Scientific Research Publishing

Materials Sciences and Applications, 2019, 10, 53-64
http://www.scirp.org/journal/msa
ISSN Online: 2153-1188
ISSN Print: 2153-117X

Low Porosity in Cast Magnesium Welds by Advanced Laser Twin-Spot Welding

Karl Fahlström[1,2*], Jon Blackburn[3], Leif Karlsson[2], Lars-Erik Svensson[2]

[1]Swerea KIMAB, Kista, Sweden
[2]University West, Trollhättan, Sweden
[3]TWI Ltd., Cambridge, UK
Email: *karl.fahlstrom@swerim.se, jon.blackburn@twi.co.uk, leif.karlsson@hv.se, lars-erik.svensson@hv.se

How to cite this paper: Fahlström, K., Blackburn, J., Karlsson, L. and Svensson, L.-E. (2019) Low Porosity in Cast Magnesium Welds by Advanced Laser Twin-Spot Welding. *Materials Sciences and Applications*, **10**, 53-64.
https://doi.org/10.4236/msa.2019.101006

Received: October 19, 2018
Accepted: January 13, 2019
Published: January 16, 2019

Copyright © 2019 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/
Open Access

Abstract

Porosity is reported to be a major issue when welding cast magnesium. Therefore, it is important to understand the pore formation mechanisms and find procedures that could be used to reduce porosity. This study investigated the possibility of using twin-spot optics for reducing the porosity in laser welded cast magnesium. Two twin-spot welding setups were compared using either a beam splitter or twin-spot welding with primary and secondary (placed in front of the primary optic) optics. The results showed that welding with a dual optic setup with a defocused secondary beam reduced the volumetric porosity in the weld to 5%. The highest levels of volumetric porosity were 30%, and were a result of using the dual optic setup, but with a defocused primary beam. No clear relation between the level of porosity and power or welding speed was found. It was found that the amount of porosity depended on the balance of the energy input (controlled by defocusing) between the two beams. Porosity formation can be reduced if the energy from the first beam results in the nucleation and initial growth of pores. Reheating by the second beam then allows the pores to grow and escape from the molten material without melting additional base material. Furthermore, twin-spot welding is shown to be a promising combination of a production friendly solution and high quality welding.

Keywords

Laser Welding, Cast Magnesium, Twin-Spot, Metallurgy, Porosity, Automotive, AM50 Alloy

1. Introduction

Compared with high strength steel and aluminium, magnesium alloys provide further possibilities to reduce the weight of a structure due to their good strength-to-weight ratio. Hence, magnesium alloys are suitable for automotive and aerospace industry. However, the tensile strength of these alloys has a rather low range of 190 - 310 MPa, which limits suitable applications; to e.g. seat frames, steering wheels or structural dashboard cross beams [1] [2] [3] [4]. A common engineering magnesium alloy is the AM50 alloy (Mg + 4.4 - 5.5 wt% Al and 0.26 - 0.6 wt% Mn, according to ISO 16220(00)). The advantages of AM50 compared with most other magnesium alloys are its higher strength, higher hardness, high elongation and excellent castability, which makes it a good candidate for light weight structures [5].

One way to utilize the properties of magnesium is to cast the alloy into complex shapes with high pressure die casting [6] [7] [8] [9]. However, casting of large and complex details requires a huge effort and expensive and large machines [9]. An alternative is to cast less complicated parts and join them by welding. Laser welding utilizes a high power density with a relatively high welding speed, giving a fairly low heat input. This is often an advantage as a narrow fusion zone and HAZ will form, reducing the negative impact on material properties [2].

A number of studies have been made focusing on weld quality of laser welded cast magnesium [2] [5] [10]-[15]. Pores are reported to be one of the main issues when welding cast magnesium. Therefore, it is important to understand the pore formation mechanisms and find procedures that could be used to reduce this pore formation [2] [10].

In a previous study [16], AM50 was laser welded bead-on-plate to study pore formation. The influence of welding parameters including laser power, welding speed, focal position, single-pass and two-pass welding and surface cleaning was investigated. Low porosity (~3%) content was found when increasing the welding speed and decreasing the laser power, or when using two-pass welding. The relatively low amount of porosity achieved for single-pass welding was explained by that, with a proper selection of welding parameters, pre-existing pores originating from the base material did not have enough time to expand. The low porosity content in the two-pass welds was explained as a result of the first pass causing the pre-existing pores to grow, while the second pass caused de-gassing of the pores formed during the first pass. Two-pass welding is unfortunately not a productivity friendly scenario, but the results of degassing are wanted.

