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Laser welding of dissimilar copper and aluminum sheets by shaping the laser pulses

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Abstract

Dissimilar metal joining of thin copper and aluminum sheets is very important in the battery connections. The main problem while joining this dissimilar combination is formation of brittle intermetallic phases that degrade the electrical and mechanical properties of the joint. For joining copper and aluminum sheet with laser, very high intensity in the range of 10^7 W/cm^2 is required. Intermixture of copper and aluminum is vital for joint ductility. In this paper, the effect of combined oscillation and shaping of the laser pulses on the overlap welding of copper-aluminum is studied. Precise control of intermixing can be achieved by modifying the laser pulse i.e. the percentage of power with respect to the pulse time. Investigation on different pulse shapes with ramp up and ramp down profile is conducted by cross-section and microstructural analysis.

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Keywords: Laser welding; Dissimilar metal joining; Cu-Al joints; Intermettalic compounds (IMC); Pulse modulation

1. Introduction

Dissimilar Al-Cu connection is widely used in electrical and electronics applications. The low solubility of Al-Cu system favors the formation of the intermetallic compounds that are brittle and reduce the ductility of the joint [1]. The laser welding of copper and aluminum pose multiple challenges like reflectivity, high thermal conductivity and large difference in thermal expansion and melting points [2]. Laser braze welding from the aluminum side to copper side is achieved by controlling the thickness of intermetallic compounds formed to 3-6µm and limited to phases such as Al_2Cu, Al_4Cu_9 [3][4]. However thermal ageing introduces additional phases AlCu, Al_3Cu_4 [5]. For laser welding

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the spatial beam oscillation is effective in increasing the weld seam width and decreasing the depth [6]. Controlling the depth of fusion in Al-Cu system close to interface is beneficial as mixing can be kept to minimum [7][4].

Very sparse literature is available for the configuration joining from copper side (Cu-Al) [8][9][10]. For laser joining from a highly reflective copper side, a very high intensity in the order of 10^7 W/cm^2 is desirable to form keyhole which increase the energy coupling into the material in vapor phase [11]. The laser welding by pulsed mode is beneficial to minimize the thermal effects on the material. The pulse width for investigation are in the range of 5ms-10ms [12]. Square wave is the simplest waveform for pulsed mode of operation. However, alternative profiles can be programmed i.e. pulse power as a function of time. Such a modulation is proportional to change in temperature with respect to time. Therefore, the heating, active welding and cooling zones exist within a pulse. Such a pulse modulation for copper-aluminum spot weld was studied by [13]. The author introduced preheat phase, sinusoidal heating phase and cooling phase by modulation of laser peak power with respect to pulse time.

In this study, the power modulation as a function of time for seam welding of thin sheets of Cu-Al (Copper on top) in overlap configuration is studied. This configuration favors rapid interdiffusion of the joining partners and all the dangerous brittle intermetallic phases of Cu-Al system are formed in the seam [8]. Therefore, the idea here is not to control the intermetallic layer formation as in Al-Cu configuration (Al on top) [3] but to distribute over the cross-section so that their concentration is reduced. Distribution of intermetallic phases and control of their intermixing inside the seam is achieved by combined oscillation (stirring effect [14]) and pulse wave mode of operation. The main objective of this paper is to study the combined laser beam oscillation and pulse modulation and show to that the ductile behavior can be achieved with the presence of intermetallic compounds in Cu-Al configuration.

2. Methods and experimental

2.1. Experimental setup

The materials used are pure copper (Oxide free 99.95% pure) and aluminum (Al 1050) sheets with dimensions (40mm × 50mm) and thickness of 0.4 mm. For laser welding 2000 W disk laser with wavelength of 1030 nm was used. The 400 μm copper and aluminum sheets are placed in overlap configuration (Fig. 1(a)) with focus of laser placed on the top of the copper sheet (Z=0) and spot diameter of the laser is 89 μm.

