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Laser beam welding of aluminum alloys under the influence of an electromagnetic field

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Abstract

During laser beam welding of aluminum alloys an electromagnetic field may favour pore outgassing through the top oxide layer. High frequencies cause a small penetration depth and thus exert a stabilizing effect on the weld surface. The point at which the laser beam between the two magnetic poles hits the workpiece surface is crucial to the influence of the magnetic field on the weld surface roughness. Using analyzed parameters for different laser points of application cause a change in weld surface roughness could be observed. The weld surface roughness could be reduced by 50%. The outgassing effect in terms of a reduction of pores could be observed for all parameter sets investigated.

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Keywords: electromagnetically controlled laser beam welding; surface roughness; porosity prevention; aluminium alloys

1. Introduction

Aluminum tends to form pores in laser beam welding, Verhaeghe and Hilton, 2004. Molten bath instabilities in the root area may cause gas bubbles. So called process pores occur due to the keyhole dynamics in partial penetration welding, Seto et al., 2001. The high affinity of aluminum to oxygen can give rise to the formation of an oxide layer on the melt very quickly, which impedes gas bubbles escape, Mathers, 2002. With the help of an AC magnet the pores can escape from the liquid melt and pass through the oxide layer. An oscillating magnetic field applied above the weld pool causes a force that presses particles with higher electrical conductivity (molten aluminum) down to the weld pool bottom, Bojarevics et al., 1989. The

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resulting lifting force pushes particles with lower electrical conductivity (gas bubbles) in the direction of the maximum magnetic field. Literature confirms that this is possible by means of electromagnetic forces, Avilov and Moldovan, 2009 and Takahashi and Taniguchi, 2003. The achievable result is not attributable to the ferromagnetic effect, but rather to a Lorentz force in the molten bath, Moffatt, 1991. The AC solenoid can further influence the weld surface right up to smoother surface formation, Avilov et al., 2012. The appropriate critical process parameter is the point at which the laser beam between the two magnetic poles strikes the workpiece surface. Early ending of the magnetic influence on the melt results in solidification at a highly dynamic torque and thus in a very rough surface. By contrast, late onset of the magnetic field influence may additionally increase the melt dynamics and thus favour the melt ejection. The roughness of the weld surface depends on the position of the two poles of the electromagnet in relation to the laser point of application (lpa).

### Nomenclature

| Symbol | Description |
|--------|-------------|
| B      | magnetic flux |
| b      | average weld width |
| f      | frequency |
| lpa    | laser point of application |
| P      | power of laser beam |
| \( z_{\text{rms}} \) | root mean square of all measurement points |
| \( V_1 \) | missing material volume below the sample surface |
| \( V_2 \) | excess material volume above the sample surface |
| v      | welding speed |
| \( \bar{z} \) | average of all measurement points |
| \( z_+ \) | average of all measurement points above the sample surface |
| \( z_- \) | average of all measurement points below the sample surface |
| \( z_{\text{max}} \) | maximum measurement values |
| \( z_{\text{min}} \) | minimum measurement values |