Another example where two-pass laser welding has been applied is in a study by Harooni *et al.* [17]. In that case, two-pass laser welding was done for AZ31B magnesium alloy in a lap-joint configuration. In this study, the origin of the pores was concluded to be the oxide layers at the faying interface between the two sheets. It was found that the first welding pass decomposed the magnesium hydroxide into magnesium oxide and water while the second pass helped the vaporized water to escape, and thereby produced a pore free weld.

As stated by Shibata *et al.* [18] twin-spot optics can be used for avoiding several laser welding defects mainly caused by process instabilities. Shibata *et al.*

used twin-spot optics for reduction of distortions and for increasing the strength of the joint during laser welding of aluminium alloys AA5182 and A6N01. Furthermore, as a continuation of the two-pass study, Harooni *et al.* [19] studied twin-spot laser welding of an AZ31B magnesium alloy. The aim of the study was to decrease the amount of porosity caused by the oxide layer at the faying interface between the sheets. Harooni *et al.* found that pre-heating with the first beam provided a lower amount of porosity, and hence a twin-spot setup was beneficial from a weld quality point of view.

Thus, welding with twin-spot optics in cast magnesium alloys seems to have a significant potential for reducing the porosity content in the weld metal. Therefore, this study aims to investigate the possibility to use twin-spot optics by comparing two different setups for reducing the porosity in cast magnesium welds. It was decided to minimize the effect of surface oxides to get a more fundamental understanding of pore formation and degassing mechanisms by studying full penetration bead-on-plate welds.

2. Experimental

2.1. Material

In the present study, 3 mm thick sheets of high pressure die cast magnesium alloy AM50 were welded. The sheets had dimensions 100 × 170 mm and the surface of the sheets were prepared by wire brushing and degreasing with acetone prior to welding. For composition of AM50 according to ISO 16220(00) and composition measured with glow-discharge optical emission spectroscopy, see **Table 1**.

2.2. Welding

Welding was done with IPG 5 kW (with a 150 μm fiber, for twin-spot) or 10 kW (with a 200 μm fiber, for single-spot) fiber lasers. The fiber laser was equipped with one (for single-spot and twin-spot with beam splitter) or two optics (for twin-spot with primary and secondary optics). The primary optics was aligned perpendicular to the sheet to be welded, while the secondary optics had a 12 degree angle (see **Figure 1**). Laser welding parameters and optical setup were varied to study their influence on porosity. When using two optics, both optics had identical lens setups. The welding parameters varied were power, welding speed and focus position (see **Table 2**).

Both single-spot and twin-spot optics were used with different focus and collimator lenses. Twin-spot was produced in two ways, either with a beam splitter

Table 1. Alloying elements of AM50 magnesium alloy in wt%. ISO 16220(00) specification and measured values are shown.

	Al	Mn	Zn	Si	Fe	Cu	Ni
ISO 16220(00)	4.4 - 5.5	0.26 - 0.6	<0.2	<0.1	<0.004	<0.01	<0.002
Measured	4.9	0.48	0.2	0.04	<0.001	<0.008	0.001

Table 2. Parameters and optics setup for laser welds in AM50.

	Sample ID	Power [W]	Welding speed [m/min]	Focus pos. relative surface	Optics [type] [focus/collimator]	Spot size [mm]	Distance between spots, cc [mm]
Single-spot and twin-spot with beam splitter	W14	2200	3	0	Single, 120/400	0.66	-
	W15	2200	3	0	Single, two-pass, 120/400	0.66	-
	W16	1700	3	0	Single, 120/500	0.625	-
	W17	1700	2	0	Twin, beam split, 120/500	0.625	1
	W18	1100	3	0	Twin, beam split, 120/500	0.625	1
	W19	1700	3	0	Twin, beam split, 120/500	0.625	1
	W20	2300	3	0	Twin, beam split, 120/500	0.625	1
	W21	1700	4	0	Twin, beam split, 120/500	0.625	1
	W22	1700	3	0	Single, 120/160	0.2	-
	W23	1700	2	0	Twin, beam split, 120/160	0.2	0.32
	W24	1100	3	0	Twin, beam split, 120/160	0.2	0.32
	W25	1700	3	0	Twin, beam split, 120/160	0.2	0.32
	W26	2300	3	0	Twin, beam split, 120/160	0.2	0.32
	W27	1700	4	0	Twin, beam split, 120/160	0.2	0.32
Twin-spot with primary and secondary optics	W28	2000	2	0/0	Twin, Prim. and sec., 120/500	0.625	1
	W29	1700	2	0/0	Twin, Prim. and sec., 120/500	0.625	2.5
	W30	2000	2	0/0	Twin, Prim. and sec., 120/500	0.625	5
	W31	2000	3	0/0	Twin, Prim. and sec., 120/500	0.625	5
	W32	2000	2	0/+5	Twin, Prim. and sec., 120/500	0.625	1
	W33	2000	2	0/+20	Twin, Prim. and sec., 120/500	0.625	1
	W34	2000	2	0/-5	Twin, Prim. and sec., 120/500	0.625	1
	W35	2000	3	0/+20	Twin, Prim. and sec., 120/500	0.625	1
	W36	2000	2	+10/0	Twin, Prim. and sec., 120/500	0.625	1
	W37	2000	3	+10/0	Twin, Prim. and sec., 120/500	0.625	1

