Lasers in Manufacturing Conference 2015

Influence of laser power modulation on the time-resolved temperature distribution in the weld pool during laser welding of copper to aluminum

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Abstract

Temperatures were measured with high temporal resolution of 0.1 ms at two positions on the weld pool surface simultaneously at distances of 1 mm and 2 mm behind the keyhole during disk laser welding of Cu-OF to Al99.5 in overlap configuration. The cw welding process shows inherent instabilities resulting in large periodic oscillations of the temperature signals at a rather broad frequency bandwidth between 15 Hz to 30 Hz. These instabilities can be suppressed when laser power modulation is applied at modulation frequencies between 100 Hz and 300 Hz. Thus, the welding process is dominated by the laser power modulation. This leads to a significantly reduced temperature fluctuation range (up to 70%) in this frequency range and the temperature signals as well as the temperature gradient oscillate mainly with the respective frequency of the laser power modulation. The influence of the laser power modulation is reduced at higher modulation frequencies and the characteristic instabilities of the cw welding process appear again but are still superimposed by the laser power modulation.

Keywords: laser welding, copper, aluminum, temperature measurement, dissimilar materials, laser power modulation

1. Introduction

The material combination of copper and aluminum is of increasing interest, especially in fields dealing with high electrical currents as e.g. in e-mobility, Walter et al., 2014. This requires appropriate joining technologies for these materials. Laser welding offers numerous advantages over conventional joining

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technologies such as higher flexibility, higher processing speed and higher productivity, Katayama, 2004. However, the formation of brittle intermetallic phases in the weld seam make laser welding of dissimilar metals a challenging task due to the reduced mechanical strength and electrical conductivity of these intermetallic phases, Katayama, 2004, Rabkin et al., 1970, Braunovic and Alexandrov, 1994. The mechanical strength of the weld seam depends on its crystallographic microstructure whose formation is influenced by the spatial and temporal temperature gradients during the solidification, Callister and Rethwisch, 2013, Kurz and Fisher, 1992.

2. Basics

2.1. Thermal radiation

Basis for non-contact temperature measurement is Planck's radiation law, Planck, 1901 which describes the temperature dependent spectral distribution of the thermal radiation of an ideal emitter, a so called black body. The emission characteristics of a real emitting body are considered by its emissivity ε_λ, Bernhardt, 2004. The signal, S_P, measured by a single band pyrometer

$$S_P(\lambda, T, \varepsilon) = C_{aq} \cdot \int_{\lambda_1}^{\lambda_2} L_{\lambda,s}(\lambda, T) \cdot \varepsilon_\lambda(\lambda, T) \cdot d\lambda \tag{1}$$

is proportional to the emitted radiance of the measurement object in the spectral range from λ_1 to λ_2 of the pyrometer. Where $L_{\lambda,s}$ is the spectral radiance of a black body and T the thermodynamic temperature. The acquisition constant C_{aq} considers the geometrical conditions as well as the acquisition parameters during the measurement. From Eq. (1) it can be seen that the temperature measured by a pyrometer also depends on the emissivity of the measurement object. Thus, for an accurate pyrometric temperature measurement the emissivity of the measurement object has to be known. In general, the emissivity is a material dependent property that also depends on temperature, wavelength, emission angle and surface condition. However, for most metals only few data of the emissivity and its temperature and wavelength dependence in the liquid phase are reported in literature and so is for copper and aluminum, Watanabe et al., 2003, Dausinger, 1995, Krishnan et al., 1990, Krishnan and Nordine, 1993. According to Krishnan et al., 1990 the emissivity of most liquid metals increases in the NIR with increasing temperature. If the emissivity considered for the measurements was lower than the actual emissivity of the measurement object, this would lead to an overestimation of the measured temperature. However, the actual increase of the emissivity of copper in the NIR with increasing temperature is not known.

