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Electromagnetic porosity reduction in laser beam welding of die-cast aluminum alloy

André Fritzsche[a,b,*], Kai Hilgenberg[a,b], Fabian Teichmann[c], Helge Pries[c], 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
[c] Technical University Braunschweig, Institute of Joining and Welding, Langer Kamp 8, 38106 Braunschweig, Germany

Abstract

Due to the possibility of producing complex geometries with a high dimensional accuracy, aluminum die casting is widely used for manufacturing of automotive and aircraft components. Although the application of fusion welding processes is favorable for joining die-cast aluminum parts, the relaxation of dissolved gases remains a major problem until now.

In the present investigation, the advantages of the laser beam welding process (low distortion, high productivity) are deployed under improved degassing conditions. An oscillating magnetic field is utilized to generate Lorentz forces within the weld pool. Due to the different electrical conductivities between gases and molten aluminum, the contained gases are accelerated to the top of the melt.

Depending on the magnetic flux density and the frequency of the magnetic field, a significantly reduction of the porosity can be detected in partial penetration welding. This method offers great potential for further applications.

Keywords: laser beam welding, die-cast aluminum, electromagnetic weld pool influence

1. Introduction

Die-cast aluminum is a favorable material for manufacturing of lightweight components in the automotive and aircraft industry as various and load-optimized geometries with high dimensional accuracies can be produced. The focus of the present investigation is to join die-cast aluminum by a laser beam welding

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

process. In contrast to mechanical joining techniques, laser beam welding is challenging because of the relaxation of dissolved gases. The gas absorption of aluminum is caused by the die-cast process, where large quantities of hydrogen, nitrogen and air pores get into the aluminum. The main sources of hydrogen are the organic piston lubricant and the mold release agent, Pries et al., 2002 and Wiesner et al., 2001. Hydrogen can occur either dissolved or bounded in hydrides. For inert-gas fusing welding processes like MIG or TIG welding, the formation of pores can be handled. The degassing of the weld pool is improved by lower welding velocities, but the energy input is relatively high. The advantages of laser beam welding as high productivity and low distortion shall be applied for joining aluminum die casting in this investigation. Using a laser beam welding process, it must be taken into account that the solidification velocity is much higher compared to a TIG process. Furthermore the hydrogen solubility of aluminum decreases suddenly with falling temperatures. Hitting a zone which contains much hydrogen, the laser beam causes an abrupt release of a high quantity of hydrogen. Finally, pores result as the hydrogen cannot convert into hydrids again, Pries et al., 2002. If there is a disadvantageous position of inclusions within the aluminum die casting, unwanted full penetrations can appear leading to process instabilities. Beside metallurgical pores, process pores can also occur in partial penetration laser beam welding of aluminum. If there is a keyhole instability which is overtaken by the solidification front, process pores near to the keyhole tip can be caused, Seto et al., 2001.

The porosity reduction in laser beam welding of aluminum die casting was the aim of different investigations. Tolerable results were achieved by using a laser hybrid process, an electron welding process combined with a multi beam technology, a laser beam welding process under reduced ambient pressure and a laser beam welding process with beam oscillation, Pries et al., 2002, Börner et al., 2010, Dittrich et al., 2016 and Teichmann et al., 2016. Nevertheless, a certain quantity of residual porosity remains depending on the method. A laser hybrid process and a beam oscillation lead to a higher distortion compared to a regular laser beam welding process due to the increased energy input. An electron beam welding process as well as laser beam welding under reduced ambient pressure requires high effort since the vacuum resp. the reduced ambient pressure must be generated.

The present investigation deals with the porosity reduction by applying an electromagnetic field. The functional principle is shown in *Fig. 1*.

