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Influence of an oxygen-free atmosphere on laser beam brazing of aluminium with prior surface deoxidation by pulsed laser radiation

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Abstract

Aluminium alloys, like AlMgSi1 and AlMg3, cannot be joined in industrial processes by laser beam brazing without the use of fluxes due to their resistant oxide layer. The aim of this study is to dispense with the use of flux. For the investigations, an oxygen-free atmosphere was created by using the highly reactive gas monosilane and thus achieving O_2 partial pressures of 10^{-18} mbar. After removal of the oxides by a laser source with 1064 nm wavelength, pulse energies of max. 0.3 µJ and pulse durations of 45 ns, reoxidation is prevented by the oxygen-free atmosphere, so that brazing is carried out on an oxide-free material surface. The bead on plate seams show a materially bonded brazed joint in cross-section. Reference experiments without monosilane either show no wetting or an increased melting of base material. The influence of laser beam power for brazing, pulse energy for deoxidation and wire feed was investigated.

Keywords: laser beam brazing; aluminium alloy; monosilane; XHV-adequate; oxide

1. Introduction

Laser beam brazing is a widespread manufacturing process for joining galvanised steel sheets in the automotive industry, e.g. in the shell area of the car body. The advantages of the process are aesthetically appealing seams and a low heat input into the base material [1]. However, laser beam brazing of aluminium alloys requires prior application of flux that decomposes the natural oxide layer during the process and thus enables the base material to be wetted by the brazing alloy [6]. The flux residues in the joining zone, which may be harmful to the environment and health [2], must be removed after the process, for health or aesthetic reasons.

In the investigations carried out, the oxide layer in the joining zone was removed before the brazing process using short-pulsed laser radiation with a pulse duration of 45 nanoseconds. However, when the oxide layer is removed, the aluminium surface reoxidizes immediately because of its high oxygen affinity.

To prevent this, the brazing experiments are carried out in an oxygen-free atmosphere. In the first step, the closed process atmosphere is purged with argon. Commercially available argon 5.0 still contains a residual oxygen content of about 2 ppm [4], which results in renewed oxidation of the material surface. By adding the highly reactive gas monosilane (hereafter silane), the residual oxygen content is bound and oxygen partial pressures of up to 10^{-18} mbar are achieved [5]. This corresponds to the oxygen partial pressure in an extremely high vacuum (XHV). Silicon dioxide is formed as a product of silane and oxygen.

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For furnace brazing processes and the tungsten-inert gas brazing process, the reducing effect of the oxygen-free atmosphere on the oxide layer of copper and steel materials has already been demonstrated [3] [6] [7].

2. Experimental procedure

The eutectic alloy AlSi12 with a diameter of 1.2 mm is used as filler wire. The alloys AlMgSi1 and AlMg3 with a sheet thickness of 2 mm are used as base material. Especially the alloy AlMg3 is challenging in terms of brazing, due to its high magnesium content of about 3 %. Conventionally this alloy can only be brazed with the help of corrosive fluxes.

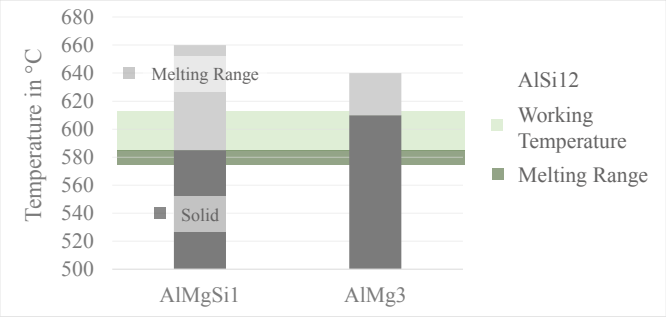


Fig. 1. Overview of alloys used and melting ranges

Figure 1 shows a comparison of the solidification ranges of the aluminium alloys used and the AlSi12 brazing material. It illustrates how close the melting ranges of the brazing material and the alloys are. The working temperature of AlSi12, where the mechanisms for wetting and bonding takes effect, is 590 – 615 °C, which is above the solidus temperature of both alloys [7]. The challenge that arises from this for the brazing of aluminium is to melt the filler wire and to preheat the base material sufficiently without melting it to an unacceptable extent. In [8], the dissolution of the base material, also called erosion, is limited to a maximum of 10 % and 20 % of the sheet thickness, respectively, depending on the assessment level.