### 2. Experimental setup

To generate the oscillating magnetic field, a specially-designed AC magnet was used, see Figure 1a. The primary coil of the U-shaped iron core was connected directly to a 5 kW amplifier. The function generator connected thereto allowed variation of the magnet frequency and output power. Using interchangeable condenser levels, the capacity of the secondary circuit of the AC solenoid could be changed. The prismatic magnetic poles consisting of magneto-dielectric material (Fluxtrol®) were mounted directly below the two secondary coils in direct contact with the U-shaped iron core. The distance between the magnetic poles was continuously adjustable up to 20 mm. By this arrangement, a maximum flux density of 500 mT can be achieved at frequencies up to 10 kHz. The welding experiments were performed on 6 mm thick AlMg3 plates with a Nd:YAG rod laser, see Figure 1b. A solid-state laser (DY044) produced a maximum output power of 4.4 kW at a focal distance of 300 mm. The laser head was tilted by 18° and mounted for pull orientation. Argon 5.0 was used as shielding gas flowing from a nozzle with an inner diameter of 10 mm at an angle of
45° behind the AC magnet. The nozzle was mounted for push orientation. The AlMg3 plates had edge lengths of 300 mm x 100 mm and were bolted to the movable table with six countersunk screws. Six welds and at least one reference weld without magnetic field were produced on each specimen and the screws created a rigid clamping. During welding, the table with the sample was moved linearly below the AC magnet. The geometry of the magnetic pole is shown in figure 2. The gap between the magnetic poles (figure 2, left, point A) was 20 mm during the series of experiments presented here. A gap between the magnet bottom side and the sample surface (figure 2, right, point B) was required which prevented a closed electric circuit. The distance between the magnetic pole and the specimen surface was 2 mm. This gap remained unchanged in y-direction during the whole welding process. Thus, frequencies up to 4 kHz were possible at flux densities up to 300 mT. The variation of the lpa is shown schematically in Figure 2 (a,b,c). In position (b) x = 0 mm, the lpa is aligned with the two magnet leading edges. The variations (c) x = 4 mm and (a) x = -4 mm show a displacement of the lpa in the positive or negative x-direction. In all experiments, the laser beam hit the specimen in y-direction centrally (y = 0 mm) between the magnetic poles.

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45° behind the AC magnet. The nozzle was mounted for push orientation. The AlMg3 plates had edge lengths of 300 mm x 100 mm and were bolted to the movable table with six countersunk screws. Six welds and at least one reference weld without magnetic field were produced on each specimen and the screws created a rigid clamping. During welding, the table with the sample was moved linearly below the AC magnet. The geometry of the magnetic pole is shown in figure 2. The gap between the magnetic poles (figure 2, left, point A) was 20 mm during the series of experiments presented here. A gap between the magnet bottom side and the sample surface (figure 2, right, point B) was required which prevented a closed electric circuit. The distance between the magnetic pole and the specimen surface was 2 mm. This gap remained unchanged in y-direction during the whole welding process. Thus, frequencies up to 4 kHz were possible at flux densities up to 300 mT. The variation of the lpa is shown schematically in Figure 2 (a,b,c). In position (b) x = 0 mm, the lpa is aligned with the two magnet leading edges. The variations (c) x = 4 mm and (a) x = -4 mm show a displacement of the lpa in the positive or negative x-direction. In all experiments, the laser beam hit the specimen in y-direction centrally (y = 0 mm) between the magnetic poles.
3. Measurement method

After welding, the samples were examined for weld pores and weld surface roughness based on non-destructive testing using radiographic testing (RT) as well as optical distance measurement.

3.1. Pore detection

For weld pore visualization, the welded samples were subjected to the radiographic testing. The pores were detected using ImageJ analysis software. The scanned radiographs were first binarized using the method described by Kapur et al., 1985, and subsequently evaluated. The binarization was done by threshold determination using the entropy of the histogram of a greyscale image. As a result, black and white weld images were obtained in which white pixels represented the pores and black pixels the material. The software ImageJ subsequently analyzed the black and white areas and thus generated the total pore area in relation to the weld top surface area. Only pores, i.e. white contiguous areas greater than 0.05 mm² were considered.

3.2. Surface measurement

The specimen surfaces were measured in the weld area using confocal chromatic distance measurement, Hamilton and Wilson, 1982. The focus of a chromatic light beam was projected on the sample. Due to the different wavelengths of the spectral colors the specimen surface was divided up into colored rings. Based on the spectral color in the ring center the spectral distance from the sensor could be determined. The applied measurement setup reached resolutions up to 60 nm at a scanning rate of 2 kHz. The step size in x-direction and in y-direction was 50 μm in each case. For each weld, measurement series with about 300,000 entries were thus obtained. These records were then processed and analyzed by means of numerical calculations. For evaluation of the measurement series, only the measurement points located in the weld area were considered. To this end, the weld edges were localized and the measurement points located outside the weld were eliminated. Further measurement points in weld sections 20 mm in length from the weld start and end were also disregarded. This procedure ensured that the starting and finishing phase of the welding process had no effect on the calculations.

