Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 83 (2016) 362 – 372

Physics Procedia

9th International Conference on Photonic Technologies - LANE 2016

High power laser beam welding of thick-walled ferromagnetic steels with electromagnetic weld pool support

André Fritzsche[a,*], Vjaceslav Avilov[b], Andrey Gumenyuk[a], Kai Hilgenberg[a,b], Michael Rethmeier[a,b]

[a]*BAM Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany*
[b]*Technical University Berlin, Institute of Machine Tools and Factory Management, Pascalstraße 8-9. 10587 Berlin, Germany*

Abstract

The development of modern high power laser systems allows single pass welding of thick-walled components with minimal distortion. Besides the high demands on the joint preparation, the hydrostatic pressure in the melt pool increases with higher plate thicknesses. Reaching or exceeding the Laplace pressure, drop-out or melt sagging are caused.
A contactless electromagnetic weld support system was used for laser beam welding of thick ferromagnetic steel plates compensating these effects. An oscillating magnetic field induces eddy currents in the weld pool which generate Lorentz forces counteracting the gravity forces. Hysteresis effects of ferromagnetic steels are considered as well as the loss of magnetization in zones exceeding the Curie temperature. These phenomena reduce the effective Lorentz forces within the weld pool. The successful compensation of the hydrostatic pressure was demonstrated on up to 20 mm thick plates of duplex and mild steel by a variation of the electromagnetic power level and the oscillation frequency.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: laser beam welding; thick-walled steel; ferromagnetic steel; weld pool support

1. Introduction

The demand for powerful systems leads to thicker-walled dimensions due to the constructive requirements. Especially the safety of joined components has priority in welding of thick-walled components in high-risk sectors. There is a growing application of duplex steels having good properties in terms of strength and corrosion resistance

* Corresponding author. Tel.: +49-30-8104-1552 ; fax: +49-30-8104-1557 .
E-mail address: andre.fritzsche@bam.de

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2016.08.038

in the pipeline and reactor construction industry, in the chemical apparatus engineering and offshore wind power plants [*Bargel and Schulze* (2008)]. Nevertheless non- and low-alloyed steels are widespread in a variety of industrial applications. Compared to conventional arc welding processes, laser beam welding offers many advantages: By developing modern high power solid-state lasers, there is the opportunity of welding thick plates in single-pass, contactless, automatically and with a concentrated energy input. This results in small heat affected zones (HAZ) and a favorable weld shape with almost parallel side walls. Regarding to the achievable welding speed and the low distortion, full penetration laser beam welding excels in comparison with regular arc welding. Apart from the high demands on the joint preparation resulting from the low tolerance of laser beams towards offset and tilting, the challenge of full penetration laser beam welding in single-pass configuration and flat (PA-) position is the rising hydrostatic pressure in the melt pool with increasing plate thickness. Illegitimate sagging or gravity drop-out of the melt are caused (see Fig. 1).

Fig. 1. Reference full penetration weld in PA position of 15 mm mild steel S235JR with IPG fiber laser using 9.2 kW laser beam power at a welding velocity of 0.5 m min^{-1}, (a) Cross-section; (b) Longitudinal section.

The hydrostatic pressure at the root side of the weld pool is calculated by:

$$p_h = \rho \, g_0 \, h \,, \tag{1}$$

where ρ, g_0 = 9,81 m s^{-2} and h are the melt density, the gravity acceleration and the plate thickness. Exceeding the surface tension, gravity drop-out occurs. The resulting Laplace pressure due to the surface tension on the root side of the weld pool is for arbitrarily curved surfaces according to *Thamsen* (2009):

$$p_\gamma = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \tag{2}$$

Under the assumption of a significantly larger radius R_2 ($R_1 = R$ und $R_2 \to \infty$) in welding direction, the equation is simplified as [according to *Avilov et al.* (2012)]:

$$p_\gamma = \frac{\gamma}{R} \,, \tag{3}$$

where γ and R are the surface tension coefficient and the curvature radius of the liquid metal drops. R depends on the contact angle α. At α = 90°, the maximum value of the Laplace pressure is reached. This means that the curvature radius is identical with the half width of the weld pool (b/2), see Fig. 2 (left). Gravity drop-out of the liquid melt can be prevented by the surface tension as long as the following condition is fulfilled [*Avilov et al.* (2012)]:

