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Laser spot welding of copper-aluminum joints using a pulsed dual wavelength laser at 532 and 1064 nm

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Abstract

A modulated pulsed laser source emitting green and infrared laser light is used to join the dissimilar metals copper and aluminum. The resultant dynamic welding process is analyzed using the back reflected laser light and high speed video observations of the interaction zone. Different pulse shapes are applied to influence the melt pool dynamics and thereby the forming grain structure and intermetallic phases.
The results of high-speed images and back-reflections prove that a modulation of the pulse shape is transferred to oscillations of the melt pool at the applied frequency. The outcome of the melt pool oscillation is shown by the metallurgically prepared cross-section, which indicates different solidification lines and grain shapes. An energy-dispersive x-ray analysis shows the mixture and the resultant distribution of the two metals, copper and aluminum, within the spot weld. It can be seen that the mixture is homogenized the observed melt pool oscillations.

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Keywords: Pulsed welding; aluminum, copper; power modulation; grain structure

1. Introduction

Laser welding of copper to aluminum is challenging due to several restrictions, which can be derived from the material properties listed in Tab. 1.

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Nomenclature

Al	aluminum
A_{Rip}	amplitude of the modulated power signal in kW
Cu	copper
d_f	focus diameter in µm
EDX	energy-dispersive X-ray spectroscopy
P_{peak}	maximum pulse power in kW
P_1	pulse power in the timeslot t_2 in kW
λ	laser wavelength in nm
λ_{Rip}	wave duration of the modulated power signal in ms
f_{Rip}	frequency of the modulated power signal in Hz
t_1	duration of the peak pulse signal in ms
t_2	duration of the constant or modulated pulse signal in ms
t_3	duration of the decreasing signal in ms

One main challenge is the low absorption of aluminum and especially copper at the laser wavelength of 1 µm. Thus a green laser source in addition to infrared laser light proved to enhance incoupling efficiency and stabilize the welding process [1][2][3][4][5][6][7].

Table 1. Material properties of aluminum and copper [9][10][11].

	Aluminum	Copper (Cu-ETP)
Heat conductivity κ in W/(mK)	235	390
Heat capacity c_p in J/(gK)	0.89	0.386
Density ρ in g/cm^3	2.70	8.93
Absorption at 1 µm in %	6	3

The other challenge is given by the metallurgy of the two mixing materials. Intermetallic phases are likely to form and possess very brittle properties, which are probably resulting in crack formation. Therefore, the mixing behavior of the two metals is of major interest and discussed in several publications [12][13][14][15][16]. As the phase diagram of aluminum and copper, depicted in Fig. 1, reveals, especially between 50 and 80 at.-% of copper intermetallic phases are likely to form.

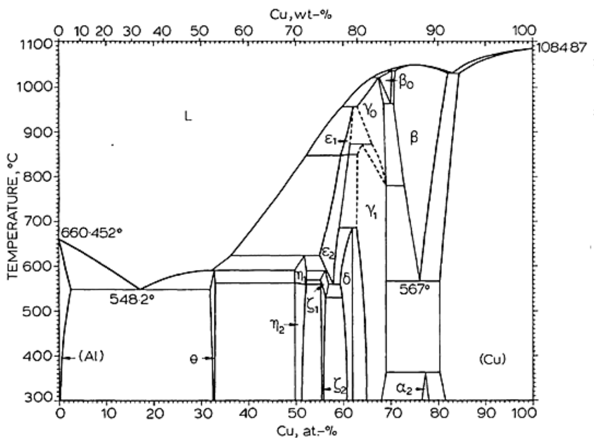

Fig. 1. Phase diagram of aluminum and copper [17].

In order to avoid the brittle intermetallic phases a copper content either below 50 at.-% or above 80 at.-% is suggested. However the composition is likely to change within the cross-section of the weld. Thus strategies to achieve homogeneous distributions across the weld are requested.

For pulsed laser welding the power modulation of a pulse led to a better mixing behavior [18][19][20][21][22][14][23][24]. Thus, in the case of a dissimilar weld of steel and bronze, cracks could be prevented with this strategy [19]. So far it is not clear how the modulated pulse shape influences spot welds of copper to aluminum. The resultant process of such welds is as well addressed within the following sections as the metallurgically achieved weld quality, regarding the mixture of the involved metals.