in the primary optics resulting in two identical laser beams perpendicular to the surface, or by using two separate optics. In the case with two separate optics the primary optics are perpendicular to the sheet surface, while the secondary is placed in front of the process, but with a small angle. The laser power is equally divided between the two optics.

Both optic solutions had the focus position placed on the surface of the material as the standard setup.

Bead-on-plate welds were produced with 100 mm length across the sheet. Pure argon (gas type I1 according to ISO 14175:2008) was used as shielding gas both at the weld face and root, with a flow rate of 40 l/min and 5 l/min respectively. At the weld face a trailing gas shield was used with a "panpipe" design to

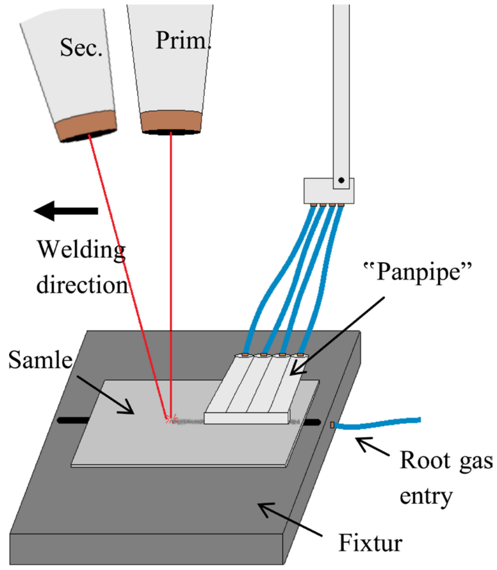

Figure 1. Schematic image of the laser welding setup with twin-spot optics. The primary optics was aligned perpendicular to the sheet to be welded, while the secondary optics had a 12 degree angle. A trailing gas shielding was used on the top side with a "panpipe" design to distribute the gas. The root gas was applied through a 10 mm gap in the fixture along the weld line.

distribute the gas. The root gas was applied through an efflux channel with a 10 × 10 mm cross-section (**Figure 1**).

2.3. Evaluation

Transverse cross-sections were prepared to study the microstructure and the porosity of the resulting welds. After cutting, all sections were grinded with 4000 grit paper, followed by polishing with 6 μm diamond suspension slurry.

Micrographs were taken in LOM. The porosity was made clearly visible by using an extra external ring shaped light source (directed from the sides onto the sample) causing light to be reflected in the edges of the pores. This yielded a high contrast image suitable for image analysis. To count porosity, image analysis was done with "Image J" which is an open source Java-based image processing software [20].

3. Results

Macrographs were taken to illustrate the porosity amount. One can see that both the porosity amount and the weld metal cross-sectional geometry clearly vary between the different setups, e.g small spot size with narrow weld geometry and high porosity content (**Figure 2**, W25), large spot size with wide weld geometry and high porosity content (**Figure 2**, W28), and large spot size with medium weld geometry and low porosity content (**Figure 2**, W35).

Porosity

From image analysis, the percentage of the fusion zone cross-sectional area covered by pores (hereafter "area fraction pores", given in %) has been calculated, see Figure 3. In the figure it is clear that twin-spot welding with a beam splitter does not result in a lower porosity amount (area fraction pores 9% - 15%) compared with single-spot welding (area fraction pores of ~9%). More lens setup variations than presented in Figure 3 were tested namely (focus/collimator focusing lengths) 120/400, 120/300 and 120/250 combinations. However, the results from those tests were in line with the 120/500 and 120/160 setups, and are not presented in detail.

