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Laser welding of copper alloys using a pulsed laser source at a green wavelength

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Abstract

Welding of copper with solid state lasers is a challenging issue in electronics production. Different requirements have to be fulfilled with respect to the welding process to meet industrial quality standards. Particular attention is paid to the formation of spatters, since they can induce a short circuit in circuit boards. Therefore, a stable, spatter-free process must be provided. Using infrared laser radiation, only a small fraction of the energy is absorbed by the copper material during the welding process. As a consequence, process instabilities occur. Using green laser radiation is a promising approach, since the absorptivity of copper materials is significantly higher at green wavelengths. Different studies have already shown an improvement of the process stability compared to infrared solid state lasers. As frequency doubling is restricted to low average laser powers, only thin sheets could be welded until now. In this paper, experimental investigations are presented to identify suitable welding strategies for low spatter welding of copper alloys in lap joint configuration. A prototype of a pulsed green laser with a pulse power of 4000 W was used to weld 0.8 mm thick pure copper to 0.8 mm thick sheets of a copper alloy. Different welding strategies, e.g. non-overlapping and overlapping spots, were considered. A spatter detection was developed to evaluate the process stability during the welding process. For this purpose, an industrial camera with a high frame rate was mounted to the scanning optics to record the process through the optical path. The recorded process pictures were evaluated by a machine vision algorithm to count the spatters for each parameter set and welding strategy. Using a full factorial design of experiments, the influence of the welding parameters on the spatter formation, the electrical resistance, and the mechanical strength of the weld seam were analysed.

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1. Introduction

Driven by the increasing electrification of automobiles, good and reliable joining technologies for copper materials become more important. On the one hand, a precise and flexible process is required. On the other hand, good mechanical and electrical properties of the joint must be ensured. For this, laser welding is a suitable process. Nevertheless, laser welding of copper with state-of-the-art solid state lasers is a challenging task since copper has a low absorptivity at infrared wavelengths. Further issues are the high heat conductivity as well as high and unstable melt pool dynamics, which can be linked to melt ejections. In electronics production, these effects have to be minimized. The absorptivity of copper is considerably higher at green wavelengths compared to infrared laser radiation. However, frequency doubling is limited to low average powers. Hence, laser welding at green wavelengths was restricted to thin sheets. To counteract this, a prototype of a pulsed laser at a green wavelength was used for this study. Moreover, a simple spatter detection was developed and validated to evaluate the spatter formation. Afterwards, a suitable welding strategy was identified for an overlap joint of pure copper (CW004A) and CuCrAgFeTiSi.

2. State of the art

2.1. Copper welding

Kaplan and Powell derived a threshold to describe the process of spatter formation during laser welding for a material with the density ρ [1], see equation 1:

$$\rho v_z^2 > \frac{2\sigma}{R} \tag{1}$$

If twice the quotient of the surface tension σ and the curvature of the melt pool R is smaller than the vertical component of momentum ρv_z^2, spatters can be detached from the molten metal [1]. To provide a better keyhole dynamics to reduce the vertical velocity v_z in copper welding or to increase the quotient, different approaches were developed to weld copper.

Multi-mode lasers are commonly used to weld copper in industry. Liebl et al. investigated the process stability of copper welding with multi-mode fibre lasers [2]. The influence of different feed rates and shielding gases was examined. Low feed rates led to melt ejections and an unstable process, whereas high feed rates resulted in a stable process and non-porous weld seams. The use of helium as shielding gas increases the surface tension and the process limitations are shifted towards lower feed rates. Furthermore, the weld seam geometry is changed to a wider weld seam and a lower penetration depth. [2]

To improve the process (stability), the influence of laser power modulation was analysed by Heider et al., Mehlmann, and Lee et al. [3][4][5]. The keyhole was stabilised by applying a sinusoidal modulation of the laser power. Thus, the number of melt ejections could be reduced significantly [3]. Despite this, more pores can occur during the welding process, if the modulation frequency is too low [3][6]. Laser welding with beam oscillation also improves the process stability for copper welding. A spatter-free process can be achieved for circular oscillations and suitable sets of parameters [4][5]. Lee et al. account this to the fast movement of the keyhole. Furthermore, a better absorptivity can be obtained by using single-mode fibre lasers with small spot diameters, since they provide up to tenfold higher intensities [4].