2. Experimental setup

The experiments were conducted with a rofin-lasag green mix laser source [1] which emits mainly at the infrared wavelength of 1064 nm but also converts a small friction of light in the green wavelength by second harmonic generation. As has been shown in previous publications the green laser light increases the incoupling efficiency and stabilizes the welding process.

In order to analyze the welding process itself, diagnostics to detect the reflected laser light and observe the spot weld area with a high speed camera were applied. Fig. 2 shows this experimental setup.

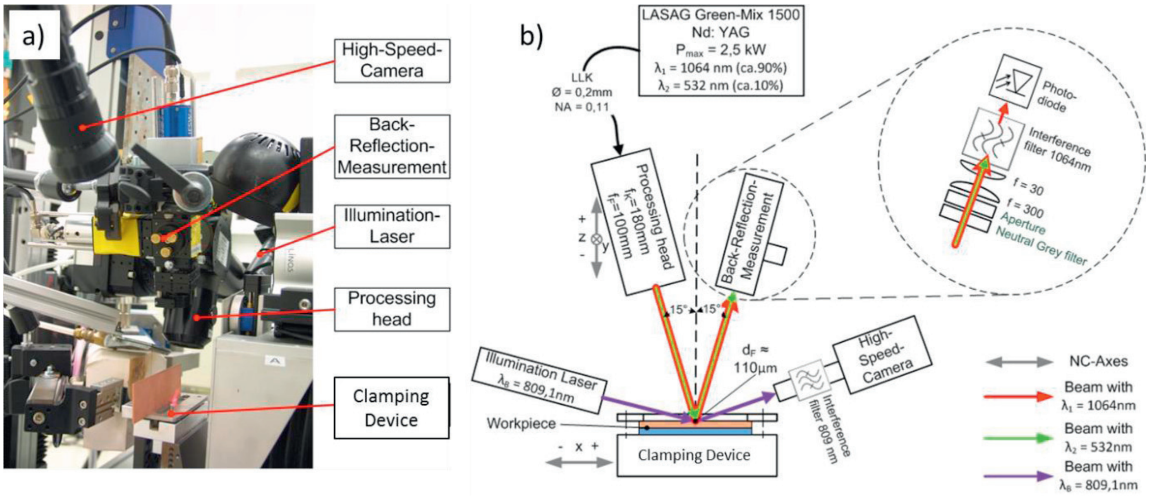

Fig. 2. (a) picture of the experimental setup; (b) schematic sketch of the experimental setup.

The photodiode was positioned in the reflectance angle of the incident laser beam and filtered at the laser wavelength of 1064 nm. To achieve a sufficient quality of the high speed videos, an illumination laser with a wavelength of 809 nm was used.

The spot weld joint was in the overlap configuration with aluminum (al 99,95%) on the top and copper (cu 99,9%) underneath it. The laser beam was focused on the workpiece surface, which led with the used optics to a focal diameter of 110 µm.

The spot welds were performed with different laser pulse shapes. The applied 10 ms lasting pulse power signals can be seen in Fig. 3.

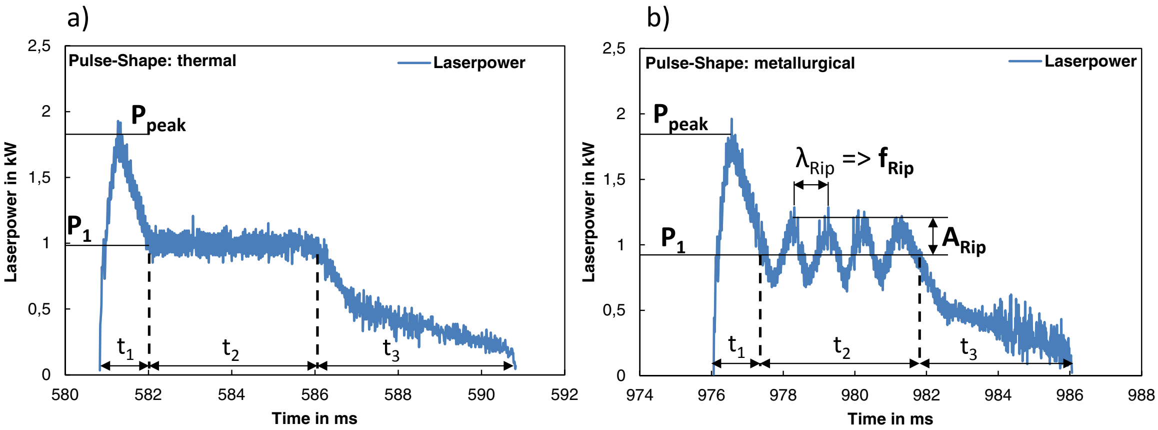

Fig. 3. (a) Shape-parameters of a thermal optimized pulse; (b) Shape-parameters of a metallurgical optimized pulse.