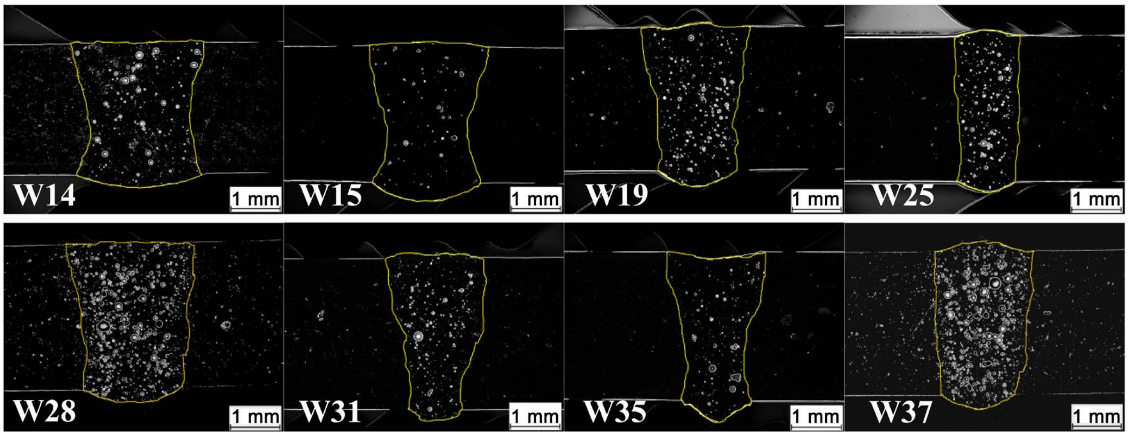

Figure 2. LOM images showing porosity content for different welding scenarios: single-spot welding (W14), single-spot with double pass (W15), beam splitter 120/500 (W19), beam splitter 120/160 (W25), twin optics with both in focus and 1 mm distance (W28), twin optics with both in focus and 5 mm distance (W31), twin optics with defocused secondary optics (W35) and twin optics with defocused primary optics (W37). The lowest porosity content was found in (W15) and (W35). The yellow contour shows the fusion zone.

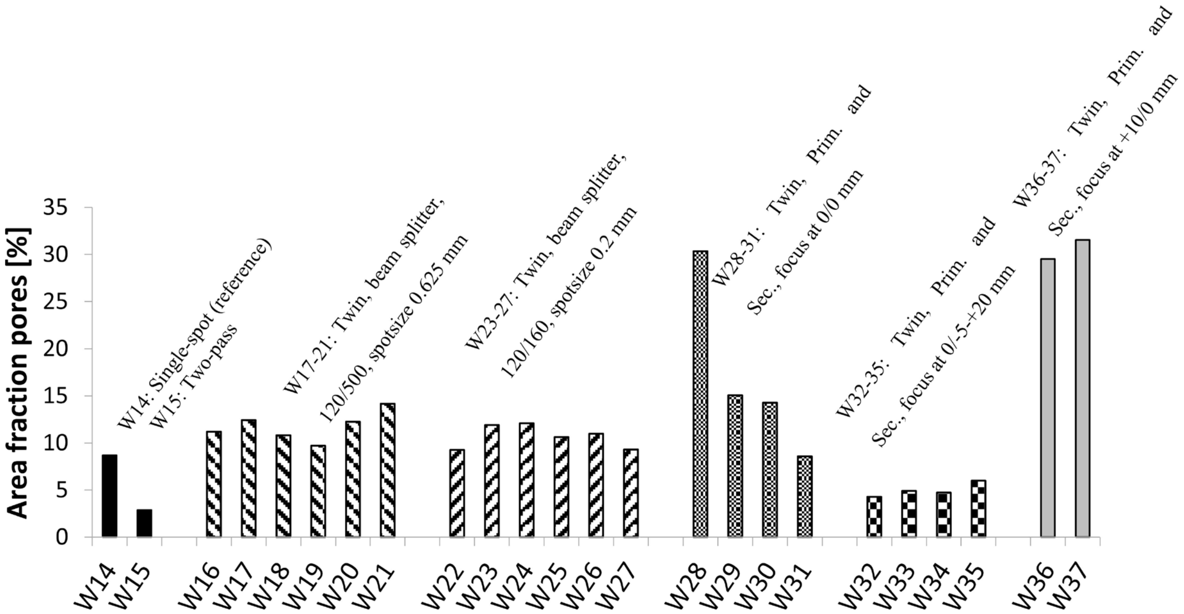

Figure 3. Area fraction of pores with welded samples samples grouped according to welding setup. Twin-spot welding with primary and secondary optics with a defocused secondary optics (W32 - W35) gives the lowest porosity of around 5%. The highest porosity of around 30% was seen in twin-spot welding with primary and secondary optics with a defocused primary optics (W36 - W37).