$$\frac{h\,b}{2} < l_{cap}^2 \,, \tag{4}$$

with

$$l_{cap} = \sqrt{\frac{\gamma}{\rho g_0}}, \tag{5}$$

as the capillary length. *Avilov et al.* (2016) calculate a capillary length of 5.3 mm for liquid steel. Only determined by the surface tension, it leads to a permitted stabilty threshold between the width of the weld pool and the plate thickness, see Fig. 2 (right). It has to be mentioned that the width of the weld pool must not be too small. The keyhole needs a certain minimum size to enable the transport of energy in vertical direction of the weld pool [*Weberpals et al.* (2007)]. In practice single-pass welding in PA position without gravity drop-out of the melt has been shown for up to 16 mm thick steel plates and beyond [*Farson and Duhamel* (2001), *Gook et al.* (2009), *Rethmeier et al.* (2009) *and Vollertsen et al.* (2010)]. However, the correction of welding irregularities like sagging requires an additional effort, such as time-consuming grinding or the usage of a mechanical melt support which must be removed after welding.

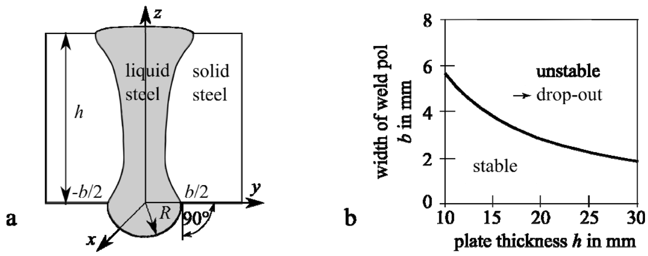

Fig. 2. Melt sagging and drop-out taken from *Avilov et al.* (2016); (a) Description of the Laplace pressure and its characteristic factors on the root side of the weld pool; (b) Stability criterion to prevent gravity drop-out determined by the surface tension .

An innovative approach is the development of an electromagnetic and contactless weld pool support. It is based on generating Lorentz forces within the weld pool. These are produced by an oscillating magnetic field orientated perpendicular to the welding direction and counteract the hydrostatic pressure of the molten steel, see Fig. 3. The externally applied magnetic field ***B*** induces eddy currents ***j*** parallel to the welding direction. Both together, magnetic field and eddy currents cause a time-averaged Lorentz force component, mainly directed in vertical direction:

$$F_L = \langle j \times B \rangle \tag{6}$$

The corresponding electromagnetic pressure resulting from the Lorentz forces can be described as:

$$p_{EM} = \frac{B^2}{2\mu_0}, \tag{7}$$

where μ_0 is the magnetic field constant ($4\pi \cdot 10^{-7}$ H m^{-1}). For a full compensation, the electromagnetic (p_{EM}) and hydrostatic (p_h) pressure on the root side of the weld pool have to be equal, see Fig. 3 (right). Furthermore, the penetration depth of the magnetic field, called skin depth $\boldsymbol{\delta}$, has to be taken into account. As the temperature of the melt and zones of the HAZ exceeds the Curie temperature, the relative permeability μ_r equals 1, due the fact that the material is non-ferromagnetic. Therefore, the standard skin effect theory can be applied for a qualitative estimate of the electromagnetic processes in the weld pool, see e.g. *Landau and Lifshitz* (1984). The skin depth is

$$\delta = \left(\pi f \sigma \mu_0 \mu_r\right)^{-\frac{1}{2}}, \tag{8}$$

where f and σ are the frequency and the electrical conductivity. The laser, which is positioned above the specimen, generates a weld pool. Two magnet poles below the workpiece, located left and right aside the weld pool, supply the oscillating magnet field. This method was used for welding of non-ferromagnetic metals and has shown that a generated electromagnetic pressure can compensate the hydrostatic pressure successfully at welding in PA position of up to 30 mm thick aluminum (-alloys) as well as up to 20 mm thick samples made of austenitic steel [*Avilov et al.* (2012) and *Bachmann et al.* (2014)].

