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Reliable Copper Spot Welding with IR Laser Radiation through Short Prepulsing

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Abstract

We demonstrate a technique, which significantly enhances the stability of copper welding with laser radiation. After modelling spot welding stability we conclude that oxide layer morphology typical for native oxide layers has to be avoided. We locally normalize the surface oxidation degree using laser pulses in the nanosecond pulse duration regime (short prepulsing). Thereby, the absorptivity is reliably increased, setting uniform starting conditions for laser welding. A process window is identified, where all experimental repetitions lead to successful welds. With prepulsing, the spot weld diameter variation is decreased to 2% and the necessary welding energy is decreased up to 40%.

Keywords: Copper; Welding; Stability; Reliability; Laser; Prepulsing

1. Introduction

Copper is used in all areas of electronics for its high electrical conductivity. The best conductivity is achieved with nonalloy, i.e. pure copper. However, this type of copper also has properties leading to a very low welding reliability when welding with IR laser radiation: The absorption degree for IR laser radiation is small (~3%) and varies significantly (~17%) even on a single work piece [1]. As a consequence, the laser energy input into the work piece varies for each weld. This can lead to melt ejection or lack of melt volume if too much or insufficient energy is introduced [1-3].

Welding other metals with laser radiation has become established for many applications [4], where the advantages of lasers as a heat source are needed.

For copper spot welding with IR laser radiation, the process stability has to be improved. Frequency doubled ('green') spot welding laser sources are proven to be beneficial in this regard. However, the required pulse properties limit the technical feasibility to low laser powers: Green spot welding lasers are available with a mean power of up to 5 W, whereas IR spot welding lasers have a mean power of up to 500 W.

While short and ultrashort pulsed laser material processing is known to be reliable for practically any given material [5], copper spot welding with IR laser sources lacks stability and has to be better understood.

We develop a basic model for spot welding stability and oxide layer influence on absorptivity. We derive a concept for increasing spot welding stability and verify the results with analyses and welding experiments.

2. Modelling spot welding stability

Although the lack of process stability in copper spot welding with IR laser radiation is widely known, the reasons have only been discussed at a rudimentary level. To understand the relevant mechanisms, a theoretical stability model is proposed.

In the case of copper, the absorptivity of laser radiation is an example of a varying specimen property

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[1] and is particularly evaluated for modelling spot welding stability.

The time t_m required to heat the work piece surface to melting temperature with a given heat source is defined by the work piece properties W_i, like geometry, heat conductivity, heat capacity and absorptivity. A distinct property of laser spot welding of copper is that melting time t_m is typically in the same order of magnitude as the total processing time. Therefore, changes in melting time due to varying material properties lead to varying welding results.

The central idea to achieve a formalized expression for spot weld stability is to evaluate the variation of melting time $\delta_i t_m$ upon changing process and work piece properties W_i

$$\delta_i\, t_m = \frac{\partial t_m}{\partial W_i}. \tag{1}$$

With the total processing time τ, the stability coefficient S_i is defined by

$$S_i = 1 - |\delta_i t_m| \frac{W_i}{\tau} = 1 - \left|\frac{\partial t_m}{\partial W_i}\right| \frac{W_i}{\tau}, \tag{2}$$

where a stable condition is achieved if $S_i \longrightarrow 1$.

2.1. Application to absorptivity change and 1D heat conduction case

To characterize the stability coefficient, the melting time t_m is expressed formally. Therefore, different analytical solutions for the general heat conductivity equation can be used. We choose the transient solution of the surface temperature for a semi-infinite plate [6]. The surface temperature evolution is a function of time t, ambient temperature T_0, laser absorptivity A, laser intensity I, heat conductivity λ and thermal diffusivity $\kappa = \frac{\lambda}{\rho\, c_P}$, with mass density ρ and heat capacity c_P:

$$T(t) - T_0 = \frac{A\, I}{\lambda}\sqrt{\frac{4\,\kappa}{\pi} t} \;\Rightarrow\; t_m = \frac{(T_m - T_0)^2\, \lambda^2}{A^2\, I^2\, \kappa}\frac{\pi}{4}, \tag{3}$$

with the time t_m to reach melting temperature. Using the expression for t_m and evaluating for the absorptivity A, Equation 2 leads to the stability coefficient S_A with

$$S_A = 1 - \left|\frac{\partial t_m}{\partial A}\right| \frac{A}{\tau} = 1 - \frac{1}{2}\pi \left|\frac{c_P (T_m - T_0)^2\, \lambda\, \rho}{A^2\, I^2\, \tau}\right|. \tag{4}$$