SCHMITZ compared various pulsed welding strategies to contact cylindrical lithium-ion battery cells [6]. As a minimum heat input is desired, pulsed laser welding was chosen to contact nickel-plated steel samples (hilumin). Despite of affecting the total joint area, the resistance showed no dependency on the welding strategy. In contrast to this, the ultimate tensile strength is depending on the connected area. The sloping pulse which was performed as a SHADOW® (Stepless High Speed Accurate and Discrete One Pulse Welding) weld seam showed the highest tensile strength [6]. The advantages of the SHADOW® or also called long pulse welding strategy and conventional spot welding were compared by OLOWINSKY ET AL. [7]. Applying this strategy in combination with small circles, the weld depth showed a linear behaviour for an increasing power. Apart from a reduced heat input, the peak power could be reduced. Furthermore, fewer weld defects and a better surface quality were achieved. [7]

Besides the high melt pool dynamics, the low absorptivity of copper for infrared laser radiation in the solid phase is a challenging issue. Measurements of ENGLER ET AL. and RAMSAYER ET AL. [8][9] showed a lower absorption of infrared laser light compared to green laser light in both, solid and liquid phase. Concerning the efficiency of deep penetration welding of copper materials, an absorptivity of up to 70 – 80 % of the laser energy was measured for both wavelengths [8]. GANSER ET AL. measured an absorptivity of 45.5 % for pure copper (CW008A) in the near-infrared spectrum [10].

HESS ET AL. and RUETTIMANN ET AL. investigated a hybrid process that consists of a high power solid state laser and a low power frequency doubled laser at a green wavelength. Using a preceding focused beam of green laser radiation leads to an increased absorption or ideally to a small domain of molten material [11]. For this configuration, the deep penetration threshold can be reduced [11][12]. In contrast, a subsequent beam reduces the amount of melt ejections [11].

KAISER ET AL. carried out a comparative study for pulsed laser welding at green and infrared laser wavelengths [13]. The transition to deep penetration welding was reached faster when applying green laser radiation, opposed to infrared laser radiation. Furthermore, reproducible and uniform weld spots could be guaranteed. Shielding gases like argon or nitrogen improve the grain structure, whereas spatter formation could not be reduced [13]. A spatter-free process up to a material thickness of 1 mm was observed for pure copper (SE-Cu) using a pulse shape, see figure 1.

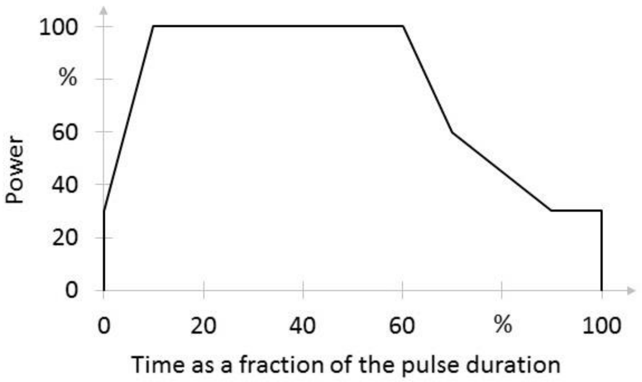

Fig. 1. Pulse shape for a spatter-free welding process developed by KAISER ET AL. [13]

The influence of the weld seam geometry for overlap joints with respect to the electrical resistance was examined by BRAND ET AL. to provide a good electrical connection for batteries [14]. Pure copper (CW008A) and pure aluminium EN AW-1050 showed a hyperbolic decrease of the resistance for an increasing ratio of weld seam length to specimen width. The resistance of the joint could be reduced to the level of the base material when a second seam was welded in a sufficient distance. Moreover, an enhancement of the electrical conductivity for wider weld seams is only observed for small ratios of weld seam length to specimen width. [14]

2.2. Spatter detection

Assessing the process stability of the presented approaches is carried out in varying ways. ENGLER ET AL. and RAMSAYER ET AL. evaluated the weld seam´s surface by eye [8][9]. In contrast, SCHWEIER ET AL. used an automated image processing algorithm to evaluate the spatter formation in laser welding of stainless steel with beam oscillation [15]. Thereby, the high-speed camera was arranged parallel to the scanning optics. Applying a multihypothesis tracking, multiple counts of spatters were avoided. HAUBOLD ET AL. published an automated validation method for a spatter detection by computer vision algorithms [16]. For this, images with a known number of spatters are desired. In order to avoid counting spatters by eye, an approach to generate artificial spatter images was presented [16].