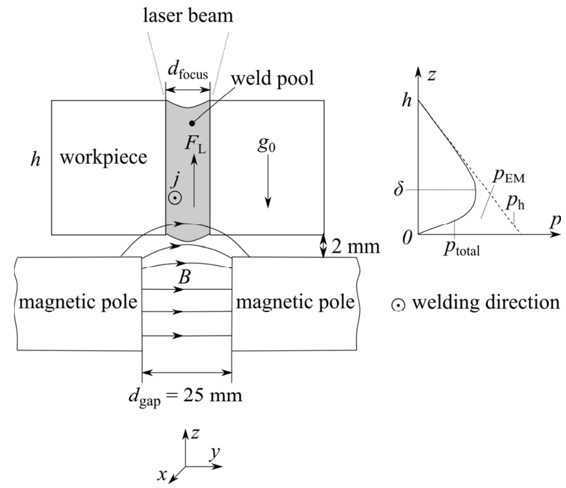

Fig. 3. Description of the weld pool support taken from *Avilov et al.* (2006).

The challenge in the present investigation is to transfer the application of laser beam welding with an electromagnetic weld pool support to thick-walled ferromagnetic metals. Zones next to the HAZ remain ferromagnetic, which is why the magnetic field prefers flowing through regions with a higher value of the relative permeability ($\mu_r \gg 1$), see Fig. 4 a. The skin depth for solid, ferromagnetic steel estimated by *Popovic and Popovic* (2000) for a frequency about 1 kHz is 0.16 mm. This value would not sufficient to generate adequate Lorentz forces in the melt to compensate the hydrostatic pressure. Another fact which has to be considered are the Hysteresis effects of ferromagnetic steels. By using an oscillating magnetic field, magnetization reversal occurs causing ac-power losses rising directly proportional to the chosen frequency. These phenomena reduce the effective Lorentz forces within the weld pool. Due to the higher relative permeability, these effects are much more pronounced at carbon steels compared to duplex steels, see Fig. 4 b. Duplex steels used in the present experiments (AISI 2205, 1.4462) consist of a mixed two-phase microstructure, 50 % ferritic and 50 % austenitic steel.

The experimental investigation concentrates at first on duplex steels as an intermediate step and is subsequently extended to mild steels. Doing this, the influences of the frequency, magnetic flux density and ac-power of the externally applied, oscillating magnetic field on the properties of the weld are investigated on up to 20 mm thick plates of duplex steel (AISI 2205, 1.4462) and mild steel (S235JR). The electromagnetical characteristics (magnetic flux density, ac-power etc.) are given as root mean square values.

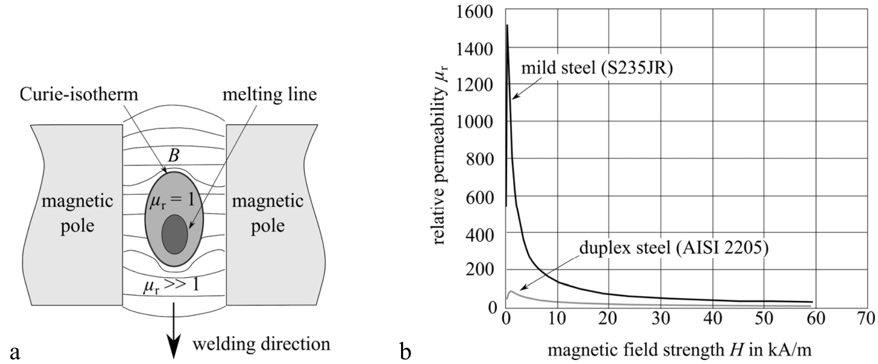

Fig. 4. Schematic description of the electromagnetic supported laser beam welding with ferromagnetic metals; (a) Schematic illustration of the distribution of the magnetic field in steel with ferritic microstructure considering the Curie temperature taken from *Bachmann et al.* (2016); (b) Development of the relative permeability μ_r in dependence on the magnetic field strength H taken from *Aue et al.* (2010).