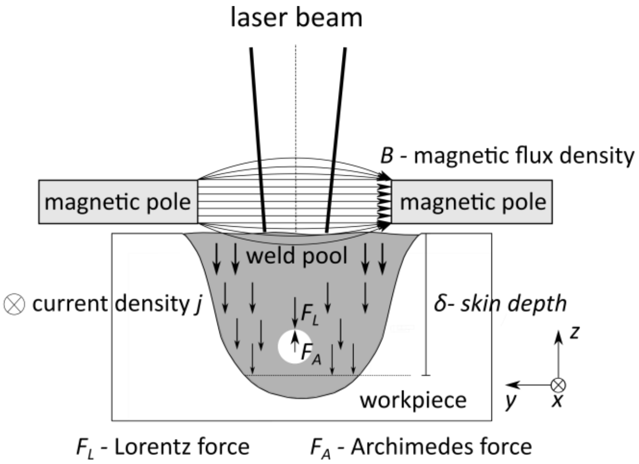


Fig. 1. Principle of the electromagnetic porosity reduction

The weld pool is formed by the laser beam. An AC magnet above the workpiece generates an oscillating magnetic field ***B***. The magnetic field between two magnetic poles positioned left and right aside the weld pool can be used to affect the welding process. The orientation of the magnetic field is perpendicular to the welding direction. Thereby, eddy currents ***j*** are induced within the weld pool, parallel to the welding direction:

$$j = \frac{B}{\mu_0} \tag{1}$$

where μ_0 is the magnetic field constant (= $4\pi \cdot 10^{-7}$ H m^{-1}). The resulting Lorentz force is mainly directed upwards. By neglecting the time-depending oscillation of the magnetic field, the time-averaged Lorentz force is defined by:

$$F_{\mathrm{L}} = j \times B \tag{2}$$

When phases with lower electrical conductivity (for example gas bubbles) occur within the weld pool, the current density changes locally. The electrically well conductive aluminum melt is pressed by the Lorentz force down to the melt ground. By this, a buoyancy force F_A on the poorly conductive phases is caused:

$$F_{\mathrm{A}} = \rho V_{\mathrm{phase}}(g_0 + g_{\mathrm{EM}}) \tag{3}$$

where ρ is the density of the melt and V_{phase} is the volume of the phase. This force, also known as Archimedes force, includes an acceleration part consisting of the gravitational constant g_0 = 9.81 m s^{-2} and an electromagnetic component g_{EM}:

$$g_{\mathrm{EM}} = \frac{B^2}{2\mu_0 \delta \rho} \tag{4}$$

Due to the electromagnetic component, the buoyancy force on the gas bubbles is much higher than by gravity alone. The phases are driven to the upper surface of the melt pool, see Fig. *2*. The buoyancy force is counteracted by the flow resistance force F_R of the phase, which depends on its projected surface A, its velocity v and the flow resistance coefficient c_w:

$$F_{\mathrm{R}} = \frac{1}{2} c_w A \rho v^2 \tag{5}$$

The higher the ratio between volume and projected surface of the phase, the higher is the resulting buoyancy velocity.

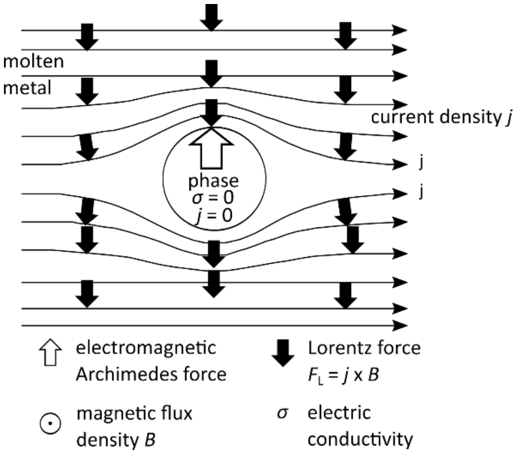


Fig. 2. Effect of removing phases with lower electrical conductivity from the melt according to Zhang and Guo, 2009

According to the skin effect theory, the influence of the magnetic field and the Lorentz forces is limited by a frequency-depending penetration depth, Landau and Lifshitz, 1984, see Fig. *1*. The skin depth is defined as:

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu_0 \mu_\mathrm{r}}} \qquad (6),$$

where f and σ are the frequency and the electrical conductivity of aluminum at melt temperature (σ = 4.037 S m^{-1}) , Mills, 2002. The relative permeability μ_r is 1 because aluminum is paramagnetic.