2.3. Objective and approach

Due to the rapid development of electric vehicles, a robust and reliable copper welding process is in great demand by the automotive industry. To cope with high currents, thicker materials as well as suitable joining technologies have to be used. Only a few spatters and a uniform weld seam for thin sheets could be achieved in previous studies using a laser source at a green wavelength. Thicker materials were welded in this study by applying frequency doubled and pulsed laser sources. A combination of pure copper and a copper alloy with an overall thickness of 1.6 mm was used since pure copper itself has poor mechanical properties. A high-power frequency doubled pulsed laser was used; the study focused on spatter formation, electrical resistance, and mechanical strength.

3. Experimental setup

All experiments were carried out with a frequency doubled prototype laser of TRUMPF Laser GmbH, Schramberg, Germany. Therefore, a fibre-guided system consisting of a TruDisk Pulse 421 and a programmable focusing optics (PFO) 20 was used. The chosen parameters are listed in table 1. The spatters were recorded by an industrial camera of the type ace acA640-750uc from Basler AG, Ahrensburg, Germany. A framerate of 751 fps with a resolution of 640 px to 480 px was provided. With this resolution one pixel is equivalent to 12.5 µm. In contrast to the setup of SCHWEIER ET AL., the interface designed for process monitoring of the focusing optics was used for the high-speed camera. As a consequence, the line of vision is coaxial to the laser beam, see figure 2. Furthermore, a camera lens and a band-pass filter were not necessary. Limited by the internal memory of the used computer, 7200 pictures were taken for each parameter set during the welding process. The specimens of 50 mm by 50 mm were welded in an overlap joint configuration with pure copper (CW004A) above the chosen copper alloy CuCrAgFeTiSi. The specimen geometry and the contact points of the clamping device are shown in figure 2.

Table 1. Properties of the laser source and the focusing optics

Parameter	Number	Unit
Peak power	4000	W
Maximum pulse duration	10	ms
Average power (cw)	400	W
Wavelength	515	nm
Focal length of the focusing lense	264	mm
Focal length of the collimation lense	90	mm
Beam diameter in focus (86-%-criterion)	305	µm
Angle of incidence	0	°