2. Experimental set-up

The set-up for the welding experiments of up to 20 mm thick plates of duplex steel AISI 2205 (1.4462) and mild steel S235JR can be seen in Fig. 5. The experiments were performed by use of a 16 kW Trumpf TruDisk 16002 as well as a 20 kW IPG YLR 20000 laser. The characteristic parameters of the lasers are listed in Table 1. In both setups the laser optic and the magnet system were fixed and the welding velocity was realized by moving the sample, mounted at a positioning stage, relative to the laser. All welds were generated in PA position as a full penetration weld in a bead-on-plate configuration. The distance between magnet and workpiece was constant at 2 mm in vertical direction, the gap between both magnet poles was 25 mm. The cross section of the magnetic poles was 25 mm x 25 mm. There was no filler material used to stabilize the balance of the phases at duplex steel. The experiments were just performed to demonstrate the application of an electromagnetic support at ferromagnetic metals. The most important parameter for an industrial application is the ac-power needed for the compensation of the hydrostatic pressure. In contrast to non-ferromagnetic materials, the correlation between electromagnetic pressure and ac-power is nonlinear for ferromagnetic metals. The solution has to be found experimentally about the sagging (convexity or concavity curvature) of the root side. The parameters for the welding tests are listed in Table 2.

The welding velocity was 0.5 m min^{-1} to ensure a full penetration in single-pass laser beam welding of 20 mm thick steel plates with the given laser beam power. Another reason for the chosen velocity is the wider cross-section of the weld pool. This improves the possibility of the compensation of the both irregularities, offset and tilting, at laser beam welding. Starting from a reference case without any electromagnetic influence, the applied ac-power was increased stepwise within the test series keeping the frequency on a constant level.

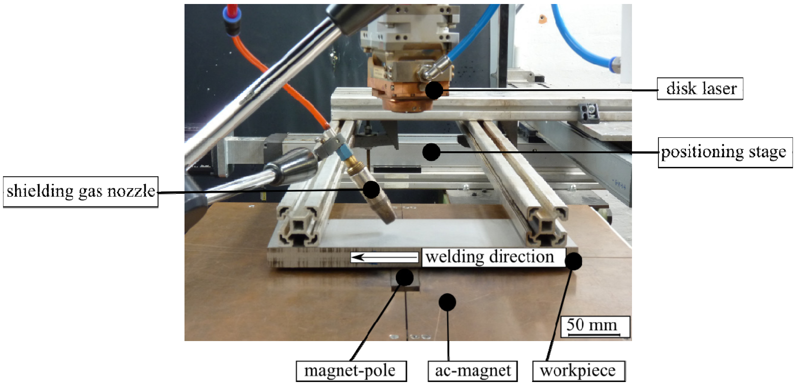

Fig. 5. Experimental set-up for the welds with the Trumpf disk laser.

Table 1. Characteristic parameters of the laser and optical components used for welding experiments.

	IPG YLR 20000	Trumpf TruDisk 1602
Max. laser beam power	20 kW	16 kW
Wave length	1070 nm	1030 nm
Laser fiber diameter	200 µm	200 µm
Beam parameter product	11.5 mm × mrad	8 mm × mrad
Optic	BIMO HP	Precitec YW 52
Focal length	350 mm	300 mm
Laser spot diameter	0.56 mm	0.5 mm

In the experiments with duplex steel, a shielding gas nozzle was used with a volume flow of 26 l min^{-1} argon. The nozzle had a leading orientation and was positioned with an impingement point in advance of the laser beam having an angle of 55° towards the ground of the workpiece. All welding tests with mild steel were performed on the IPG fiber laser, 15 mm duplex steel was welded on the disk laser as well as on the fiber laser. The measurement of sagging was done with cross-sections, taken from the middle of each weld.

Table 2. Parameters of the welding tests.