A further aspect which has to be considered is the Garnier-Moreau effect, Garnier and Moreau, 1983. An electromagnetic field can prevent rough seam surfaces which are caused by the intensive Marangoni flows in laser beam welding of aluminum. The regular surface tension is not sufficient to avoid these undulating surfaces. By using an electromagnetic field, the surface dynamic of the weld pool can be stabilized.

The porosity reduction (> 90 %) as well as the smoothing effect (up to 50 %) was successfully demonstrated by applying an electromagnetic field to influence the weld pool in partial penetration laser beam welding of wrought aluminum AlMg3, Bachmann et al., 2014. Within a previous investigation, Avilov et al. recommend to use a magnetic flux density of around 300 mT and a frequency of 4 kHz to eliminate the process pores of the melt at welding velocities up to 2 m min^{-1}, Avilov et al., 2012. Electromagnetic fields were also used for a TIG welding process at the aluminum alloy 5083. It was shown that already weak magnetic flux densities between 5 mT and 15 mT can successfully prevent the formation of pores at comparably low frequencies between 0.5 Hz and 10 Hz, Matsuda et al., 1978.

The present investigation deals with the porosity reduction in partial penetration laser beam welding of aluminum die casting by applying an electromagnetic field. Up to now, this procedure was only used for wrought aluminum. The intention of this paper is to transfer this method to a standard die-cast aluminum alloy and to investigate the influence of the magnetic process parameters.

2. Experimetal set-up

The laser beam welding experiments were done at 6 mm thick aluminum die casting AlSi9MnMg (Silafont 36) in flat position in bead-on-plate configuration. The parameters for the manufacturing process of the die-cast aluminum are given in Table *1*. No optimization of the aluminum die casting took place during its manufacturing regarding its hydrogen content. Before welding, the workpieces were cleaned with ethanol. Another pretreatment method like pickling or grinding was not applied. Several sheets with obviously different defect volumes within the base material were used. That is why the density index of 9.4 % in *Table 1* serves only as a rough guide. The parameters of the used disk laser and its optical components can be found in Table *2*.

Table 1. Parameters of the die-casting process

Material	AlSi9MnMg
Release agent	Safety-Lube 7477
Mixing ratio	1:100
Piston lubrication	Power-Lube 824
Vacuum	Without vacuum
Density index	9.4 %
Piston temperature	20 °C
Mold temperature	220 °C
Oven temperature	740 °C

Table 2. Parameters of the laser and its optical components

	Trumpf TruDisk
Used laser beam power	3 kW
Wave length	1030 nm
Laser fiber parameter	200 µm
Focal length	300 mm
Beam parameter product	8 mm × mrad
Laser spot diameter	0.5 mm

The set-up of the experiment is shown in Fig. *3*. The laser and the magnet are positioned above the workpiece in a fixed configuration whereby the laser hits the workpiece in the center of the gap between the magnetic poles. The angle of entry is 10 degree to avoid unwanted reflections which could damage the laser optics. The workpiece is mounted on a positioning stage with a vertical distance of 3 mm to the magnetic poles. A ceramic shielding gas nozzle with argon gas was utilized with an angle of 20 degree in forehand orientation. The laser beam was orientated in backhand position.