3. Experimental setup

Laser welding of Cu-OF to Al99.5 was carried out in overlap configuration. Sheets with a thickness of 1 mm were used for both materials with the copper sheet always on top. The processing head was inclined by an angle of 10° with respect to the surface normal in trailing position in order to avoid damage to the processing optics by back reflected laser light. A sketch of the experimental setup is shown in Fig. 1(a). A TruDisk5001 disk laser with a wavelength of 1.03 µm and a maximum output power of 5 kW was used. The laser power was modulated sinusoidally with the average power of 3.5 kW and modulation amplitude of 1.5 kW kept constant and the modulation frequency varied between 0 Hz and 700 Hz, where 0 Hz denotes the cw welding process.

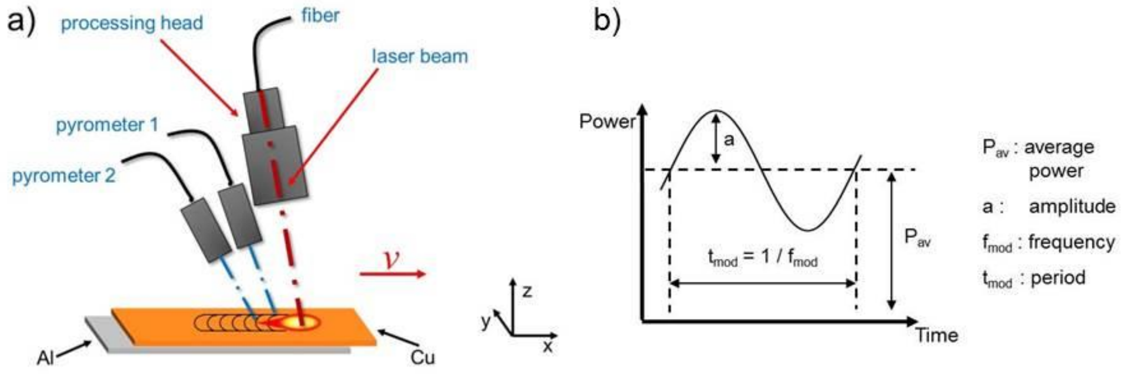


Fig. 1. (a) Experimental setup; (b) modulation parameters of the laser power modulation.

A definition of the modulation parameters of the laser power modulation is given in Fig. 1(b) and the welding parameters are summarized in Table 1. Two LASCON® pyrometers of Dr. Mergenthaler GmbH & Co. KG. were used for temperature measurements on the weld pool surface during the welding process. They were operated in single band measurement mode covering the wavelength range from 1.65 µm to 2.0 µm using InGaAs-diode-detectors. The sampling rate was 10 kHz and for each measurement point the signal was averaged over 0.2 ms. An emissivity value of the liquid copper of $\varepsilon_{Cu} = 0.07$ was taken for the pyrometric measurements, according to Watanabe et al., 2003 where the normal spectral emissivity of liquid copper at its melting point ($T_{M,Cu}$ = 1358 K, Haynes, 2013) was measured in the NIR. The pyrometers were calibrated for absolute temperature measurements using a black body calibration source.

The temperature was measured at two positions on the weld pool surface with pyrometer 1 oriented onto measurement position 1 at a distance of 1 mm behind the keyhole and pyrometer 2 oriented onto measurement position 2 at a distance of 2 mm behind the keyhole (Fig. 2). Pyrometer 1 and 2 were inclined against the surface normal by angles of 25° and 30°, respectively. The size of the measurement spots of the pyrometers was 400 µm in diameter and the data acquisition was synchronized between the two pyrometers.

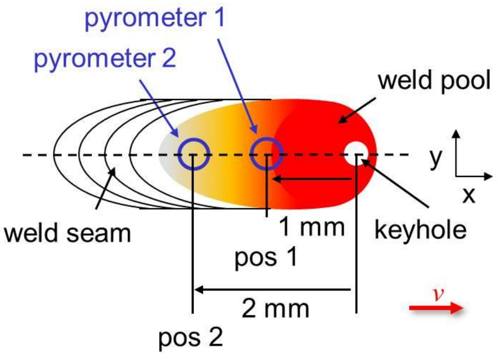


Fig. 2. Positions for process diagnostics.