The same high porosity amount (area fraction pores 8% - 31%) was seen for twin-spot with two optics when both optics had the focus position at the surface. Even higher was the porosity amount (area fraction pores 29% - 32%) when the primary optics was defocused to +10 mm above the sheet surface. However, good results (area fraction pores 4% - 6%) were achieved when the secondary laser beam was defocused ranging from −5 to +20 mm. This result is comparable with the two-pass welding from the previous study (area fraction pores 3%) [16]. Different from the previous study is that no clear relation between porosity and power or welding speed was observed.

4. Discussion

4.1. Influence of Heat Input

In a previous study [16] it was found that a lower heat input for single-spot welding gave lower porosity content. The welding speed had the largest effect, *i.e.* a higher welding speed reduced porosity. However, for twin-spot welding in the present study, no clear relationship between heat input and pore area fraction could be seen (see **Figure 4**). This suggests that several parameters influence the porosity when using twin-spot, not only heat input.

4.2. Pore Formation

Several mechanisms for porosity formation in the weld metal have been suggested in literature. One explanation [11] [12] [15] is that pores already existing in the base material grow larger when re-melted during welding. The undissolved gas expands to form bubbles in the liquid metal resulting in pores during solidification. The bubbles have little time to escape from the molten pool because of the rapid solidification in laser welding. This could be part of the explanation of the pore behavior in the present study, but it's not the full explanation.

An alternative explanation, in line with the findings from Haboudou *et al.* [21] who performed twin-spot welding of cast aluminium, is that the keyhole is stabilized. Haboudou *et al.* stated that a twin-spot stabilizes the weld pool and

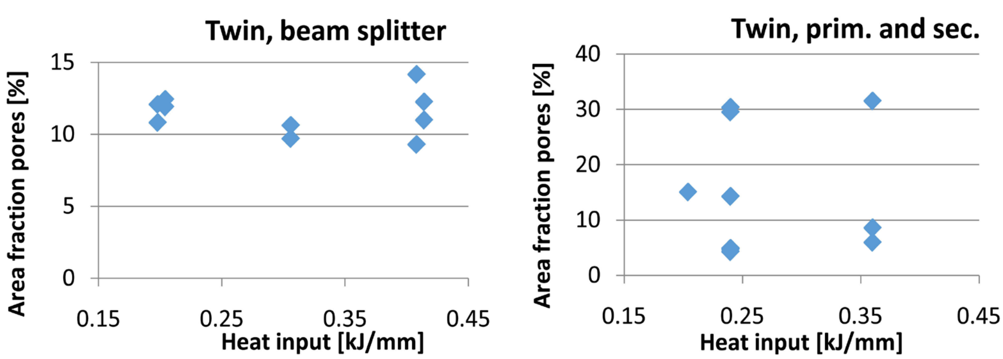

Figure 4. The area fraction pores in relation to heat input for twin-spot welding with beam splitter (left) and twin-spot welding with primary and secondary optics (right). No clear relationship between the heat input and the area fraction of pores can be seen.

keyhole dynamics, which reduces the porosity amount to below 2%. If the keyhole is stable and somewhat larger when using twin-spot, the degassing of large pores should occur to a larger extent. This could be part of the explanation, but since several setups with twin-spot welding do have a large amount of porosity in the present study, at least one other factor do influence as well.

In Figure 5 a hypothesis for the observed porosity occurrence is suggested. Some of the existing inclusions (oxides, precipitates etc.) 1) in the material will remain undissolved and are distributed in the molten material during welding together with remainders of the broken up surface oxide 2). Most of the pores from 1) are dissolved in the melt due to higher solvability in liquid state. During cooling of the melt the inclusions can act as nucleation points 3) for pores. The higher the density of inclusions, the more nucleation points. While still in the liquid state, during subsequent heating, either as an effect of the energy input from the first beam or by the second beam (by beam splitter, or the second optics), the nucleated pores grow 4) due to that dissolved gas is diffusing to pores and increase volume and/or that small pores coalesce.