4. Results and discussion

4.1. Pores

In the reference weld without magnetic field the pore area fraction in relation to the total weld area is about 3 %. In three welds produced with a magnetic flux between 200 mT and 250 mT at a frequency of approximately 3 kHz, the pore area fraction was reduced by 60 % to 80 %. The greatest reduction was found at a lpa between x= 0 mm and x= 4 mm, see figure 3, figure 4 and table 1. In figure 3, the pore distribution is visualized by RT. It is shown, that the quantity of the pores in the welding seam was clearly reduced, when a magnetic field is applied (comparison reference weld with welds a, b, c). Furthermore, it was found that the projected pore surface also decreases, by an shift of the lpa in positive direction, see figure 4 and table 1.

\[\text{http://rsbweb.nih.gov/ij/index.html}\]
Fig. 3. RT picture of the reference weld and variation of lpa. Nd:YAG rod laser; welding power 4.4 kW; welding speed 1.5 m/min; focus -3 mm; shielding gas argon. Parameters of the reference weld and magnetic influenced welds a, b, c are listed in table 1.

The critical value for pores for the quality level B by EN ISO 13919-2 is 3 % from the projected area of the weld seam. This 3 % are based on a work-piece thickness of 6 mm. The reference weld has a projected pore area of 2.96 % and barely fits this requirement. All three welds with a magnetic field (a,b,c) fulfill this criteria easily. Furthermore, the welds b) and c) have the lowest pore area with around 0.6 %.

4.2. Surface condition

In the experiments with a laser beam power of 4.4 kW and a welding speed of 1.5 m/min the weld surface roughness (z_{rms}) was found to be highly dependent on the lpa. A lpa at x= -4 mm produced a roughness of 253 μm. Displacement of the lpa to x= 0 mm in the positive x-direction results in a roughness of 201 μm. At x= 4 mm the weld surface roughness is 174 μm, which means a reduction of 31 %, see figure 4. Furthermore, it was found that the mean value (Z) of 9 μm (at x= -4 mm) had dropped to -36 μm (at x= -4 mm). This means that, on average, light weld reinforcement has transformed to weld concavity. This is also reflected in the material volumes accumulated above the sample surface. The material volumes below (V_1) and above (V_2) the sample surface are the sum of z values in positive or negative measurement direction multiplied with the square of the step size in x- and y-direction. The material volume (V_2) decreased from 25 mm³ (at x= -4 mm) to 17 mm³ (with x= 4 mm), which means a reduction in weld metal volume of 32 %. The volume below the sample surface (V_1) only changed to a minor extent. While the weld concavity of 22 mm³ at x= -4 mm increased to 27 mm³ at x= 0 mm, it changed only marginally to 28 mm³ in the step to x= 4 mm. The optimal lpa turned out to be x= 4 mm. Compared to the reference weld the roughness was reduced by 55 % and the average value of all evaluated measurement points decreased from 66 μm to -35 μm. The volume of the weld reinforcement decreased from 39 mm³ in the reference weld to 17 mm³ in the weld with a lpa of x= 4 mm. By contrast, the volume of the weld concavity remained nearly unchanged, as in the above described results. The measured and calculated results of these four welding experiments are listed in table 1.
Fig. 4. Surface roughness and pore area for different lpa. Nd:YAG rod laser; welding power 4.4 kW; welding speed 1.5 m/min; focus -3 mm; shielding gas argon. Parameters of the welds are listed in table 1.