Table 1. Welding parameters.

Parameter	value
Average power	3.5 kW
Amplitude	1.5 kW
Frequency	**0-700 Hz**
Feed rate	5 m/min
Focal position	0 mm
Rayleigh-length	6 mm
Fiber core diameter	200 µm
Focal length of focusing lens	300 mm
Spot diameter	350 µm

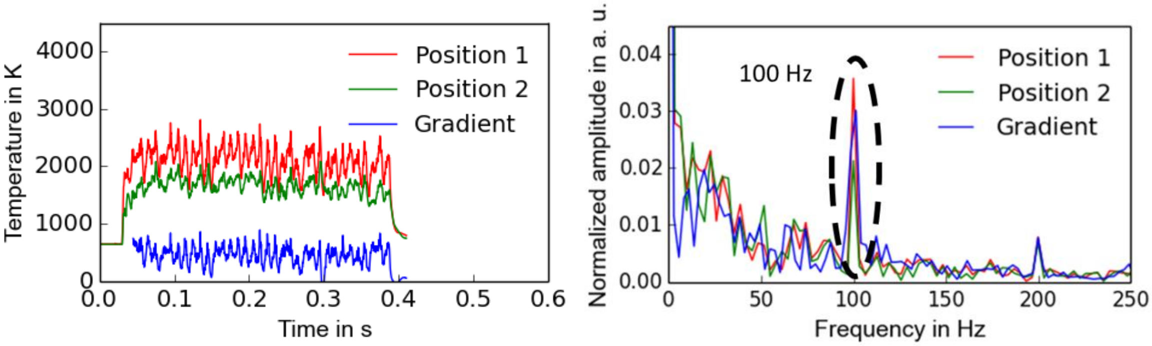
4. Results and discussion

For welding with a modulation frequency of the laser power of 50 Hz it has already been shown by Jarwitz et al., 2014 that the temperature signals in the weld pool and the respective temperature gradient oscillate with the respective frequency of the laser power modulation and these oscillations being more pronounced closer to the keyhole. The same behavior was seen for all modulation frequencies of the laser power which were investigated in this work. Fig. 3(a), left shows a typical result of time-resolved measurements of temperatures on the weld pool surface for a modulation frequency of the laser power of 100 Hz. The red and green curve show the temperatures measured at measurement position 1 and 2, the blue curve the respective temperature gradient between the two measurement positions. The results of the frequency analysis of the temperature signals (Fig. 3(a), right) by fast Fourier transform (FFT) show that the oscillations in the temperature signals are clearly dominated by a frequency of 100 Hz which corresponds to the modulation frequency of the laser power.

Hence, when laser power modulation is applied the welding process is clearly influenced by the laser power modulation and this can be measured in the temperature signals from the weld pool surface.

However, there also appear oscillations in the temperature signals on the weld pool surface and in the temperature gradient in the case of an unmodulated (cw) welding process (Fig. 3(b)). These oscillations appear to be rather periodic and not just random and are quite large in amplitude. But in this case there is no single, sharply defined frequency which dominates the oscillations of the temperature signals. Instead they show a broader bandwidth which significantly features the temperature signals. This characteristic bandwidth is seen at low frequencies between 15 Hz to 30 Hz (Fig. 3(b), right). This indicates that the cw welding process itself is not very stable but shows inherent instabilities leading to more or less periodic oscillations of the welding process at low frequencies. This behavior was seen to be especially pronounced when the penetration depth was in the transition range to penetration into the lower aluminum sheet.