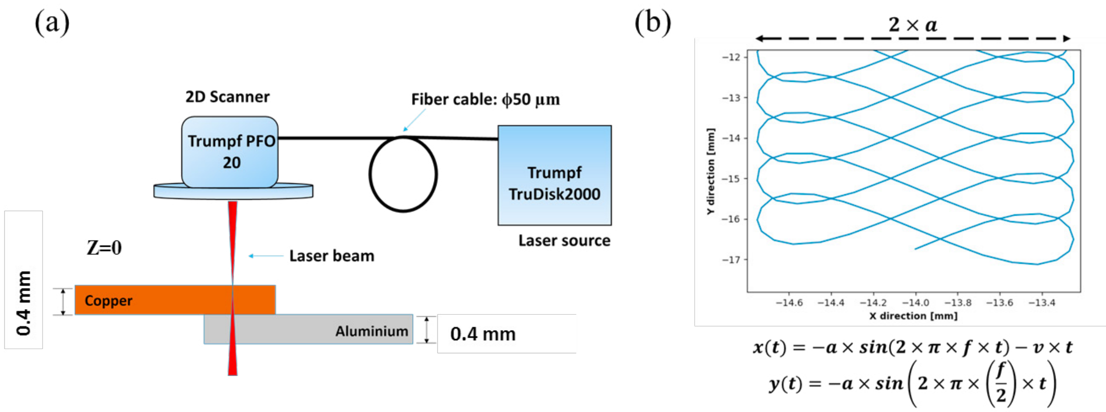

Fig. 1. (a) Schematic of Cu-Al laser welding process. (b) Spatial beam oscillation (Infinite shape) in x and y direction. The oscillation parameters are amplitude (mm), frequency (Hz) and feed velocity (mm/s).

The laser beam irradiation is on the copper sheet with a high intensity of 10^7 W/cm^2 and the process is based on keyhole welding. No additional shielding gas is considered in this study. It was shown in [15] that the influence of shielding gas on dissimilar Al-Cu welding is negligible. Similar choice have been made by [7] and [16] in welding aluminum and copper. The oscillation of laser beam (infinite shape) in x and y direction is shown in Fig. 1 (b). The oscillation parameters like amplitude (a in mm) is 0.75 mm, frequency (f in Hz) is 50 Hz and the feed velocity (v in mm/s) is 30 mm/s.

2.2. Laser pulse power modulation

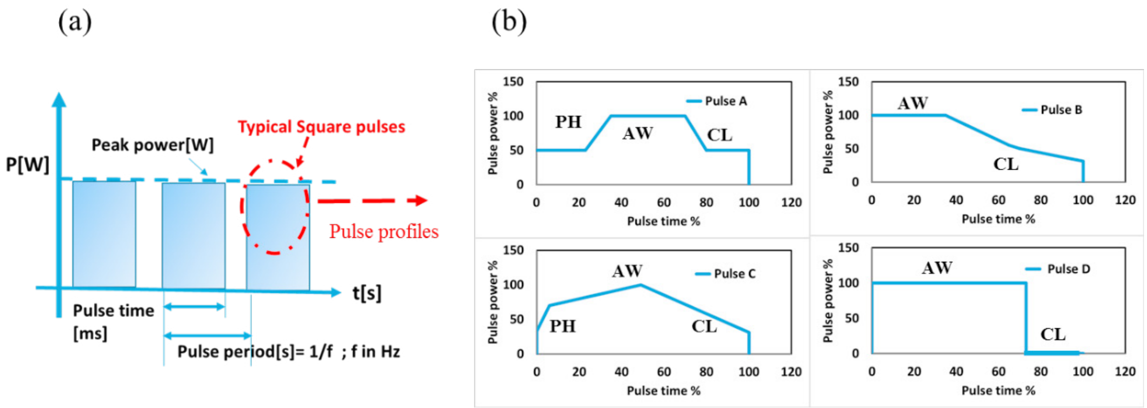

Fig. 2. (a) Pulse mode of operation defined by peak power (W), pulse time (ms), frequency (Hz). (b) Profiles of the pulse A, B, C, D i.e. pulse power as a function pulse time. Area under the pulse in (b) is same for all the profiles.

In pulsed wave mode of operation, the influencing process parameters are pulse time, frequency and peak power. Based on initial experiments considering the reflectivity and threshold for melting copper, pulse peak power is fixed to 1100 W, pulse time as 5 ms and frequency as 150 Hz. These parameters represent a full depth of penetration (0.8 mm) into Cu and Al sheet. Since the main objective is to understand the profile of the modulated pulse, the oscillation parameters and pulsing parameters is fixed. The pulse profile is defined by preheat (PH), active welding (AW) time and cooling (CL) phases within the pulse width. Such regions were also defined by the authors in [13]. The profiles of the pulse is shown in Fig. 2. The energy of all the pulse profiles (i.e. Area under the curve) A, B, C, and D for peak power of 1100 W and pulse time (5 ms) is 4.02 J. Since the maximum peak power and energy of the pulse for welding is same, the effect of pulse profile/shape alone is studied.