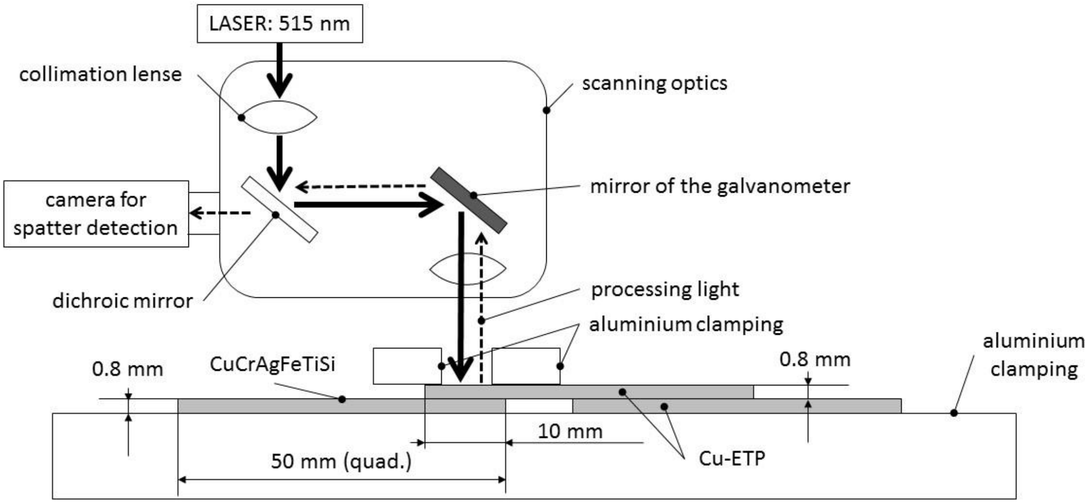

Fig. 2. Experimental setup

4. Spatter detection

4.1. Algorithm

An automated spatter detection was done to count the spatters. Since it has a high computational expense, the image processing was done after the welding. For this purpose, an algorithm was implemented using the software Halcon 11 of MVTec GmbH, Munich, Germany. After acquiring the pictures, the laser spot was identified using the blue component of the (RGB) picture to avoid interfering effects due to weld fumes. Since the melt pool cannot be distinguished from a spatter by the algorithm, the area of the laser spot and previous spot welds was masked. Afterwards, a spatter detection and counting was carried out by a threshold operation in the red and green part of the picture. It was assumed that there is no multiple counting of spatters due to the low frame rate. The classification number K_S is defined as a function of the counted spatters n_S and the recorded length of the weld seam l_r, see equation 2:

$$K_S = \frac{n_S}{l_r} \tag{2}$$

The recorded length can be calculated as shown in equation 3, with the number of taken pictures n_P, the feed rate v_s and the frame rate of the camera f_C:

$$l_r = v_s \cdot \frac{n_P}{f_C} \tag{3}$$

The feed rate for a pulsed laser process is given by the beam diameter d, the repetition rate of the laser f_L, and the overlap of the spot welds $\bar{O}$, see equation 4:

$$v_s = d \cdot f_L \cdot (1 - \bar{O}) \tag{4}$$

4.2. Validation

To prove the quality of the spatter detection, the validation method presented by HAUBOLD ET AL. was used. Therefore, the spatter detection was applied to the artificial images of HAUBOLD ET AL. As the spot is already masked in those pictures, the algorithm was adapted to this circumstance. The threshold for spatter detection was taken from the real experiments. Each number of spatters was evaluated based on five pictures. For non-overlapping spatters, the error of not detected ones is illustrated in figure 3. The error is defined as the difference between predetermined and detected spatters.

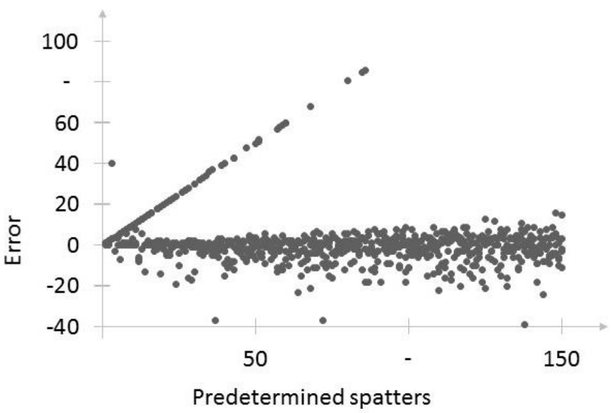

Fig. 3. Error of not detected non-overlapping spatters

The error shows an almost constant behaviour for an increasing number of spatters. The fluctuation for increasing numbers of spatters is higher. Furthermore, figure 3 reveals that there are too many spatters detected as negative errors. The linearly ascending error can be referred to an inappropriate threshold, since the threshold values are taken from the experimental setup.

5. Design of experiments

5.1. Factorial designs

Two full factorial designs of experiments were developed for spot welding. The first factorial design considers the laser peak power, pulse duration, and spot diameter, see table 2. The laser power, pulse duration, repetition rate, and overlap of the spot welds were taken into account in the second experimental design, see table 3. For both designs, the pulse shape of KAISER ET AL. according to figure 1 was applied, since it influences spatter formation positively. Referring to KAISER ET AL., a shielding gas was not used, since no positive effect on the spatter formation was observed.

Table 2. Design of experiments for a constant repetition rate of 13 Hz and a pulse shape according to figure (1)

Parameter	Minimum	Maximum	Unit
Peak power	3500	4000	W
Pulse duration	8	10	ms
Spot diameter	564	720	µm

Table 3. Design of experiments for a constant spot diameter of 720 µm and a pulse shape according to figure (1)

Parameter	Minimum	Maximum	Unit
Peak power	3500	4000	W
Pulse duration	8	10	ms
Repetition rate	8	13	Hz
Overlap of spot welds	0.43	0.82	-

5.2. Evaluation

A main effect plot was used for the analysis, since the influences and the associated tendencies are clearly visible. This plot was calculated by averaging the values for each increment of the analysed parameter. Afterwards, a linear interpolation between the determined points was performed.