Experimental setup

A continuous wave (cw) diode-pumped disk laser beam source (TruDisk 16002, Trumpf Laser- und Systemtechnik GmbH) with a maximum power of 16 kW and a wavelength of 1030 nm is used for the brazing process. The experiments were conducted with a collimation length of 200 mm, a focal length of 600 mm and an optical fiber with a diameter of 600 mm, resulting in a spot diameter of approximately 1.8 mm. With a defocusing distance of 37 mm, a spot diameter of approximately 2.9 mm is achieved.
Deoxidation of the material surface is carried out using the pulsed wave (pw) G4 200W EP-Z fiber laser beam source from SPI Lasers Ltd. with pulse peak powers of up to 10 kW at pulse durations from 10 ns up to 2000 ns and a wavelength of approximately 1064 nm. The radiation is guided into the process area by a 2-axis scanner (Superscan IV-15, Raylase GmbH) and an f-theta objective with a focal length of 340 mm. This results in a spot diameter of about 65 µm and a working range of 205 mm x 205 mm.

In order to preserve the oxygen-free atmosphere, a gas-tight sealed process chamber is necessary. Therefore, a glove box is used for the experimental procedure. The setup is shown in Figure 2.

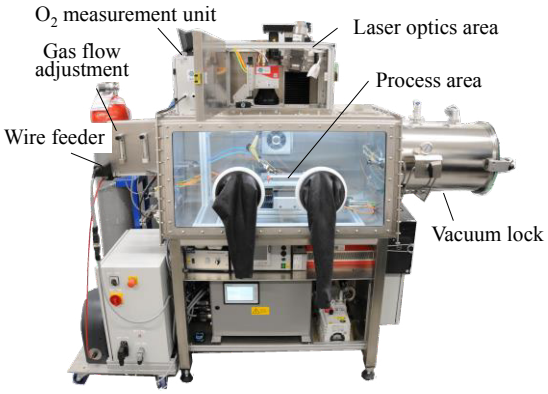


Fig. 2. Experimental setup for laser beam brazing in oxygen-free atmosphere [8]

By doping the argon atmosphere with silane, an oxygen partial pressure of approximately 10^{-18} mbar was measured by oxygen sensor. Prior to the actual laser beam brazing process, the surface of the base material was deoxidized with the pulsed laser radiation. The parameters used are shown in Table 1. The brazing speed v_B remains constant at 0.9 m/min. The wire feed v_W, the laser power P_{cw} and the pulse energy E_{Puls} are varied.

Table 1. Experimental plan

Alloy	Wire feed v_W in m/min	Pulse energy E_{Puls} in µJ	Laser beam power P_{cw} in kW
AlMgSi1	2.0	60 – 240	1.8 – 2.4
AlMg3	1.3	120 – 240	1.4 – 2.0
AlMg3	1.8	180 – 240	1.6 – 2.0