Table 1. Description of pulse types with peak pulse power, frequency, pulse energy, preheat time, active welding time and cooling time.

Pulse type	Preheat (PH) [ms]	Active welding (AW) [ms]	Cooling (CL) [ms]	Pulse peak power[W]	Frequency [Hz]	Pulse Energy [J]
Pulse A	1.75	1.75	1.5	1100	150	4.02
Pulse B	0	1.75	3.25	1100	150	4.02
Pulse C	0.3	2.15	2.55	1100	150	4.02
Pulse D	0	3.65	1.35	1100	150	4.02

For pulse A, preheat is done at 50 % peak power for 1.75 ms, active welding at 100% peak power for 1.75 ms and ramp down cooling for 1.5 ms. Pulse type A, is hypothesized to preheat (PH) the material then active welding (AW) can initiate keyhole just enough to create molten Cu-Al and succession cooling (CL) to terminate the further intermixing. For a direct comparison, pulse D with longer active welding time of 3.65 ms is used. However, the energy (E=4.02J) for all the pulse type remain constant. The pulse B is defined by active welding for 1.75 ms and ramp down cooling for 3.25 ms. For pulse C, ramp up heating and ramp down cooling profile is used.

2.3. Metallography preparation

For metallography sample preparation, compression mounting system (Buhler SimpleMet 4000) with Phenolic powder as mounting media is used. The pressure, heating time and temperature setting on the molding machine is 220 bar, 4.20 minutes and 180ºC respectively. The grinding and polishing were performed in steps (shown in Table 2) using semiautomatic grinding machine (Buehler MetaServ 250). Between each step, the specimen is cleaned with ethanol in ultrasonic bath for 2 minutes.

Table 2. Metallography preparation of weld cross-sections

Step	Description of the Procedure	Time [min]	Speed [RPM]	Force [N]	Lubricant
Grinding	SiC paper 320 grit	6 min	250	20-25	Water
	SiC paper 800 grit	4 min			
	SiC paper 1200 grit	4 min			
Polishing	Hard, woven cloth with 6 µm diamond suspension	3 min	150	20-25	Water based
	Short napped velvet cloth with 3 µm diamond suspension	2 min			
	MicroFloc-Soft, long napped cloth with 1 µm diamond suspension	2 min			
	MicroFloc-Soft, long napped cloth with 0.25 µm diamond suspension	1 min			

For etching the Al-Cu weld seam, Keller and Macro etchant Cu (Table 3) are used. The etchant is applied by immersing the polished metallography specimen in chemical solution for specified time and finally rinsing it with water. For analysis of the microstructure light optical microscope (Leica DM 4000 M) was used.

Table 3. Chemical etchant used for analysis of Cu-Al weld seam [17]

Etchant name	Chemical composition	Etching time [s]	Temperature [°C]	Etching method
Keller	950 ml H_2O; 25 ml HNO_3; 15ml HCl; 10 ml HF	10	25°C	Immersion
Macro Etchant (Cu)	15% Ammonium persulfate; 85% H_2O	5-10	25°C	Immersion

2.4. Testing procedure

Copper and aluminum test coupons/tabs of dimensions (40 mm × 50 mm × 0.4 mm) are used. Before welding, the samples are cleaned with acetone. The schematic of the welded sample for shear test is shown in Fig. 3. The sheets are held in position by clamps at each end. The tensile shear test is carried out in Zwick Z010 machine at room temperature (25°C). The feed rate of crosshead is 1.2 mm/min [10].

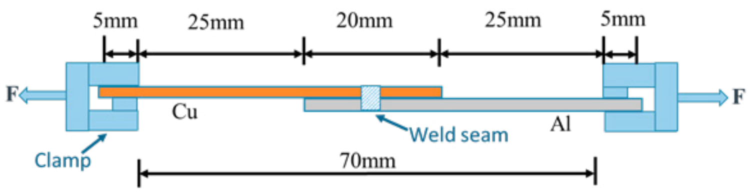

Fig. 3. Schematic of Cu-Al laser welded specimen for tensile shear test setup.