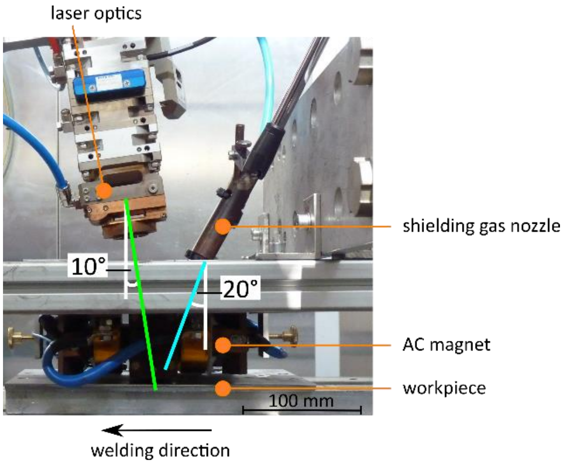
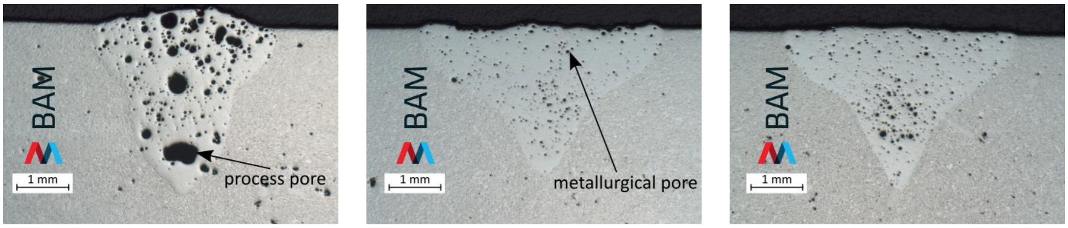


Fig. 3. Experimental set-up

First of all, the experimental program was designed to find the best welding parameters without using the AC magnet. These values form the basis for the further investigations with the AC magnet. Within the welding experiments with activated magnet, the frequency and the magnetic flux density were varied. The test evaluation takes place by means of cross sections. These were cut from the middle of the weld seam, grinded and polished. The analysis was done by optical microscopy, the remaining porosity was measured by a threshold method. Additionally, CT images of three weld seams were taken.

3. Results and Discussion

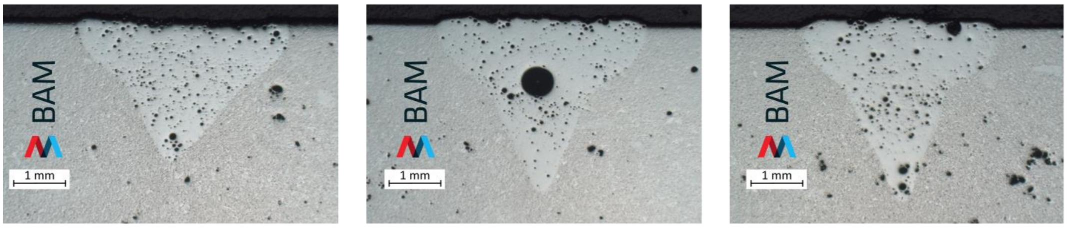
In this subsection, the results of the laser beam welding experiments with electromagnetic porosity reduction are presented. The preliminary study shows that the best reference welds were reached with a laser beam power P_L of 3 kW, a focus position of -6 mm and with a welding velocity u_{weld} of 2 m min^{-1}. The first test series with an electromagnetic weld pool influence was performed on the same sheet. Fig. *4* shows the cross section images of these experiments. The reference weld seam without an electromagnetic weld pool influence contains a high defect volume with a big process pore at the center of the root area and also many big metallurgical pores. The weld reinforcement is 0.4 mm and higher than on the electromagnetic influenced seams. These show a weld reinforcement from 0.13 mm to 0.25 mm without a clear trend with regard to the frequency f or the magnetic flux density B. Nevertheless, it indicates that a smoothing of the seam surfaces takes place by applying an electromagnetic field. The most remarkable changes are the reduction and the size of the included pores. In comparison to the reference seam, the diameter of the metallurgical pores is much smaller. The diameter seems to become smaller the higher the magnetic flux density is. The seam width of the reference seam is 3.4 mm and the depth is 3.18 mm. The widths of the electromagnetic influenced seams vary from 3.7 mm to 4.7 mm. The depths are between 2.6 mm and 3.3 mm. There is no clear tendency of the used magnetic parameters. However, it can be seen that the seam width increases and the weld reinforcement decreases when an electromagnetic field is applied.