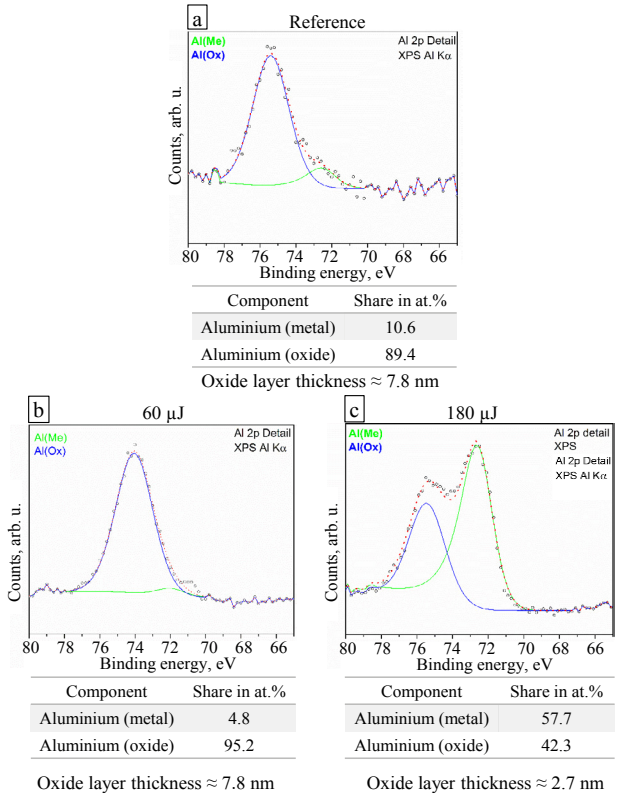
3. Results

3.1. Deoxidation

In the first step, it was ensured that the native oxide layer was removed by pw processing of the material surface. For this purpose, a sample of the alloy AlMgSi1 with dimensions of 10 mm x 10 mm was processed with pulsed laser radiation with a pulse energy E_{Puls} of 60 µJ and 180 µJ, respectively, within the silane-doped atmosphere. In order to measure the influence of pw processing on the oxide layer by X-ray photoelectron spectroscopy (XPS), the sample must not be exposed to oxygen from the place of processing to the measuring device. This was realised by means of a special transport and transfer system in which the sample remains within the silane-doped and thus oxygen-free atmosphere until it is introduced into the ultra high vacuum (UHV) of the XPS system.

Figure 3 shows the detail spectra of the examined surfaces. In addition to the deoxidised samples, an untreated reference sample was measured. The evaluation of the detail spectra shows an oxide layer thickness of about 7.8 nm for the untreated sample. A treatment with pulse energies of 60 µJ does not lead to a reduction of the oxide layer.

Moreover, the deposited silicon dioxide on the surface makes the measurement more difficult.
An oxide layer thickness of 2.7 nm was measured on the irradiated sample with a pulse energy of 180 µJ. Experience shows that during the transfer process into the UHV chamber, a slight oxidation occurs due to residual oxygen and water, which corresponds to the measured oxide layer thickness. Therefore, it was concluded that the sample surface was completely deoxidized directly after irradiation and prior to the brazing experiments conducted. Experiments regarding the behaviour of AlMg3 have to be carried out additional.



Component	Share in at.%
Aluminium (metal)	10.6
Aluminium (oxide)	89.4

Oxide layer thickness ≈ 7.8 nm

Component	Share in at.%
Aluminium (metal)	4.8
Aluminium (oxide)	95.2

Oxide layer thickness ≈ 7.8 nm

Component	Share in at.%
Aluminium (metal)	57.7
Aluminium (oxide)	42.3

Oxide layer thickness ≈ 2.7 nm

Fig. 3. Analysis of oxide layer thickness by XPS of AlMgSi1. Reference sample (a) and surface treated by pw irradiation with pulse energy of 60 µJ (b) and 180 µJ (c)

3.2. Laser beam brazing

The influence of the laser power P_{cw} and the pulse energy E_{Puls} on the brazing result was subsequently investigated. In particular, the melting depth and the seam width were assessed. Figure 4 summarises the results for the alloy AlMgSi1 at a wire feed of v_W = 2.0 m/min.

At a pulse energy of 60 µJ, a comparatively low laser power of 2 kW results in a melting depth of about 0.27 mm with a seam width of 2.8 mm. As previously shown, a pulse energy of 60 µJ has no influence on the oxide layer. Here, a mechanical bond only occurs when both filler and base material melt. The results are different for pulse energies of 120 µJ and 180 µJ. Here, at power levels of 1.8 kW and 2.0 kW, there is no melting and a maximum seam width of 2.0 mm. At higher powers the melting depth increases. At a pulse energy of 240 µJ, the melting is more pronounced and the seam width is higher. This might be explained by a change in the surface topography and an associated change in the absorption properties. Further experiments regarding this phenomenon are necessary.