3. Result and discussion

3.1. Tensile shear behavior of Cu-Al joints with no beam oscillation

In this section, the shear strength of Cu-Al joints without beam oscillation is presented to represent a typical brittle response of the Cu-Al joint. In the configuration with copper on top the formation of brittle intermetallic compounds (IMC) are highly favored. Without distributing IMC over cross-section of the seam (i.e. without beam oscillation), the behavior of the joint is highly brittle with low mechanical strength. Fig. 4 shows the brittle shear curve with maximum shear force of 745 N.

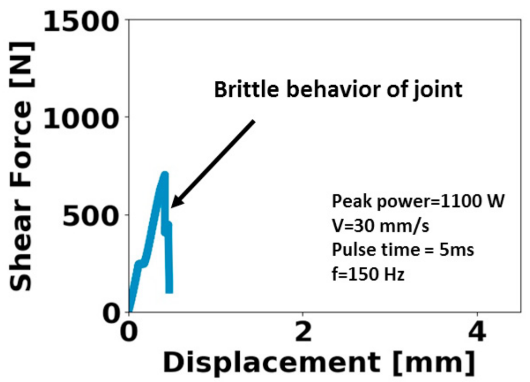

Fig. 4. Tensile shear test: Brittle behaviour of the Cu-Al joint with no spatial beam oscillation.

3.2. Shear test of combined beam oscillation and pulse modulation

The combined spatial beam oscillation and pulsed laser welding of thin copper and aluminum sheets for different pulse types A,B,C,D is shown in Fig. 5. The sample size for the shear test is five (N=5). From the shear test, a high mechanical strength of over 1200 N was obtained. Pulse type A resulted in a high mean force of 1275 N (79.6 N/mm^2) and low standard deviation of 17 N in comparison to other pulse types. Pulse B and D with a flat profile resulted in a lower average shear force of 1222 N and 1237 N respectively with larger deviation of 46 N. The shear strength of the base metal Al is 1230 N with a low standard deviation of 7.4 N. Therefore, the shear strength of combined oscillation and pulsing is comparable to that of base Al (1230 N).

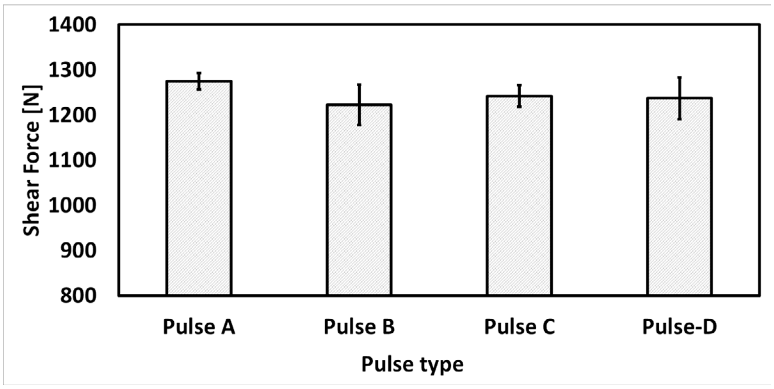

Fig. 5. Tensile shear response of combined beam oscillation and power modulation.

There is a noticeable plastic deformation of Al sheet after the tensile shear test showing a ductile behavior of the joint. Despite the present of complicated intermetallic structures, the failure is away from the joint (rich of IMC) possibly in the heat-affected zone (HAZ) of Al. Dedicated investigation on the texture of these zones are required. However, joint strength nearly strong as Al base metal (1230 N) is evident with Cu-Al configuration with presence of large amount of intermetallic compounds. The shear force of the modulated pulses are comparable and the main result is to emphasis on the fact that a ductile behavior can be obtained despite the presence of intermixing in Cu-Al configuration in contrast to Al-Cu configuration as described by [18].