(a) f_{mod} = 100 Hz



(b) cw

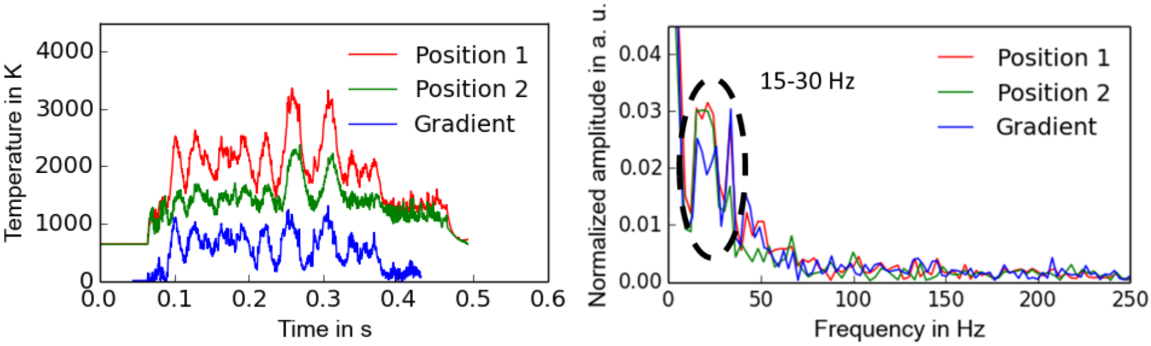


Fig. 3. Left: Temperature signals at both measurement positions and temperature gradient over time for one welding process. Right: Frequency spectra of the FFT analysis of the temperature signals. (a) P_{av} = 3.5 kW, a = 1.5 kW, f_{mod} = 100 Hz, v = 5 m/min. (b) P_{av} = 3.5 kW, cw, v = 5 m/min.

The normalized amplitudes of the oscillations of the temperature signals were obtained by FFT analysis of the temperature signals. Fig. 4 shows the experimental results of the normalized amplitude of the temperature signals obtained by FFT analysis at the respective modulation frequency of the laser power. This will be referred to as the oscillation amplitude in the following. The oscillation amplitude shows a strong decrease with increasing modulation frequency for both measurement positions and for the temperature gradient up to a modulation frequency of 150 Hz. It is decreasing by 70% at measurement position 1 and by 74% at measurement position 2 and is always higher at measurement position 1 than at measurement position 2 up to a modulation frequency of 300 Hz. The experiments show an almost constant oscillation amplitude at modulation frequencies between 150 Hz and 300 Hz. At modulation frequencies higher than 300 Hz the oscillation amplitude is then decreasing again.

These results indicate that the influence of the laser power modulation on the temperature distribution of the welding process decreases with increasing modulation frequency and is higher at distances closer to the keyhole.

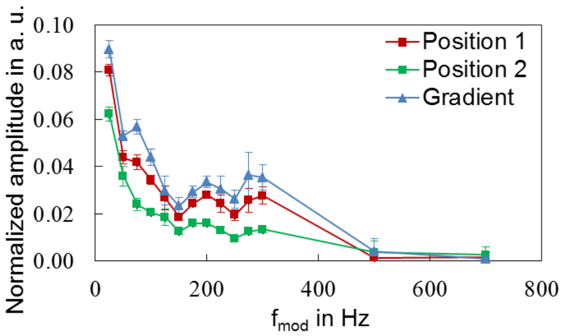


Fig. 4. Normalized amplitude of temperature signals at modulation frequency of laser power from FFT analysis. P_{av} = 3.5 kW, a = 1.5 kW, v = 5 m/min.

The difference between the 80th-percentile and 20th-percentile of the temperature signals (Fig. 5 left) is taken as a measure of the amplitude range of the entire oscillations of the temperature signals and will be referred to as the temperature fluctuation range (TFR) of the temperature signals in the following. The TFR is quite large in the case of cw welding with about 1100 K at 1 mm and 450 K at 2 mm distance behind the keyhole and shows even a slight increase when laser power modulation is applied at a modulation frequency of 25 Hz (Fig. 5 right). At further increase of the modulation frequency the TFR is then decreasing up to a modulation frequency of 100 Hz and stays almost constant up to a modulation frequency of 300 Hz. In the frequency range between 100 Hz and 300 Hz it has its lowest values with about 300 K at position 1 and about 230 K at position 2 which is a reduction of the TFR of about 70% and 50% compared to the cw welding process. The TFR is increasing again at modulation frequencies higher than 300 Hz.