The left side of Fig. 3 shows a so called thermal pulse shape, which is typical for spot laser welding applications [18][19][20][21]. The pulse starts with a high peak power at the beginning, enabling the formation of a capillary and the deep penetration welding regime. After this peak a constant laser power is provided for the time t_2 enabling further energy input and an increase in weld depth and size. Finally the pulse power is continuously reduced to zero at the end of the laser pulse.

On the right side of Fig. 3 a metallurgical optimized pulse shape is depicted. In contrast to the thermal pulse shape this laser pulse shows a modulated laser power signal during the time t_2. The power modulation is supposed to influence the melt pool dynamics and solidification process. This leads to a fine grain structure [19] and a more homogenous mixture of dissimilar metal joints [19]. Even though such experimental evidence is reported, the mechanisms how the modulation influences the welding process and correlates with experimental outcome of the welds are not totally understood so far.

3. Experimental Results

In the following the experimental results achieved when applying the two different pulse shape of the thermally optimized pulse shape and the metallurgical optimized pulse shape will be discussed.

3.1. Welding with a thermally optimized pulse shape

Measuring the reflected laser light while a thermal pulse shape was applied, resulted in the back-reflection curve depicted in Fig. 4. It can be seen that after 0,25 ms of laser power the reflection signal drops, which corresponds to the formation of a deep capillary. The remaining low back-reflection signal indicates that the capillary maintains until the laser power is reduced at the end of the laser pulse. At 217,5 ms the back-reflection signal rises almost instantaneously, representing a closure of the capillary. Finally the back-reflection signal decreases according to the continuously reduced laser power.

Having a look at the video observation of the melt pool, while the laser pulse is applied leads to images similar to the one shown on the right side of Fig. 4. In order to receive a quantitative measure derived from the recorded videos, the grey scale value in the molten area of the laser pulse is analyzed.

The grey scale value shows higher fluctuation in the deep penetration welding regime. Beside it can be seen that the capillary corresponds to brighter areas in the video pictures.

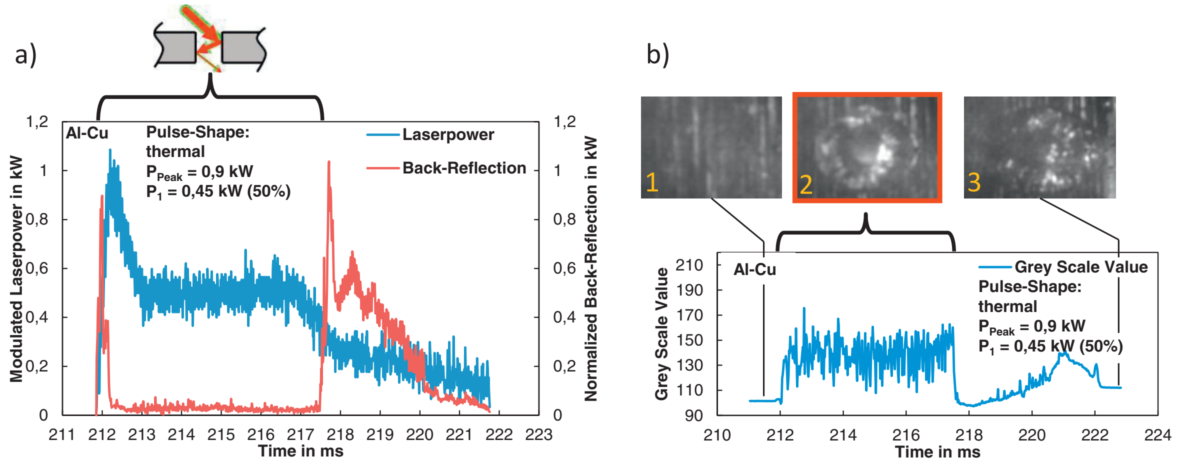

Fig. 4. Behavior of the melt zone caused by a thermal pulse: (a) back-reflection-signal; (b) grey-scale-value-analysis.