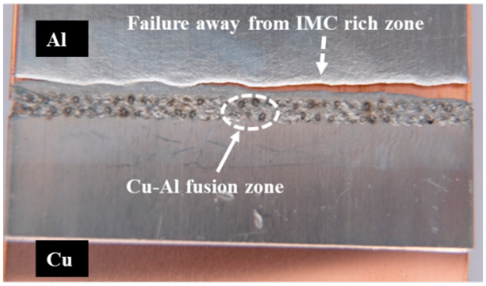

Fig. 6. Photograph of Cu-Al joint (Pulse D) after shear test showing the failure zone

3.3. Microstructure

The microstructural analysis is performed by sectioning the weld seam, subsequent grinding and polishing steps. From Fig. 7 (a) it is evident that the high rate of mixing is promoted for copper to aluminium configuration. Despite the presence of complex intermetallic structures, a significant ductile behavior of joint (Fig. 7 (b)) is achieved by oscillating the laser pulses.

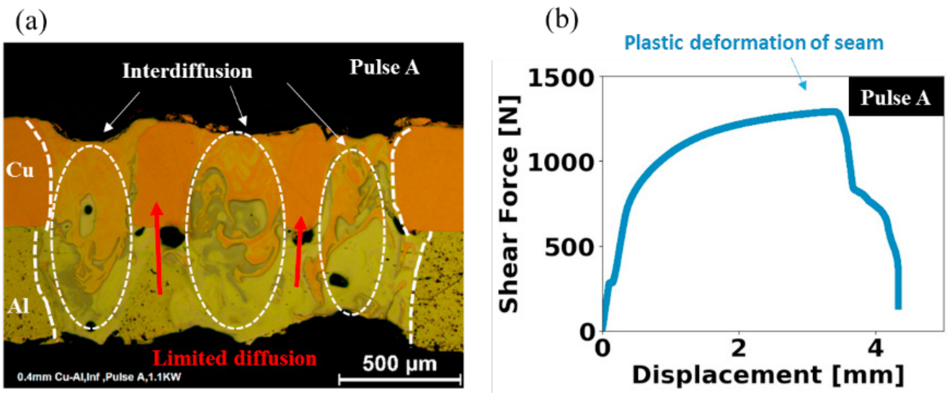

Fig. 7. (a) Cross-section of Cu-Al laser welded by pulsed type A. (b) Shear force curve for pulse A.

The oscillation of the laser beam in form of infinite shape (Fig. 1 (b)) with pulse modulation results in a discontinuous interface in the fusion zone of Cu-Al. Therefore, regions with varying level of copper and aluminum inter-diffusion is obtained. This result in a combination of brittle and ductile intermetallic compounds split over the weld cross-section. The light optical micrograph of the different pulse shapes (3 samples per pulse type) is shown in Fig. 8. The pulse shapes A, B, C and D result in different degree of mixing. Since the energy of all the pulse type is same (4.02 J), the power introduced as a function of pulse time has a clear influence on mixing. The pulse A with preheat, active welding and cooling zone has lower inter-diffusion of Cu and Al in comparison to the pulse D with a square profile because of limited active welding time of 1.75 ms. The pulse D had the largest total area of pores. The pores range from 10 µm to as large as 60 µm in diameter. The pulse A had the lowest area of pores (Fig. 8 (b)).

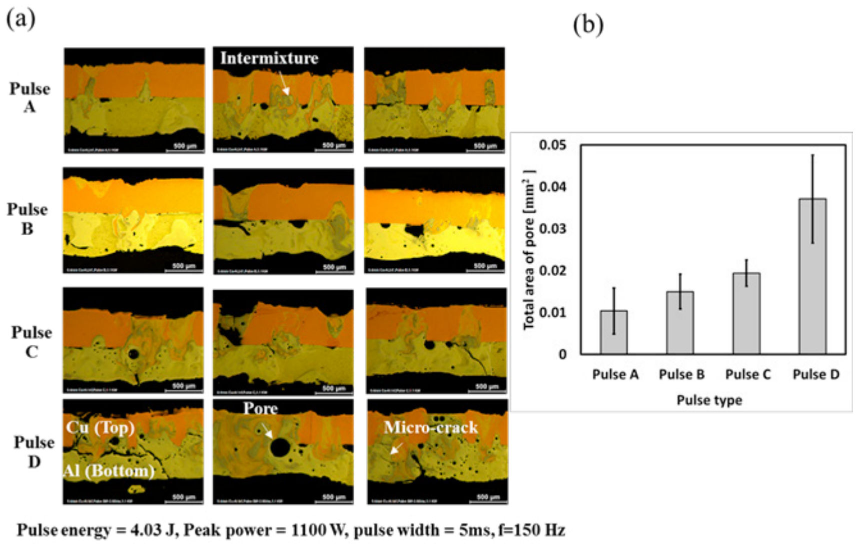

Fig. 8. (a) Micrographs of Cu-Al joints welded with different pulse types. (b) Total area of pores (mm^2) with respect to the pulse type.