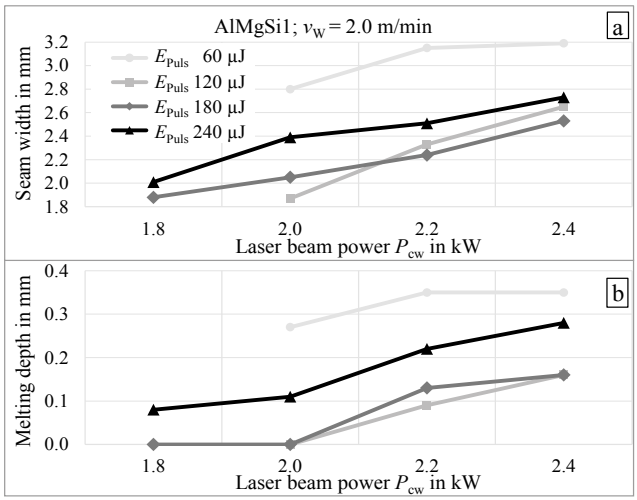


Fig. 4. Correlation between laser beam power and seam width (a) with associated melting depth (b) for different pulse energies, AlMgSi1, v_W = 2.0 m/min

The observations made could not be transferred yet to the alloy AlMg3. Figure 5 summarises the results for a wire feed of 1.3 m/min. The curves of the melting depth and the seam width are almost identical for all pulse energies used. This indicates that the pulse energy has no significant influence on the brazing result.

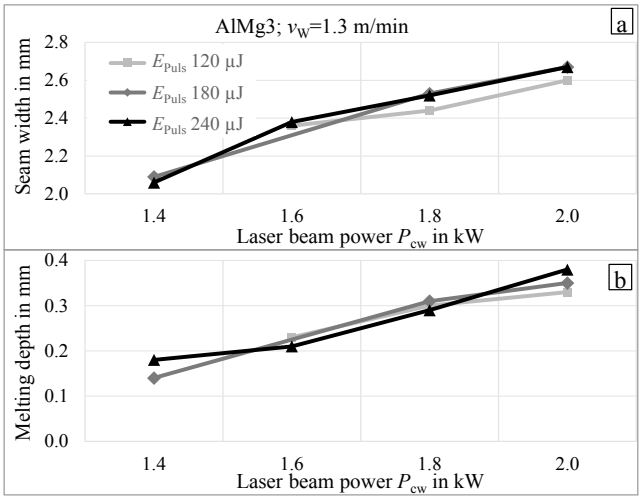


Fig. 5. Correlation between laser beam power and seam width (a) with associated melting depth (b) for different pulse energies, AlMg3, v_W = 1.3 m/min

Furthermore, it is noticeable that even at low laser powers of 1.4 kW melting occurs. There is also no significant difference between the pulse energies of 180 µJ and 240 µJ at a wire feed of 1.8 m/min, as it can be seen in Figure 6.

One explanation for the differences between the two alloys used could be the lower thermal conductivity of AlMg3. With 140 – 160 W/(mK), it is significantly lower than 170 – 220 W/(mK) of AlMgSi1, which means that the heat is dissipated more slowly in the process and melting of base material increases.

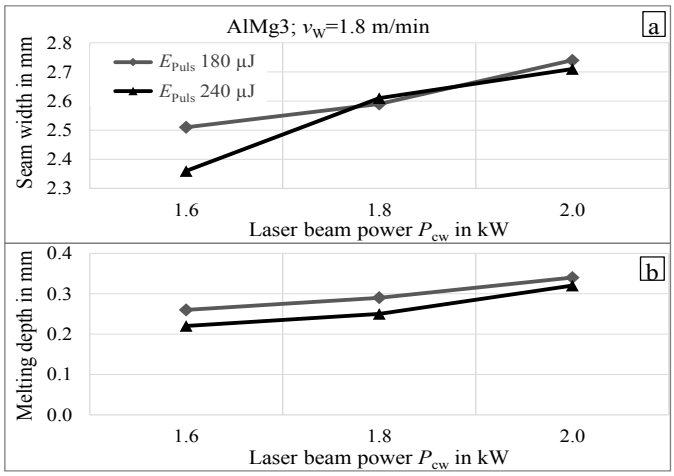


Fig. 6. Correlation between laser beam power and seam width (a) with associated melting depth (b) for different pulse energies, AlMg3, v_W = 1.8 m/min