Depending on how the twin-spot procedure is designed, a degassing effect (5) is achieved with the second beam. If the energy input into the material (in this case controlled by defocusing: more defocusing – less energy into the material) from the first beam is too high, the molten material will have little time to cool between the two beams and pores will not form until the final cooling of the melt and hence little degassing will take place. However, if the energy input from the first beam is well balanced, there will be time for nucleation and some growth before reheating by the second beam. The second beam then heats the melt and allows the pores to grow and also escape from the molten material. For illustration, see Figure 6.

The effect of defocusing on the porosity amount for the twin optics solution is explained in Figure 7. For (a) both beams are in focus. The energy input from the first beam is high, resulting in a small temperature reduction between the beams, hence little nucleation of pores occurs on cooling after passing of the first

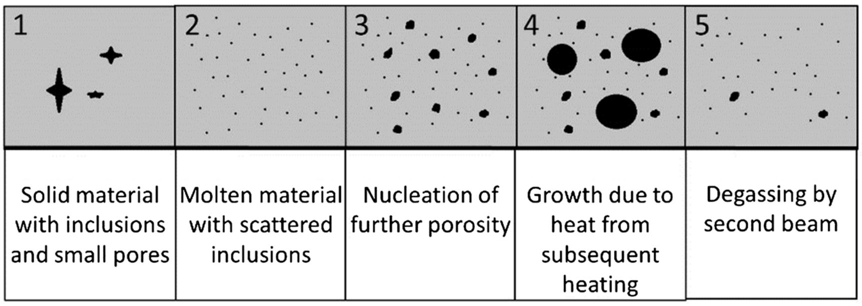

Figure 5. Suggested mechanism for porosity formation and degassing. Solid material with inclusions and small pores (1) is molten by the first laser beam resulting in a melt with a distribution of inclusions (2). The inclusions then act as nucleations points (3). When the second beam heats the material, the nucleated pores grow by diffusion of dissolved gas or coalescense of smaller pores (4). The second beam gives the pores enough time to reach the surface of the melt resulting in degassing (5).

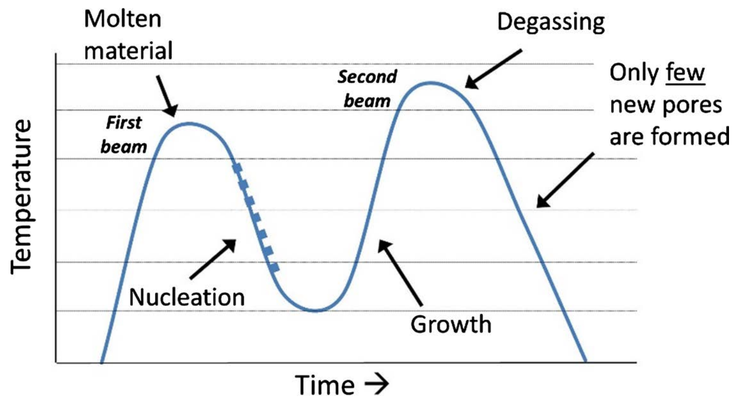

Figure 6. A schematic description of porosity formation, growth and degassing during the heat cycle of twin-spot laser welding. The blue dots represent the nucleation of pores.

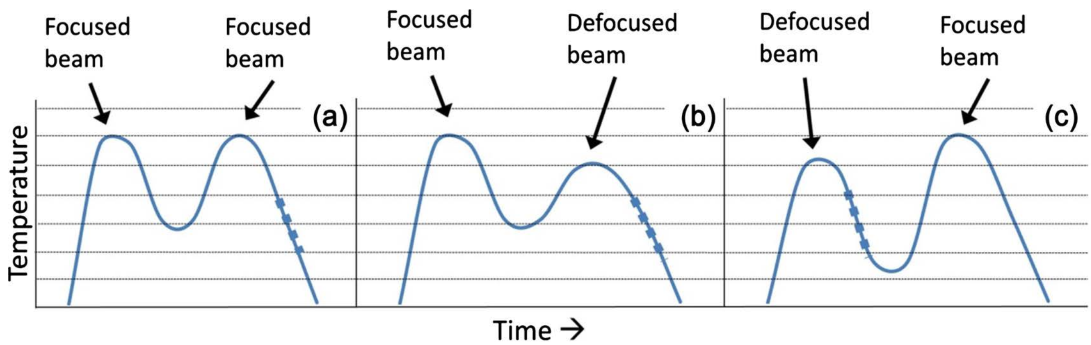

Figure 7. Explanation of how porosity content varies with different setups of the twin-spot optics. (a) and (b) will result in extensive porosity, while (c) allows degassing to occur, and hence a low porosity content. The blue dots represent the nucleation of porosity.