	Duplex steel (AISI 2205)		Mild steel (S235JR)	
Plate thickness	15 mm	20 mm	15 mm	20 mm
Laser beam power	8.6 kW	13.9 kW	9.2 kW	13.9 kW
Focus length	-4 mm	-6 mm	-4 mm	-6 mm

Before performing the welding experiments, it had to be investigated if the skin depth of the magnetic field is large enough to generate Lorentz forces in the depth of the weld pool. The magnetic flux density cannot be measured directly during the welding process due to the heating of the laser beam. Therefore a set-up was developed to ascertain the skin depth experimentally with a Hall sensor, see Fig. 6. In these so-called cold tests, the configuration corresponds to the experimental set-up. To measure the flux density, two plates of the material which has to be welded were taken (Fig. 6 a). The Hall sensor was used in a small gap between them to measure the magnetic flux density in vertical direction, under constant frequency and ac-power of the magnet system (Fig. 6 b). The skin depth can be found at the value where the magnetic flux density has decreased by a factor of $1/e$. This gives a skin depth of 6 mm at $f = 1149$ Hz for duplex steel AISI 2205, see Fig. 7. Hence, the usage of the electromagnetic support used for non-ferromagnetic metals seems to be basically possible.

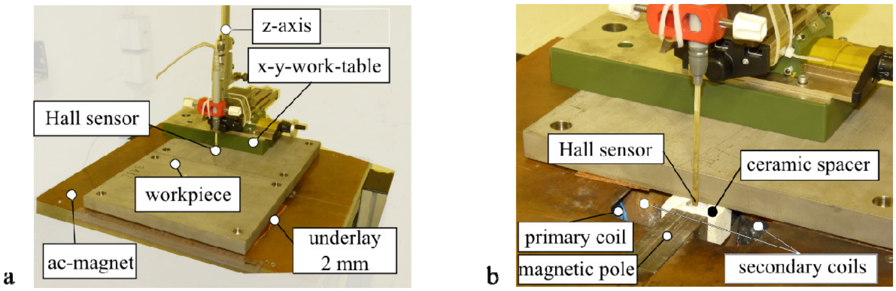

Fig. 6. Cold test set-up for the determination of the skin depth; (a) Complete experimental set-up; (b) Experimental set-up with view to the location of the Hall-sensor.

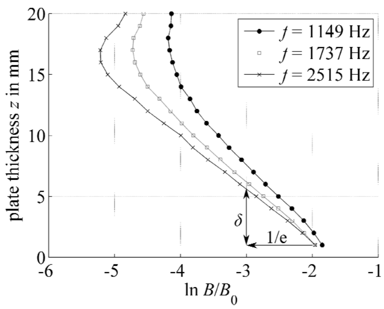

Fig. 7. Results of the cold test measurements for the configuration with duplex steel AISI 2205, with an ac-power of 640 W and B_0 = 1 T.

3. Results and Discussion

The qualitative classification of laser beam welded steels is regulated in DIN EN ISO 13919-1:1996-09. Considering the norm, the allowed root curvature in valuation group B for 15 mm thick plates is less than 2.45 mm (for 20 mm $\leq$ 3.2 mm). Within the test series with duplex steel, the frequency was constantly at approximately 1.2 kHz. Figures 8 and 9 show the welding results of 15 mm thick duplex steel (AISI 2205) with the IPG fiber laser and Trumpf disk laser. Based on the reference welds with an irregular sagging, the hydrostatic pressure was compensatetd stepwise with increasing ac-power. Already at around 800 W the welds can be ranked in group B of the norm. The range for an ideal compensation is between 1.4 kW and 1.6 kW. An applied ac-power of 2.3 kW and more leads to an overcompensation on the root side. This effect is limited by the skin depth of the oscillating magnetic field. The different utilized laser optics generate dissimilar weld pool shapes. For this reason the zones above the Curie temperature have a different size and deviations of the effective ac-power were expected. Nevertheless, the results of both used laser optics have a good match to each other. Afterwards, tests were performed with 20 mm thick plates of AISI 2205, see Fig. 10. An almost full compensation is demonstrated for an ac-power of approximately 1.7 kW. The values of the sagging are around 0.7 mm in this case. All measured values of the sagging are listed in Fig. 15.

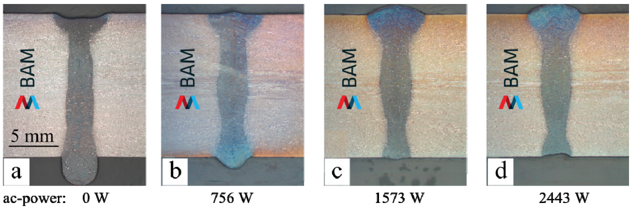

Fig. 8. Development of the root curvature with increasing ac-power at 15 mm duplex steel AISI 2205 with IPG fiber laser with constant frequency (1180 Hz), left: reference weld without magnetic support.