In order to see how the pulse shape and the observed welding behavior influence the experimental results, cross-sections of the spot welds were prepared. After grinding and polishing they were treated with NaOH (2%) for 30 seconds.

Fig. 5 shows that within the spot-weld there are several accumulations varying in their elemental composition, which indicates little mixture of the welding-pool. Furthermore it can be seen, that the volume of molten aluminum is more than twice the volume of molten copper.

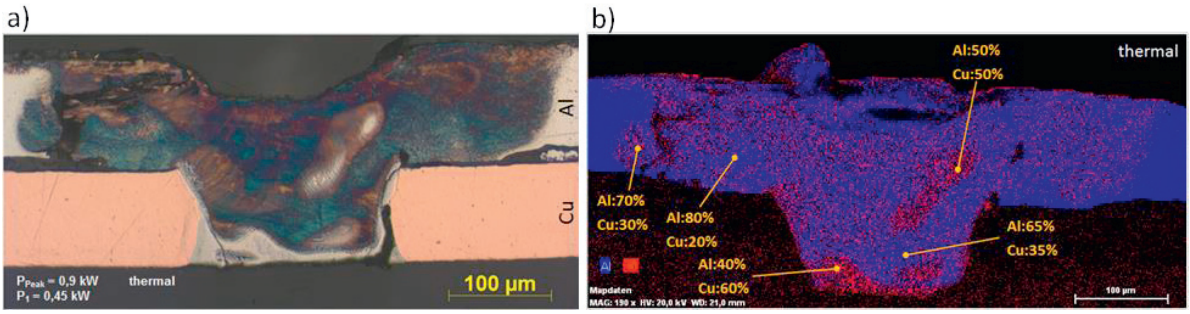

Fig. 5. Spot weld of a thermal pulse: (a) Cross-section; (b) EDX-analysis.

EDX-scans and analyses were accomplished to reveal whether different colors within the weld-point (i.e. Fig. 5 (a)) indicate different chemical compositions (i.e. Fig 5 (b)). The red color shows the copper content while the blue colors indicate aluminum content. The rather inhomogeneous distribution of the two colors in Fig. 5 (b) shows a variance of the aluminum to copper content from 80:20 to 40:60.

3.2. Welding with a metallurgical optimized pulse shape

A metallurgical optimized pulse shape according to Fig. 3 (b) is used to influence the mixture of copper and aluminum. Applying such a pulse results in the measured back-reflection signal depicted in Fig. 6 (a). It can be seen that at first a high back-reflection occurs followed by a low back-reflection signal corresponding to the deep-penetration welding process with an established capillary. At the second pulse phase t_2, the measured signal shows periodic fluctuations according to the applied modulation frequency.