6. Results and discussion

6.1. Spatter formation

For spot welding, different behaviours of spatter formation can be observed for the investigated combination of pure copper (CW004A) and CuCrAgFeTiSi. The main effects plot for the experimental design of non-overlapping spot welds is shown in figure 4. It is obvious that a higher power and pulse duration increase the number of spatters. In contrast, an increasing spot diameter reduces the quantity of spatters significantly.

The main effects plot for spot welds with overlap reveals a similar behaviour, see figure 5. For an increasing peak power, pulse duration, repetition rate, and overlap, the heat input is increased and a significant spatter formation can be observed. Furthermore, the number of melt ejections for overlapping spots is significantly higher than for non-overlapping spots.

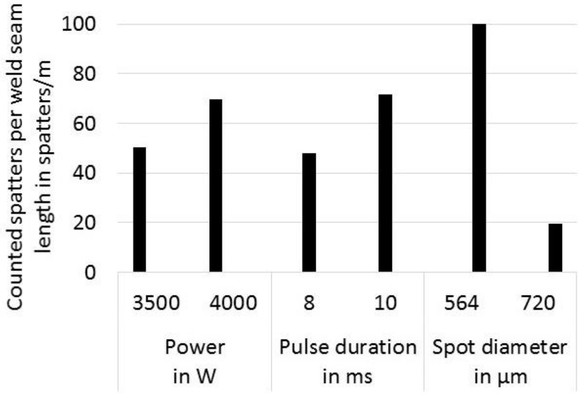

Fig .4. Main effects plot with respect to spatter formation for the experimental design for spot welds without overlap

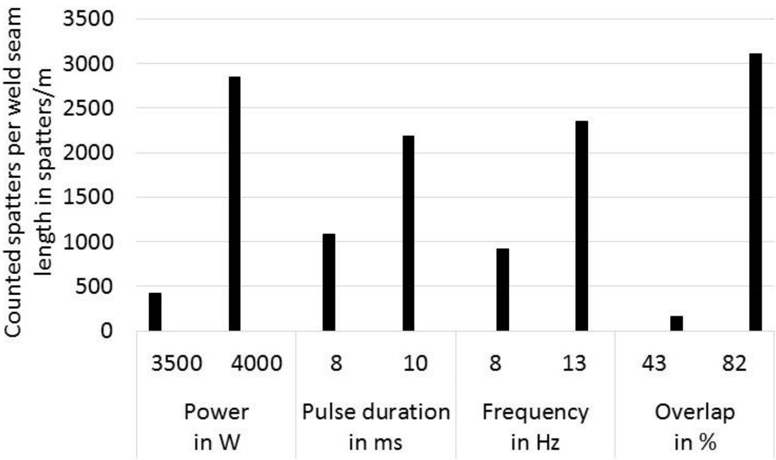

Fig. 5. Main effects plot with respect to spatter formation for the experimental design with overlapping spot welds

6.2. Electrical properties

The electrical resistance was measured by four-terminal sensing according to Brand et al. to determine the electric conductivity which is shown in figure 6 for both experimental designs. Applying a higher heat input, a larger total joint area was observed. Referring to the results of Brand et al., the conductivity increased for higher total joint areas. However, for a bigger spot diameter, the total joint area and the electric conductivity was reduced. An enhanced electric conductivity was also achieved for an enlarged heat input for overlapping spot welds. In general, the measured resistances were about 3 % higher for non-overlapping spot welds than for overlapping ones. Furthermore, it is obvious for both experimental designs that the request for good electrical properties is in direct contradiction to a lower spatter formation.