beam. Consequently few pores will exist that can grow in size making degassing unlikely when the melt pool is heated by the second beam. Furthermore, nucleation and growth will occur on cooling after passing of the second beam, leaving a weld with high porosity content (e.g. **Figure 2** W19/W25/W28). A similar scenario can be envisaged for (b) where the first beam is in focus, but the second beam is defocused. This results in a long cooling time which is unbeneficial from a porosity point of view resulting in nucleation and growth at the end of the sequence and little degassing (see **Figure 2** W37). Looking at (c), the pores can nucleate on cooling after the first defocused beam has passed (as explained in **Figure 6**), since the energy input is relatively low. The second beam then provides heating required for growth of the pores and time for degassing (see **Figure 2** W35).

4.3. Twin-Spot Welding for Reduced Porosity Content

Single-spot welding results in relatively high porosity content, roughly 9%. Using two-pass welding the porosity content is reduced to 3% [16], which is considered low. However, two-pass welding is not production friendly in the aspect of process time. Twin-spot welding could be a good combination of a production friendly solution and high quality welding. Compared with single-spot optics, a twin-spot optic setup is more complex; however, the porosity content is low (4% - 6%). Furthermore, until today no published study has been found that correlates the amount of porosity in welded cast magnesium to strength of the weld, which would give a recommendation for a strict porosity content limit to aim for.

Summarizing, the optic setup is shown to be crucial when trying to minimizing the porosity while laser welding cast magnesium. Harooni *et al.* [19] used twin-spot optics for minimizing pores with the origin from the oxide layer at the faying interface between two sheets in lap joint configuration. The present study shows that porosity also can be reduced in butt joint configuration. Single-spot welding could give low porosity welds, but degassing is limited when using single-pass welding. More intensive degassing occurs when using twin-spot, which hence shows promising results. Future work should be to further optimize the twin-spot configuration, including power and welding speed, to have as low porosity as possible.

5. Conclusions

Full penetration bead-on-plate welds were produced by laser twin-spot welded in the magnesium alloy AM50 to study pore formation. Two optical setups were tested; twin-spot welding with a beam splitter and twin-spot welding with primary and secondary (placed in front of the primary optic) optics.

- Power and welding speed had small effect on porosity.
- Twin-spot welding with a primary and a secondary optics using a defocused secondary optics gave the lowest porosity of around 5%.
- The highest porosity of around 30% was seen in twin-spot welding with a primary and a secondary optics with a defocused primary optics.
- The amount of porosity will depend on the balance between the energy input of the first and second beams, which is controlled by defocusing. For lowest porosity the first beam should provide time for nucleation and some growth of pores while reheating by the second beam should provide time for pores to grow and escape without melting additional base material.
- Twin-spot welding is shown to be a promising combination of a production friendly solution and high quality welding, compared with single-spot and two-pass welding.

Acknowledgements

Special thanks are directed towards the people involved in this work; Matt Spinks at TWI Ltd in Cambridge, Kjell-Arne Persson and Jacek Komenda at Swerea KIMAB in Kista, Edwin Bergstedt at KTH Stockholm, as well as the PhD-research school SiCoMaP at University West in Trollhättan.

Author Contributions

Conceptualization, K. Fahlström; Methodology, K. Fahlström and J. Blackburn;

Investigation, K. Fahlström, L. Karlsson and L-E. Svensson; Writing-Original Draft Preparation, K. Fahlström.; Writing-Review & Editing, K. Fahlström, J. Blackburn, L. Karlsson and L-E. Svensson; Supervision, L. Karlsson and L-E. Svensson.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Kielbus, A., Rzychon, T. and Cibis, R. (2006) Microstructure of AM50 Die Casting Magnesium Alloy. *Journal of Achievements in Materials and Manufacturing Engineering*, **18**.