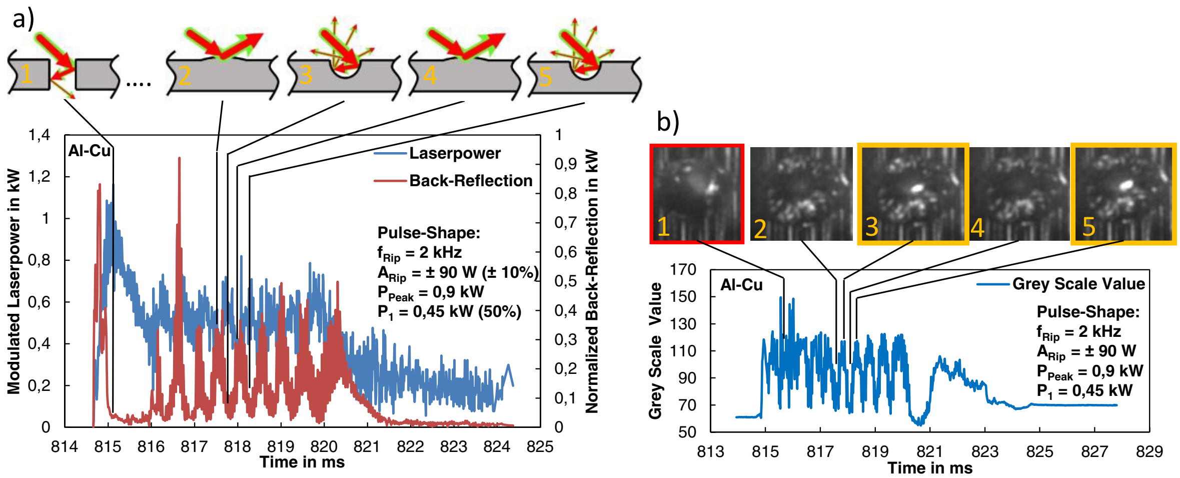

Fig. 6. Behavior of the melt zone caused by a metallurgical pulse: (a) Back-reflection-signal; (b) Grey-scale-value-analysis.

In order to investigate how the process is affected by the applied power modulation, the right side of Fig. 6 (b), shows a grey value analysis in the region of the melt pool. Since it shows periodic fluctuations at the same frequency as the applied modulation signal, it can be derived that the melt pool oscillates. However it is not clear whether these oscillations are a surface near effect or they extend to the whole melt pool size. To analyze this, the cross-section of a metallurgical optimized spot weld in Fig. 7 was prepared.

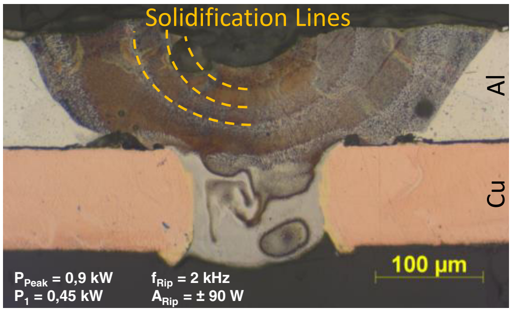

Fig. 7. Cross-section of the spot weld created with a metallurgical pulse.

The cross-section of the spot weld produced with a modulated metallurgical pulse shape in Fig. 7 shows that the width of the weld in the aluminum plate is almost three times larger than the weld width on the copper side. In the upper part of the spot weld several circular oriented solidification lines, which indicate a grain structure change, can be identified. In order to correlate these solidification lines with the retrieved microstructure the EDX-analysis depicted in Fig. 8 were done.

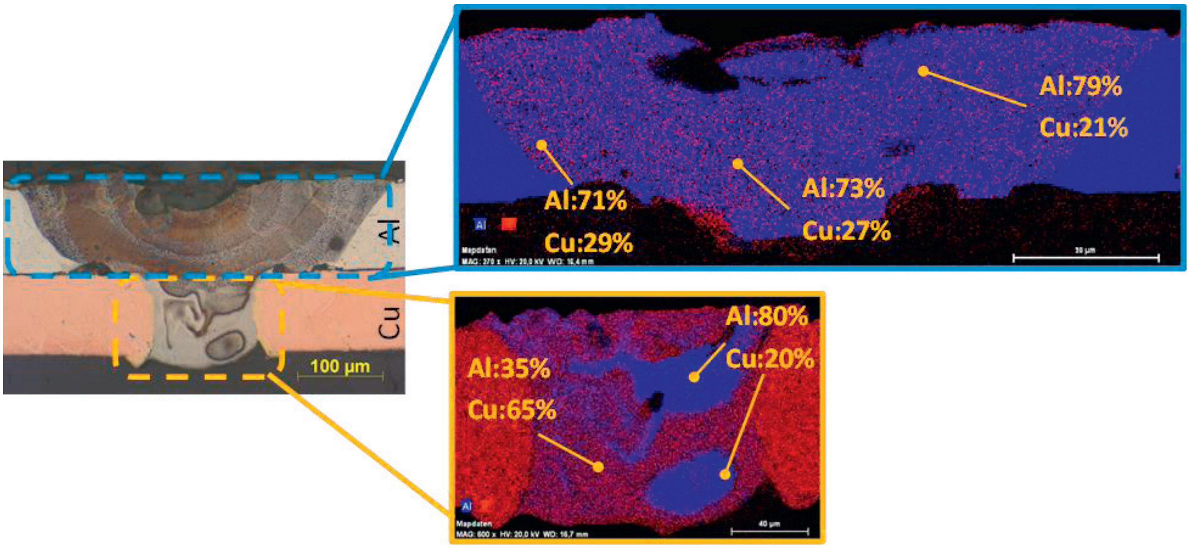

Fig. 8: EDX-analysis of the spot weld created with a metallurgical pulse.

