners applied with beam oscillation improve the welding process by enhancing the weld quality, improving the gap bridging ability or the welding of dissimilar materials [12].

Conclusions

Laser beam welding under reduced pressure improves several aspects in comparison to welding in atmosphere and EB welding. To summarize these aspects the transfer to lower pressure levels entails:

- an increase of the weld depth;
- a reduction of the spatter formation;
- a higher process efficiency
- no need of process gas;
- a reduction of the plasma plume;
- less contamination;
- a stabilization of the welding process;
- no radiation is generated;
- no high vacuum needed.

The results demonstrate that laser welding under reduced pressure produces high quality welds and depending on the process requirements, it can improve the laser welding process or substitute electron beam welding processes.

Acknowledgements

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