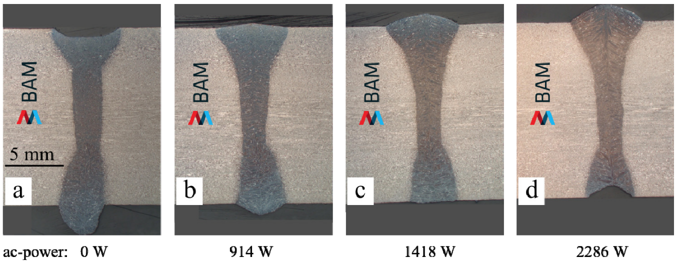

Fig. 9. Development of the root curvature with increasing ac-power at 15 mm duplex steel AISI 2205 with Trumpf disk laser with constant frequency (1209 Hz), left: reference weld.

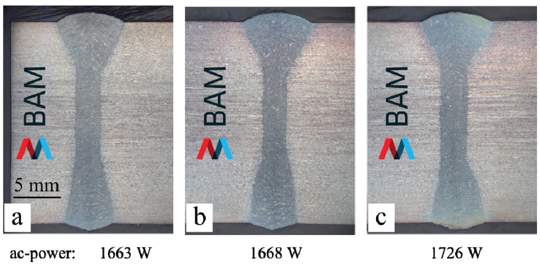

Fig. 10. Repeat attempts with the Trumpf disk laser with constant frequency (1201 Hz) and ac-power (1.7 kW) at 20 mm duplex steel AISI 2205. Laser beam power (13.9 kW), focus length (-6 mm) and welding velocity (0.5 m min^{-1}) were identical within these experiments.

Note, the experiments with duplex steel are an intermediate step. Due to the much higher relative permeabilities, a succesfull application of the electromagnetic weld pool support at mild steel is more challenging. Based on the reference weld (Fig. 11 a), the compensation of the hydrostatic pressure can also be shown for 15 mm thick mild steel S235JR with different frequencies, see Figures 11-13. The reference weld shows irregular sagging (9.15 mm). With a frequency of 784 Hz, it is possible to get an ideal compensation at 2 kW ac-power (Fig. 11). Already at 1 kW ac-power the sagging of the weld is 0.8 mm and can be ranked in valuation group B of the norm. An applied ac-power of around 1.3 kW leads also to a classification in group B for frequencies of 1.2 kHz (Fig. 12 a) and 1.7 kHz (Fig. 13 a). An almost ideal pressure compensation takes place between 1.7 kW at 1.2 kHz and 2 kW at 784 Hz ac-power. Considering the welds with a frequency of 1.7 kHz, a further increase of the ac-power to 2.9 kW does not show an appreciable effect, see Fig. 13. Using an ac-power of 1.9 kW at 1.2 kHz or 2.4 kW at 784 Hz, the penetration depth of the laser process is limited. The weld pool support seems to influence the keyhole stability resulting in a collapse of the keyhole close to the root. It can also be observed that the needed ac-power for a full compensation does not decrease with lower frequencies. There is a certain threshold since 2 kW are needed at 784 Hz and 1.7 kW for 1.2 kHz.

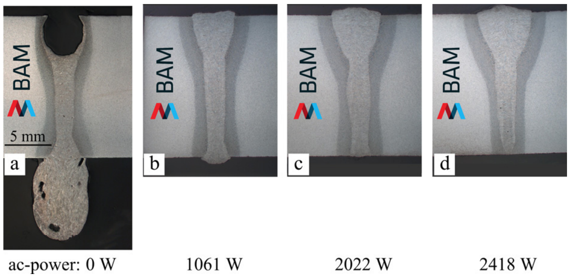

Fig. 11. Development of the root curvature with increasing ac-power at 15 mm mild steel S235JR with IPG fiber laser with constant frequency (784 Hz), left: reference weld .