Consequently, when laser power modulation is applied this leads to a significantly reduced temperature fluctuation range compared to cw welding, especially at modulation frequencies between 100 Hz and 300 Hz. The increase in temperature fluctuation range at a modulation frequency of 25 Hz might be caused by the inherent oscillations of the cw welding process in the frequency range between 15 Hz to 30 Hz which might be amplified when the laser power is modulated within this frequency range.

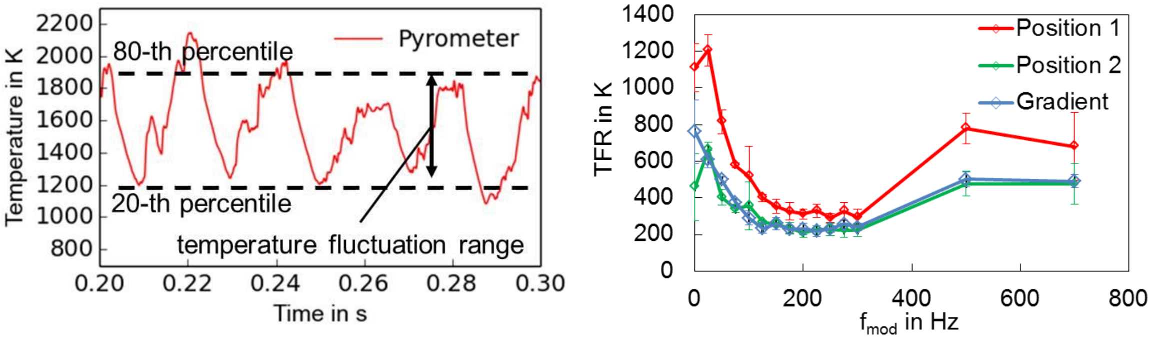


Fig. 5. Left: Definition of the temperature fluctuation range (TFR). Right: Temperature fluctuation range (TFR) of the temperature signals at measurement position 1 (red) and 2 (green) and of the temperature gradient (blue) in dependence of the modulation frequency of the laser power. P_{av} = 3.5 kW, a = 1.5 kW, v = 5 m/min.

However, the oscillation amplitude is reduced further at modulation frequencies higher than 300 Hz in contrast to the temperature fluctuation range which is increasing again. Hence, there must be some other effect leading to this further increase of the TFR at modulation frequencies higher than 300 Hz. At these higher modulation frequencies the measured temperature signals show again large periodic oscillations at low frequencies comparable to the cw welding process, but they are superimposed by periodic oscillations at the frequency of the laser power modulation.

Thus, the inherent instability characteristics of the cw welding process appear again at higher modulation frequencies but are superimposed by the laser power modulation. This also confirms that the influence of the laser power modulation decreases at higher modulation frequencies represented by the modulation at 500 Hz and 700 Hz.

5. Conclusion

The cw welding process of copper to aluminum shows inherent instabilities which lead to large periodic oscillations in the temperature signals in the frequency range between 15 Hz to 30 Hz. These instabilities can be suppressed when laser power modulation is applied at modulation frequencies between 100 Hz and 300 Hz where the welding process is dominated by the laser power modulation. The temperature signals and the temperature gradient oscillate mainly with the respective frequency of the laser power modulation which leads to a significantly reduced temperature fluctuation range (up to 70%). The influence of the laser power modulation on the welding process decreases with increasing modulation frequency. The instability characteristics of the cw welding process become dominant again at these higher modulation frequencies but are still superimposed by the laser power modulation.

Acknowledgements

All the investigations were accomplished in the context of the project “ReMiLas” which is funded by the Federal Ministry of Education and Research (BMBF). The responsibility for this paper is taken by the authors.

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