reference, f = 0 Hz, B = 0 mT

f = 3090 Hz, B = 360 mT

f = 4400 Hz, B = 360 mT



f = 1600 Hz, B = 232 mT

f = 3090 Hz, B = 234 mT

f = 4400 Hz, B = 227 mT

Fig. 4. Cross section images of the weld seams on sheet A (P_L = 3 kW, u_{weld} = 2 m min^{-1}) depending on the frequency f and the magnetic flux density B, top left: reference case without electromagnetic weld pool influence

Starting from the reference case with 20.6 %, the analysis of the remaining porosity shows a significant reduction by applying an electromagnetic field, see *Fig. 5*. Except the weld seam which was affected by a frequency of 3.09 kHz and a magnetic flux density of 234 mT, the achieved porosity is below a limit of 10 %. The best result shows a porosity of 4.9 % (reduction of 76 % to the reference). There is no clear trend of the parameter frequency which influences the skin depth of the magnetic flux density resp. the Lorentz forces within the weld pool. The effect of the Lorentz forces is limited to a half of the skin depth δ. As already mentioned above, the measured seam depths of the cross section images are between 2.6 mm and 3.3 mm. Choosing frequencies of 1.6 kHz, the Lorentz forces reach the weld pool bottom whereas it is limited to 1.89 mm at a frequency of 4.4 kHz. However, the initiated electromagnetic pressure within the weld pool appears to be high enough to generate a sufficient buoyance force. The pressure seems to be transmitted down to the bottom of the weld pool since a porosity reduction can also be observed there.

Using the same frequency, the porosity is lower the higher the magnetic flux density is. There seems to exist a limit: At a frequency of 4.4 kHz, the limiting value of porosity reduction (6.8 %) is reached at B = 360 mT. There still remain small metallurgical pores within the weld pool. They appear not to be affected by the buoyancy force as the ratio between volume and projected area of the pores is too small to remove the phases from the weld pool.

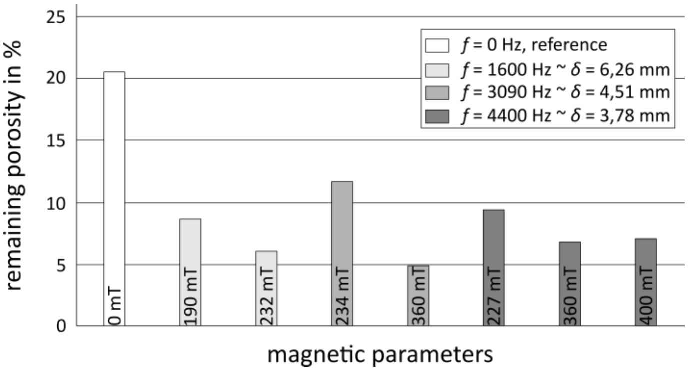
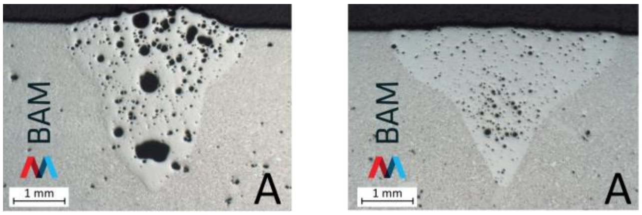