The amount of Cu-Al mixing and number of pores are proportional. As the active welding time increase (i.e. from A to D) the inter-diffusion and the defects like pores and cracks increases although same energy was delivered for all pulse type. Therefore, pulse A is effective in terminating the mixing of Cu and Al.

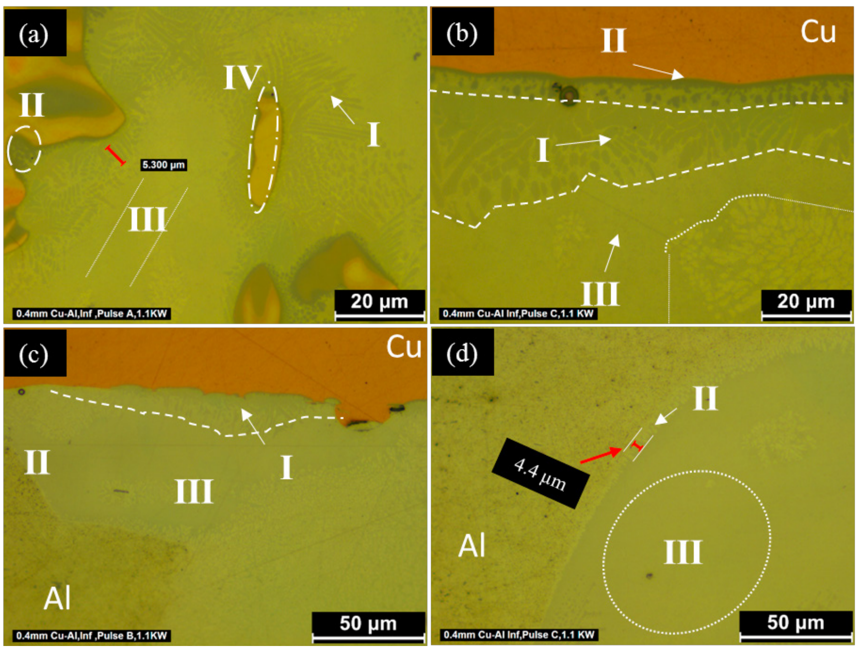

Fig. 9. Micrograph at the Cu-Al interface in pulse A (a) and pulse C (b); Micrograph showing the edge of Al fusion zone close to faiure zone in pulse B (c) and pulse C (d).

From the micrographs (Fig. 9) of Cu-Al cross-section, different morphologies exist. Light optical microscopy and etching technique was used to interpret the structures [17]. The dendritic structures represented as I, II, III, IV are all present in the weld seam. Based on intermixing wide variant of intermetallic composition may exist as described in the literature. The main composition of the IMC reported during Al to Cu joining are Al_2Cu, Al_4Cu_9, AlCu, Al_3Cu_4 [3][19][20][21]. Complex morphologies of Al-Cu are present in the seam because of rapid laser welding process from Cu-Al. Intermetallic structure II with dimensions in the range of 5-20 µm are in the interface region Fig. 9 (a) & (b). The interface of Cu-Al is rich of all variants of the Al-Cu intermetallic as reported in [17][21]. The dendritic structure II, of dimension about 4.4 µm is formed at the end of fusion zone as shown in Fig. 9 (c) and (d) close to the base metal Al.

4. Conclusion

In the laser welding of Cu-Al, the combined beam oscillation (infinite) and pulse modulation increase the ductility of the joint. In the configuration, with Copper on top, the inter-diffusion of Cu and Al is very high and most of the intermetallic phases are present in the weld seam. However, distribution of these phases over a larger weld width (by beam oscillation) leads to more ductile joint. A discontinuous interface with mixture of intermetallic rich fusion zone and fusion zone with limited intermetallic phases are beneficial for the mechanical resistance. Shaping the pulses i.e. power modulation with pulse time can influence the degree of intermixing and number of pores formed. Pulse shape A with defined preheat, active welding and cooling phase was found beneficial in both improving the shear strength and reducing the inter-diffusion with lower pores compared to square pulse D.

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