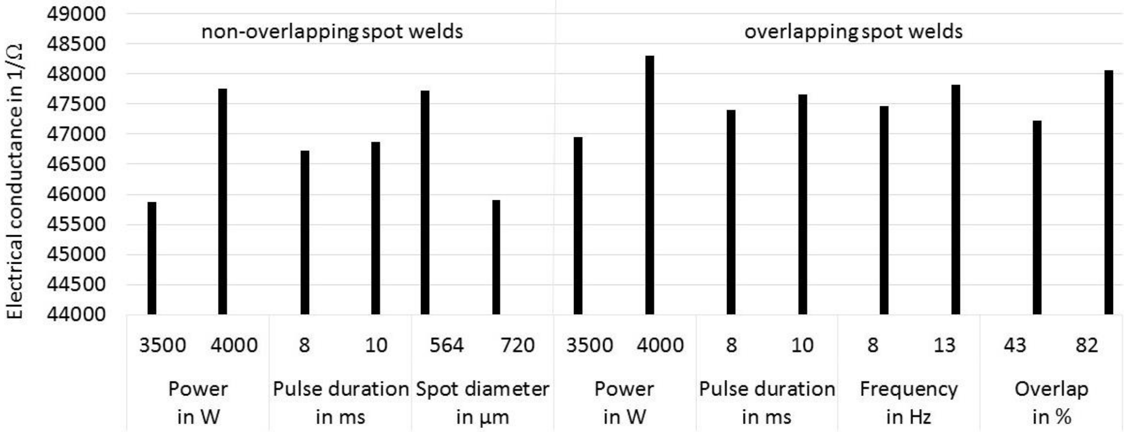

Fig. 6. Main effects plot with respect to electrical conductance for pure copper (CW004A) and CuCrAgFeTiSi

6.3. Mechanical properties

The main effects plot for the maximum tensile force, which was measured by a shear tensile test, for non-overlapping spot welds was shown in figure 7. An similar behaviour to the electric conductivity was observed. As mentioned before, high heat inputs result in a larger total joint area. It is apparent from this that the mechanical strength depends on the total joint area. An almost similar behaviour with exception of the overlap is presented for overlapping spot welds in figure 7. This negative effect of an increasing overlap on the mechanical strength can be referred to a more frequent fusing of the material. However, the maximum tensile forces are enhanced by about 25 % for overlapping spot welds.

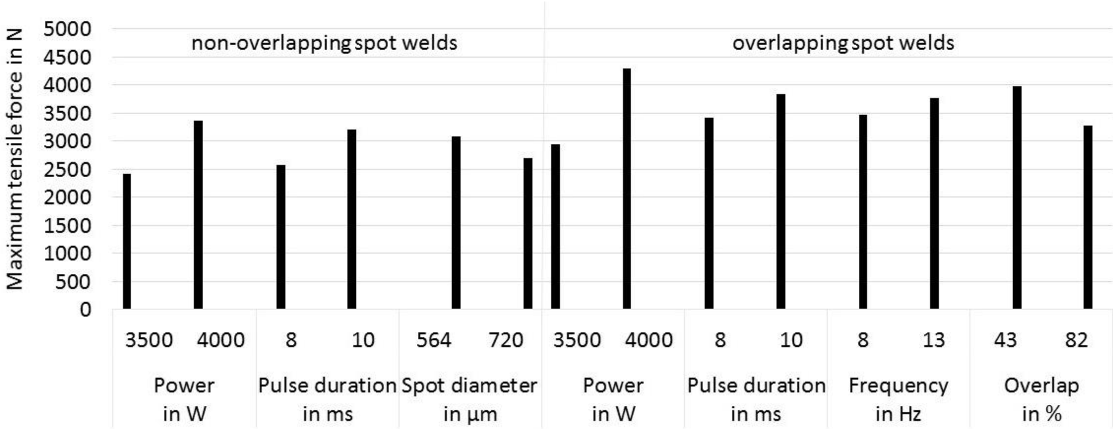

Fig. 7. Main effects plot with respect to mechanical strength for pure copper (CW004A) and CuCrAgFeTiSi

7. Conclusion

An economic and accurate method for spatter detection in pulsed laser welding processes has been presented. After a validation, this approach has been applied to a spot welding process. Using this spatter detection, a material combination of pure copper (CW004A) and CuCrAgFeTiSi in overlap joint configuration has been evaluated with respect to spatter formation, electrical resistance, and mechanical strength. Spot welds without overlap showed the best results, since the spatter formation is considerably reduced compared to overlapping spot welds. Furthermore, similar and sufficient properties with respect to mechanical strength and electrical resistance can be achieved.

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