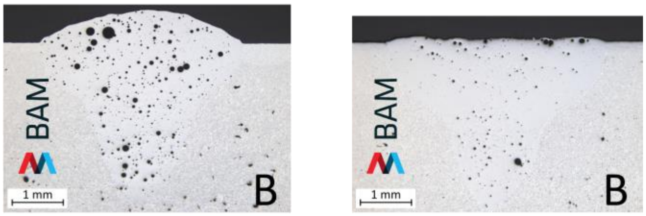
Fig. 5. Analysis of the remaining porosity in dependence of the frequency f in Hz (their corresponding skin depth δ in mm) and the magnetic flux density B in mT

After the first test series, additional tests were performed on another sheet of the same aluminum die casting manufacturing process, called “sheet B”. The welding parameters are identical. *Fig. 6* shows a comparison of the cross section images of the reference case and an electromagnetic influenced weld seam with almost the same magnetic parameters for sheet A and B. The porosity values differ strongly from each other. Using the same set-up and laser parameters, the porosity of the reference weld seam is 4.7 % at sheet B compared to 20.6 % at sheet A. The electromagnetic influenced weld seam at sheet A has a porosity of 6.8 % (reduction of 76 %) and 1.1 % at sheet B (reduction of also 76 %). The results of sheet B confirm the finding that especially big bubbles are removed from the weld pool effectively by using an electromagnetic field creating a sufficient buoyancy force.



reference, f = 0 Hz, B = 0 mT

f = 4400 Hz, B = 360 mT



reference, f = 0 Hz, B = 0 mT

f = 4325 Hz, B = 348 mT

Fig. 6. Comparison of the cross section images of sheet A and B (P_L = 3 kW, u_{weld} = 2 m min^{-1})

The computer tomography (CT) image of sheet B substantiate the results of the cross section images, see *Fig. 7*. Starting from the reference case (3.18 %), it can be observed a significant reduction of the defect volume with increasing magnetic flux density. Especially the big defect volumes from 2 mm^3 to 10 mm^3 can be eliminated with rising magnetic flux density. The best result (B = 348 mT) has a porosity of 0.39 % and defect volumes of less than 2 mm^3 per pore, which represents a porosity reduction of 88 %.

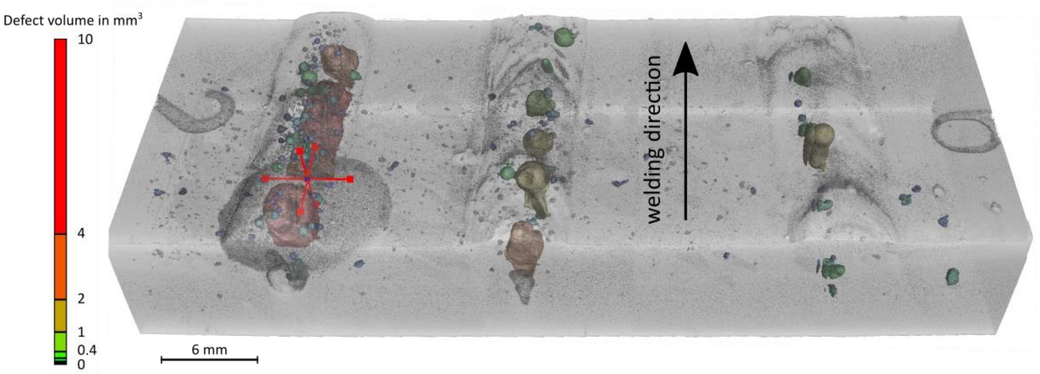


Fig. 7. Computer tomography (CT) image, left: reference case of sheet B with a defect volume of 3.18 %, center: electromagnetic influenced seam (f = 4325 Hz, B = 189 mT), right: best seam with a defect volume of 0.39 % (f = 4325 Hz, B = 348 mT)

The standard DIN EN ISO 13919-2:2001-12 allows in valuation group B (highest weld quality) a porosity of less than 3 %. The best seam of sheet B can be ranked into this group of the standard. The experiments reveal that the remaining porosity depends on the base material. The higher the volume of gases (either dissolved or bounded), the more difficult it is to reach a porosity which can be classified into valuation group B of the standard. The used sheets are manufactured by a non-vacuum supported process and show a comparably high density index (9.4 %). Moreover, this index is measured before casting; the atmosphere, the release agent as well as the piston lubricant can influence the volume of dissolved or bounded substances. However, it can be demonstrated that the usage of an electromagnetic field can significantly reduce the porosity. It can be seen as a promising method to apply the laser beam welding process at aluminum die casting. By an additional optimization of the aluminum die casting manufacturing process, lap joints with low porosity and high weld seam qualities can be produced.