It can be seen that the upper part of the spot weld, which includes the solidification lines, shows a uniform mixture of the joining partners in the EDX-scan. Across the spot weld the composition ratio of aluminum to copper varies from 79:21 to 71:29.

In contrast the lower part of the weld is designated by large al-rich accumulations and a widely uniform cu-rich base material. Thus the composition ratio of aluminum to copper varies from 80:20 to 35:65.

4. Discussions

In the previous sections it has been shown that welding of copper to aluminum with a thermal pulse shape results in an inhomogeneous distribution of the two metals within the fusion zone. As the measured back-reflection signal and the video analysis of the melt pool reveal, this is initialized by the presence of a capillary during the welding phases t_1 and t_2. Thus this deep-penetration welding process results in strong local variations of the material contents of the two joining partners in the spot weld fusion zone.

A so called metallurgical pulse shape with modulated laser power in section t_2 stimulates the melt pool to oscillate with the applied frequency. This can be concluded from the time-resolved interpretation of the grey scale value in the melt pool area. The varying grey scale value shows that the frequency of power modulation is directly transferred to melt pool movement at the same frequency.

In addition a second evidence for the occurrence of melt pool oscillation with power modulation is given by the measured periodic fluctuating back-reflection signal. If oscillating the reflection signal varies in contrary phase with the applied power modulation.

After welding the solidification lines in the cross-sectional view of the spot weld indicate that the oscillations extend circular also in depth. However with the applied metallurgical signal and the considered overlap-joint, mainly the upper part of the spot weld is influenced by the occurring oscillations. This can be concluded from the detected solidification lines in the upper sheet of the spot weld. These solidification lines are suggested to be developed when the melt solidifies. They appear if the solidification is stopped by the increasing laser power within the pulse power modulation. Recently solidified parts of the weld are remelted by such short term power increase.

It can be suggested that the occurring amplitude of the melt pool oscillations and also the melt size reduce with pulse duration, since the number of back-reflection signal oscillations and grey scale value oscillations is larger than the number of detected solidification lines. For example, when the final pulse power modulation peak leads to the same small oscillation amplitude and small remelt volume as the previous one, they cannot be distinguished in the cross-sectional view. Thus the number of solidification lines in that case is less than the number of detected back-reflection and grey scale value oscillations. Such behavior is seen within the experiments and is confirmed by the decreasing distance between the identified solidification lines.

As metallographic analysis and EDX-scans prove, the oscillations and solidification effects in the upper part of the spot weld led to a homogeneous distribution of the joining partners. The composition of the weld shows less than ten percent of variations across the weld spot. The solidification lines cannot be identified in the EDX-scans. This can be interpreted as evidence that the composition of the melt is not changing during solidification.

The melt pool region which is not affected by the power modulation is not oscillating. Therefore in the lower part of the spot weld no solidification lines are detected. The EDX-scan reveals that this region is characterized by an inhomogeneous distribution of the fusion partners.

From these experimental results it can be concluded, that melt pool oscillations and power modulated driven solidification is beneficial for homogeneous material mixture in case of welding dissimilar metals. One way to stimulate the oscillation and periodic solidification is to use a modulated laser power signal.

5. Summary

Within this paper it could be shown that the metallurgic pulse-shape with modulated laser power leads to a periodic melt pool movement at the same frequency. Such behavior cannot be seen, when a thermal pulse shape without power modulation is applied.

In case of the modulated power signal, the measured back-reflected laser light signal oscillates with a phase shift at the applied modulation frequency. Thereby this signal can be used to detect melt pool movement.

A metallurgical analysis of the spot weld showed that the resultant periodic oscillations of the melt and periodic solidification led to circular oriented solidification lines. These solidification lines correlate with a homogeneous distribution of the two fusion partner, copper and aluminum. Thus the metallurgical pulse shape with modulated laser power should be preferred compared to a thermal pulse to join dissimilar metals, since the achieved homogeneous distribution is essential to avoid the local formation of intermetallic phases.

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