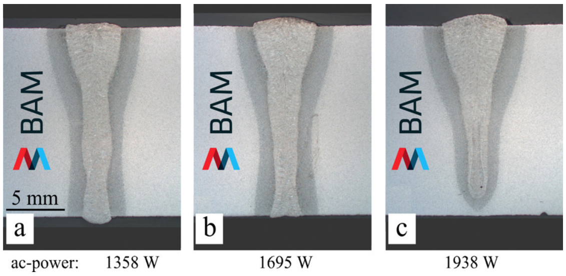

Fig. 12. Development of the root curvature with increasing ac-power at 15 mm mild steel S235JR with IPG fiber laser with constant frequency (1146 Hz), reference weld is given in Fig. 11 a.

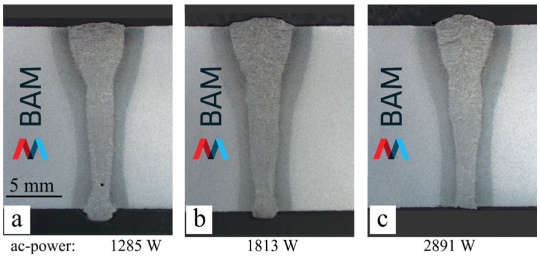

Fig. 13. Development of the root curvature with increasing ac-power at 15 mm mild steel S235JR with IPG fiber laser with constant frequency (1676 Hz), reference weld is given in Fig. 11 a.

After the successfull demonstration of the electromagnetic weld pool support, the welding experiments were extended to up to 20 mm thick mild steel. The results of this investigation can be seen in Fig. 14. The reference weld with a laser beam power of almost 14 kW and a welding velocity of 0.5 m min^{-1} shows an irregular sagging and drop-out of the melt. Using the electromagnetic weld pool support, the welds can also be classified into valuation group B, see Fig. 15. The applied frequency of the oscillating magnetic field was 636 Hz. The needed ac-power for a full compensation with 1.6 kW was lower than in the tests with 15 mm S235JR. At the ac-power of 1.9 kW, an overcompensation was noticed. Evidently the generated Lorentz forces next to the weld pool, which are expected to be much higher due to the higher values of μ_r, act beyond the weld pool. On the one hand, there seems to be a reinforcement of the effective Lorentz forces in the weld pool through neighboring cold zones with a higher relative permeability. On the other hand, there are hystereris losses with increasing oscillation frequency reducing the effect of the weld pool support. Due to this, the optimal parameters for an ideal compensation have to be determined first in an experimental way.

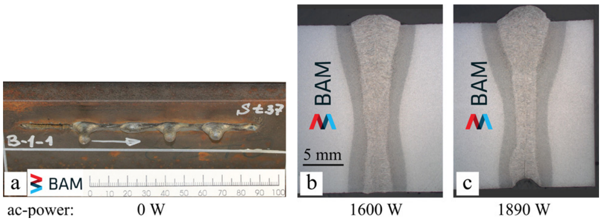

Fig. 14. Development of the root curvature with increasing ac-power at 20 mm mild steel S235JR with IPG fiber laser with constant frequency (636 Hz), (a) Reference weld; (b) Ideal compensation; (c) Overcompensation.

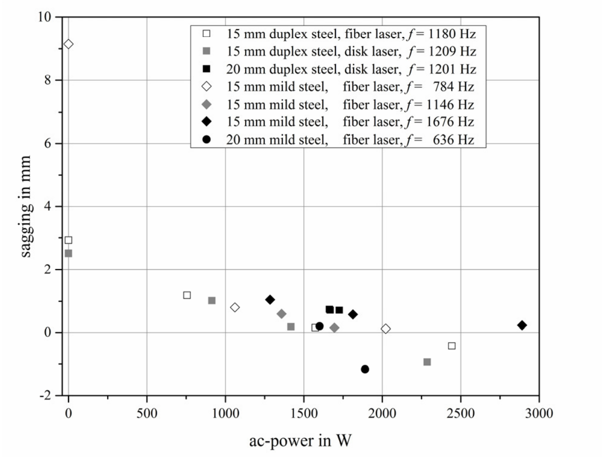

Fig. 15. Measured values of the sagging in dependence of the applied ac-power.