Figure 7 shows some examples of cross-sections of bead on plate seams of the alloy AlMgSi1 brazed in a silane-doped atmosphere. The pulse energy used increases from left to right and from top to bottom the laser beam power used increases. The wire feed rate was 2.0 m/min. As already demonstrated in Figure 4, the cross-sections with a pulse energy of 120 µJ and 180 µJ show comparable results. At 240 µJ, both the seam width and the not allowed melting increase.

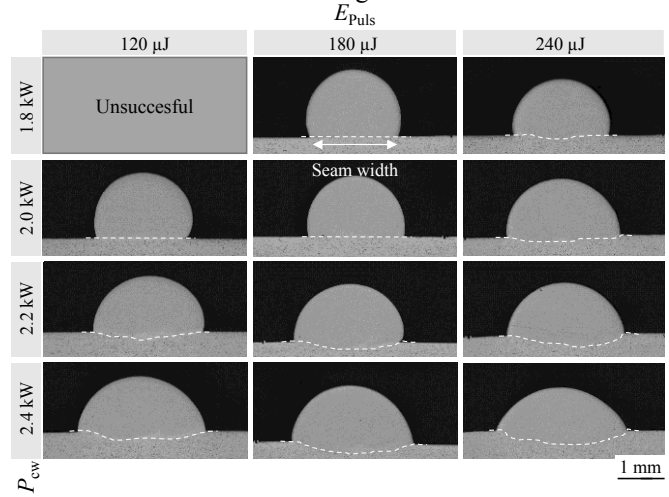


Fig. 7. Cross-sections of bead on plate seams brazed under silane-doped atmosphere on AlMgSi1 with increasing pulse energy and laser beam power with constant wire feed of 2.0 m/min

In reference tests under pure argon atmosphere, no materially bonded seams could be brazed. In figure 8, the difference is obvious.

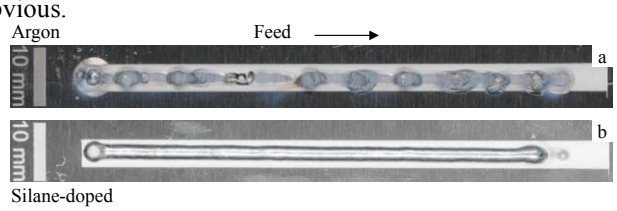


Fig. 8. Comparison of bead on plate seams brazed under pure argon (a) and silane-doped argon atmosphere (b) with P_{cw} = 2.4 kW and E_{Puls} = 240 µJ on AlMgSi1

The molten filler has beaded off directly under argon atmosphere. In contrast, under oxygen-free atmosphere a materially bonded bead on plate seam with metallic sheen could be brazed. Both were brazed with a laser beam power of 2.4 kW and a pulse energy of 240 µJ.

4. Conclusion

The findings can be summarized as follows:

- Deoxidation of aluminum alloys is possible by short pulsed laser irradiation when a certain pulse energy threshold is exceeded, which could be confirmed by XPS measurements in oxygen-free atmosphere.
- For the alloy AlMgSi1, an influence of the pulse energy on the brazing result could be observed. Pulse energies of 120 µJ and 180 µJ lead to good brazing results with minor melting of base material. Increasing the pulse energy to 240 µJ increases melting.
- Melting of based material was generally higher for the alloy AlMg3, regardless of the feed rate used.

In summary, it can be stated that a flux-free brazing process of aluminium can be realized in an oxygen-free atmosphere. In the future, it must be investigated how the seam width can be increased while reducing the melting of base material. This applies in particular to the alloy AlMg3. Furthermore, the findings should be transferred to brazing of butt joints.

Acknowledgements

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