[2] Harooni, M., *et al.* (2014) Pore Formation Mechanism and Its Mitigation in Laser Welding of AZ31B Magnesium Alloy in Lap Joint Configuration. *Materials and Design*, **58**, 265-276. https://doi.org/10.1016/j.matdes.2014.01.050

[3] Zhu, J., Li, L. and Liu, Z. (2005) CO_2 and Diode Laser Welding of AZ31 Magnesium Alloy. *Applied Surface Science*, **247**, 300-306. https://doi.org/10.1016/j.apsusc.2005.01.162

[4] Cao, X., *et al.* (2005) Continuous Wave ND:YAG Laser Welding of Sand Cast ZE41A-T5 Magnesium Alloys. *Materials and Manufacturing Processes*, **20**, 987-1004. https://doi.org/10.1081/AMP-200060436

[5] Cao, X., *et al.* (2006) A Review of Laser Welding Techniques for Magnesium Alloys. *Journal of Materials Processing Technology*, **171**, 188-204. https://doi.org/10.1016/j.jmatprotec.2005.06.068

[6] Gertsman, Y., *et al.* (2005) Microstructure and Second-Phase Particles in Low- and High-Pressure Die-Cast Magnesium Alloy AM50. *Metallurgical and Materials Transactions A*, **36**, 1989-1997. https://doi.org/10.1007/s11661-005-0319-5

[7] Fredriksson, H. and Åkerlind, U. (2006) Materials Processing during Casting. John Wiley & Sons, Chichester. https://doi.org/10.1002/9780470017920

[8] Ma, Y., Zhang, J. and Yang, M. (2009) Research on Microstructure and Alloy Phases of AM50 Magnesium Alloy. *Journal of Alloys and Compounds*, **470**, 515-521. https://doi.org/10.1016/j.jallcom.2008.03.047

[9] Lee, G., *et al.* (2006) Effect of Process Parameters on Porosity Distributions in High-Pressure Die-Cast AM50 Mg-Alloy. *Materials Science & Engineering A*, **427**, 99-111. https://doi.org/10.1016/j.msea.2006.04.082

[10] Harooni, M., *et al.* (2012) Mitigation of Pore Generation in Laser Welding of Magnesium Alloy AZ31B in Lap Joint Configuration. *ASME-International Mechanical Engineering Congress & Exposition Proceedings*, Houston.

[11] Wahba, M., *et al.* (2012) Laser Welding of Die-Cast AZ91D Magnesium Alloy. *Materials and Design*, **33**, 569-576. https://doi.org/10.1016/j.matdes.2011.05.016

[12] Wahba, M. and Katayama, S. (2012) Laser Welding of Magnesium Alloy. *Transactions of JWRI*, **41**, 11-23.

[13] Liu, L., *et al.* (2005) Pore Formation during Hybrid Laser-Tungsten Inert Gas Arc Welding of Magnesium Alloy AZ31B—Mechanism and Remedy. *Materials Science and Engineering A*, **390**, 76-80. https://doi.org/10.1016/j.msea.2004.07.067

[14] Zhang, J., *et al.* (2013) Reducing the Porosity in Die-Cast Magnesium Alloys during

Laser Welding. *Welding Journal*, **92**, 101-109.

[15] Zhao, H. and Debroy, T. (2001) Pore Formation during Laser Beam Welding of Die Cast Magnesium Alloy AM60B—Mechanism and Remedy. *Weld Journal*, **80**, 204s-210s.

[16] Fahlström, K., *et al.* (2018) Effect of Laser Welding Parameters on Porosity of Welds in Cast Magnesium Alloy AM50. *The 71st IIW Annual Assembly & International Conference*, Nusa Dua.

[17] Harooni, M., *et al.* (2015) Two-Pass Laser Welding of AZ31B Magnesium Alloy. *Journal of Materials Processing Technology*, **216**, 114-122. https://doi.org/10.1016/j.jmatprotec.2014.08.028

[18] Shibata, K., *et al.* (2003) Welding of Aluminium Car Body Parts with Twinspot High-Power Nd: YAG Laser. *Welding International*, **17**, 939-946. https://doi.org/10.1533/wint.2003.3201

[19] Harooni, M., *et al.* (2014) Dual-Beam Laser Welding of AZ31B Magnesium Alloy in Zero-Gap Lap Joint Configuration. *Optics & Laser Technology*, **56**, 247-255. https://doi.org/10.1016/j.optlastec.2013.08.018

[20] Rasband, W. and Image, J. (2016) National Institutes of Health. Image Processing Program.

[21] Haboudou, A., *et al.* (2003) Reduction of Porosity Content Generated during Nd:YAG Laser Welding of A356 and AA5083 Aluminium Alloys. *Materials Science and Engineering A*, **363**, 40-52. https://doi.org/10.1016/S0921-5093(03)00637-3