4. Summary

The paper describes an experimental investigation of high power laser beam welding with an electromagnetic weld pool support for up to 20 mm thick plates made of duplex steel (AISI 2205) and mild steel (S235JR). The results of the welding tests show a successful application of this technology at ferromagnetic metals. Irregular sagging was suppressed successfully. An ac-power of less than 2 kW at oscillation frequencies between 800 Hz and 1.7 kHz is necessary for a full compasation of the hydrostatic pressure. Thus, it was demonstrated that the electromagnetic weld pool support is not only limited to non-ferromagnetic metals like austenitic steels. For future studies with duplex steel, the use of filler material has to take into account with regard to the balance of the mixed austenitic and ferritic phases.

Acknowledgements

This work is supported by the DFG (Deutsche Forschungsgemeinschaft, Bonn, Germany) under Grant No. DFG GU 1211/2-2.

References

Aue, H., Thale, W., Pedersen, A. E., Moe, S., 2010. Capabilities of MFL Inspection in DUPLEX Steel Pipelines. 5th Pipeline Technology Conference 2010, Hannover, Germany.

Avilov, V., Berger, P., Ambrosy, G., 2006. Electromagntic Melt Support System for Overhead Position Laser and Electron Beam Welding of Thick Metal Plates. In: Proceedings of the 5th International Conference on Electromagnetic Processing of Materials, Sendai, Japan.

Avilov, V., Gumenyuk, A., Lammers, M., Rethmeier, M., 2012. PA position full penetration high power laser beam welding of up to 30 mm thick AlMg3 plates using electromagnetic weld pool support. In: Sci. Technol. Weld Joi. 17, 128-133.

Avilov, V., Fritzsche, A., Bachmann, M., Gumenyuk, A., Rethmeier, M., 2016. Full penetration laser beam welding of thick duplex steel plates with electromagnetic weld pool support. In: J. Laser Appl. 28, 022420.

Bachmann, M., Avilov, V., Gumenyuk, A., Rethmeier, M., 2014. Experimental and Numerical Investigation of an Electromagnetic Weld Pool Support System for High Power Laser Beam Welding of Austenitic Stainless Steel. In: J. Mater. Process Tech. 214, 578-591.

Bachmann, M., Kunze, R., Avilov, V., Rethmeier, M., 2016. Finite Element modelling of the AC electromagnetic weld pool support in full penetration laser beam welding of thick duplex stainless steel plates. In: J. Laser Appl. 28, 022404.

Bargel, H. J., Schulze, G., 2008. Werkstoffkunde. Springer Verlag.

Farson, D., Duhamel, R.F., 2001. Taking advantage of laser welding. In: The Fabricator 28.

Gook, S., Gumenyuk, A., Rethmeier, M., 2009. Orbital Laser-Hybrid Welding of Pipelines Using a 20 kW Fibre Laser. In: Proceedings of the Fifth International WLT-Conference on Lasers in Manufacturing, Munich, Germany 65-70.

Landau, L. D., Lifshitz, E. M., 1984. Course of theoretical physics. Bd.8: Electrodynamics of continuous media. Oxford: Pergamon.

Popovic, Z., Popovic, B. D., 2000. Introductory Electromagnetics - Chapter 20: The Skin Effect. Prentice-Hall.

Rethmeier, M., Gook, S., Lammers, M., Gumenyuk, A., 2009. A Laser-Hybrid Welding of Thick Plates up to 32 mm Using a 20 kW Fibre Laser. In: Journal of the Japan Welding Society, 74s-79s.

Thamsen, P. U., 2009. Strömungslehre für den Maschinenbau - Technik und Beispiele. Springer-Verlag.

Vollertsen, F., Grünenwald, S., Rethmeier, M., Gumenyuk, A., Reisgen, U., Olschok, S., 2010. Welding of thick steel plates using fibre lasers and GMAW. In: Welding in the World 54.3-4, R62-R70.

Weberpals, J., Dausinger, F., Göbel, G., 2007. Role of strong focusability on the welding process. In: J. Laser Appl. 19, 252-258.