Table 1. Results of measurement and analysis. Nd:YAG 4.4 kW; focus -3 mm; welding speed 1.5 m/min; argon shielding gas.

| seam | lpa in mm | f in kHz | B in mT | pores in % | z_{rms} in μm | b | V_{1} in mm³ | V_{2} in mm³ | z | z_{min} in mm | z_{max} in mm |
|------|-----------|----------|--------|------------|---------------|---|--------------|--------------|---|---------------|---------------|
| ref. | 0         | 0        | 0      | 2.96       | 390           | 3.7| 24           | 39           | 66 | 0.31          | -0.24         | -3.3          | 1.1          |
| a)   | -4        | 2.9      | 248    | 1.21       | 253           | 4.6| 22           | 25           | 9 | 0.2           | -0.14         | -0.7          | 1.2          |
| b)   | 0         | 2.9      | 214    | 0.64       | 201           | 4.5| 27           | 21           | 24 | 0.16          | -0.19         | -1.4          | 0.5          |
| c)   | 4         | 3.0      | 205    | 0.66       | 174           | 4.7| 28           | 17           | -36 | 0.15          | -0.16         | -1.4          | 1.2          |

In figure 5 the 2D-plot of measurement top surface is shown. The reference weld has large areas with convex as well concave as shaped surface which is reflected in the measurement value of $z_{rms}$. The considered weld length for the roughness calculations for all seams is between 20 mm and 80 mm. The weld start on the left side of the plot and the weld end on the right side (blue hole) are disregarded. It is shown, that the minima and maxima of the surface height values are decreasing with increasing the lpa. The EN ISO 13919-2 specifies the undercut for the quality level B with a maximum of 0.3 mm for a work-piece thickness of 6 mm. Compared to the average of negative z-values ($z_{r}$) it is evident that the quality of the reference weld is poor. All three welds with magnetic field (a, b, c) show an undercutting smaller than 0.2 mm and achieve the quality level B easily.

Fig. 5. 2D-plot of top surface. Nd:YAG rod laser; welding power 4.4 kW; welding speed 1.5 m/min; focus -3 mm; shielding gas argon. Parameters of the welds are listed in table 1.
4.3. Discussion

During Nd:YAG rod laser welding of AlMg3 using a power of 4.4 kW and a speed of 1.5 m/min, weld porosity can significantly be influenced by an oscillating magnetic field applied above the sample surface. Thanks to the magnetic field the pores are able to break through the oxide layer formed on the weld surface and to outgas. This has a positive effect on load resistance involving higher weld strength. Scientific proof of this statement requires further welding experiments with application of a magnetic field, directing the focus of attention to the material behavior under load. Surface roughness reduction with the help of an oscillating magnetic field represents an innovative approach that can be optimized by choosing the proper lpa. The experiments have shown that roughness can be reduced by half with a suitable lpa, compared to the reference weld produced without magnetic field. A lpa placed in front of the magnet leading edge proved to be ideal, whereas a lpa aligned with the center of magnetic poles turned out to be less optimal. The reason is that, due to the high welding speed, the melt passes rapidly the region of maximum magnetic flux density and solidifies only behind the magnetic poles. The influence of the magnetic field decreases in this area and has only a minor effect on the molten metal. Furthermore, the magnetic field in the region of maximum flux density exerts strong pressure on the melt and thus increases the momentum behind the magnetic poles in the area less affected by the magnetic field. The solidification process ends in a moment of high dynamics, thus causing a rougher surface. If the lpa is in optimal distance from the magnetic poles, the melt solidifies in the area of maximum flux density. This maximum magnetic field reduces the weld pool dynamics to the extent that the melt solidifies in a moment in which the weld pool surface is more uniform. Reducing the surface roughness helps to simplify or shorten weld post treatment.

5. Conclusion

First, it can be seen that an oscillating magnetic field may reduce the weld pores up to 80 % for an optimal lpa. A similar tendency can be seen for the weld surface roughness which is reduced by around 50 % with the same parameters. These reductions are highly dependent on the selected lpa. In both cases, the displacement of the lpa in x-direction, has a positive effect on the results and the roughness was calculated from the root mean square, these values say nothing about weld reinforcement or weld concavity. All welds included areas both above and below the sample surface. This is especially evident from the determined z-values ($z_-$, $z_+$, $z$, $z_{min}$, $z_{max}$) which were both positive and negative. The calculated volumes ($V_1$ and $V_2$) above and below a sample surface are approximately equal, indicating uniform distribution of peaks and bulges in a weld. Quantitatively the roughness has decreased, but, further studies are still needed for a qualitative statement.

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