4. Summary

The present paper investigates the electromagnetic porosity reduction in partial penetration laser beam welding of 6 mm aluminum die casting AlSi9MnMg. Applying an electromagnetic field, a significant reduction of the porosity as well as smoothing of the surface of aluminum die casting can be observed. Starting from the reference case without an electromagnetic support, the porosity was reduced by 76 %. Especially big pores can be removed from the weld pool effectively due to their beneficial volume-to-area ratio whereas very small metallurgical pores tend to remain within the weld pool even when higher magnetic flux densities are applied.

References

Avilov, V., Schneider, A., Lammers, M., Gumenyuk, A., Rethmeier, M., 2012. Electromagnetic control of the weld pool dynamics in partial penetration laser beam welding of aluminium alloys, Journal of Iron and Steel Research International 19 (S.1), 233-236

Bachmann, M., Avilov, V., Gumenyuk, A., Rethmeier, M., 2014. Experimental and numerical investigation of an electromagnetic weld pool control for laser beam welding, Physics Procedia 56, 515-524

Börner, C., Krahn, O., Pries, H., Dilger, K., 2010. Wirtschaftliches Schweißen duktiler Aluminium-Druckgusslegierungen für den Einsatz in modernen Leichtbaustrukturen, DVS-Berichte Band 267, DVS-Verlag Düsseldorf, 56-62

Dittrich, D., Standfuß, J., Jahn, A., 2016. Neuartiges verfahren zum druckdichten Laserstrahlschweißen von Aluminium aus Atmosphären-Druckguss, DVS-Berichte Band 327, DVS-Verlag Düsseldorf, 289-293

Garnier, M., Moreau, R., 1983. Effect of the finite conductivity on the inviscid stability of an interface submitted to a high-frequency magnetic field, Journal of Fluid Mechanics 127, 365-377

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

Matsuda, F., Nakata, K., Miyanaga, Y., Kayano, T., Tsukamoto, K., 1978. Effect of Electromagnetic Stirring on Weld Solidification Structure of Aluminum Alloys (Report II), Trans. of JWRI 7, 33-45

Mills, K.C., 2002. Recommended Values of Thermophysical properties for Selected Commercial Alloys, Woodhead Publishing Ltd.

Pries, H., Rethmeier, M., Wiesner, S., Wohlfahrt, H., 2002. Laser- und Elektronenstrahlschweißen von Aluminium-Druckguss, DVS-Berichte Band 220, DVS-Verlag GmbH, Düsseldorf, 219-223

Seto, N., Katayama, S., Matsunawa, A., 2001. Porosity formation mechanism and supression procedure in laser welding of aluminium alloys, Weld. Int. 15, 191-202

Teichmann, F., Müller, S., Pries, H., Dilger, K., 2016. Verringerte Porenbildung beim Laserstrahlschweißen von Aluminium-Druckgusslegierungen durch reduzierten Umgebungsdruck, DVS-Berichte Band 327, DVS-Verlag Düsseldorf, 294-299

Wiesner, S., Rethmeier, M., Ruge, J., 2001. Hydrogen in aluminium die castings-Formation of hydrides and their effects on base material, heat treatability and weldability, ZEITSCHRIFT FUR METALLKUNDE, 92 Jg., Nr. 3, S. 300-306

Zhang, Z., Guo, Q., 2009. Motion behavior of non-metallic particles under high frequency magnetic field, Trans. Nonferrous Met. Soc. China 19, 674-680