In order to compare different materials with each other, we define the material factor M, reducing the expression to

$$S_A = 1 - \frac{1}{2}\pi \left|\frac{M}{A^2\, I^2\, \tau}\right|, \quad M = c_P\, (T_m - T_0)^2\, \lambda\, \rho. \tag{5}$$

With $S_A \sim 1 - \left|\frac{M}{A^2\, I^2\, \tau}\right|$ it is clear that the stability is increased by a high laser intensity I, a small material factor M, a high absorptivity A or a long pulse duration τ. Increasing the laser intensity I is a limited measure for welding stability, since melt expulsion is increased and the process is shifted towards laser drilling.

Figure 1 shows the stability coefficient as a function of the absorptivity for copper, iron and aluminium for a typical spot welding parameter set (laser power 1500 W, pulse duration 1 ms, laser spot diameter 100 µm).

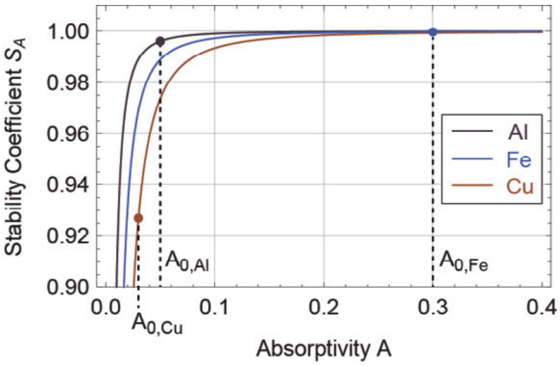

Fig. 1: Stability coefficient S_A as a function of absorptivity for copper, iron and aluminium. Bullet points mark the values at natural absorption degrees of the respective materials ($\lambda_{IR} = 1064\, nm$, $P_{IR} = 1500\, W$, $\tau_{IR} = 1\, ms$, $d_{IR} = 100\, \mu m$).

The stability coefficient functions of all shown materials show a distinct positive slope at an absorptivity of up to 5 %. With a higher absorptivity, the stability S_A of all materials converges towards 100 %. This indicates that given a high enough absorptivity, all shown materials could be processed reliably. However, the absorptivity is usually fixed and is material dependant (native absorptivity). In Figure 1 the bullet points mark the materials stabilities at the respective native absorptivity for the laser wavelength λ=1064 nm. Here, S_A for copper features a distinctively smaller value compared to aluminium and iron in accordance to common knowledge about copper welding with laser radiation.

3. Spot welding stability as a function of discrete oxide layers

In order to examine the relationship between oxide layer thickness and spot welding stability, an absorptivity model is developed. Taking into account Snell's law, the Fresnel equations and using the algebraic method described by Sernelius [7] the absorption of light in a multilayer system can be calculated. For most technical cases, native oxide layers between 1nm and 5nm thickness [8] can be assumed which usually consist of Cu_2O [9]. Therefore, the reflectivity is calculated for a varying oxide thickness assuming a structure of semi-infinite Cu, finite Cu_2O and semi-infinite air. The calculations account for partial reflections, interference and attenuation due to volume absorption.

The absorptivity as a function of oxide layer thickness is used in Equation 5. In Figure 2 and Figure 3 the stability coefficient S_A is shown as a function of Cu_2O thickness and incident laser intensity. The results are as expected, since a distinct difference between the 532 nm and the 1064 nm welding stability is visible.

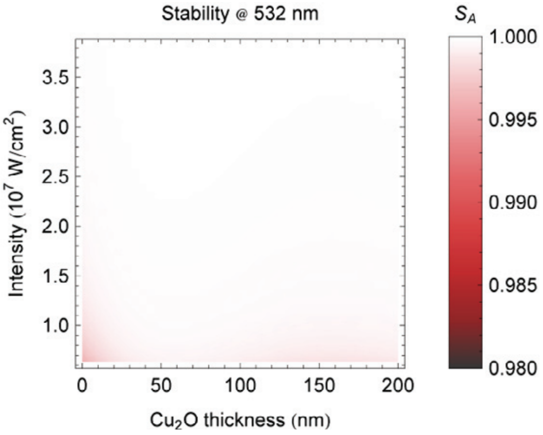

Fig. 2: Stability coefficient S_A for copper welding with 532 nm radiation as a function of Cu_2O thickness and laser intensity (pulse duration $\tau = 1\ ms$).

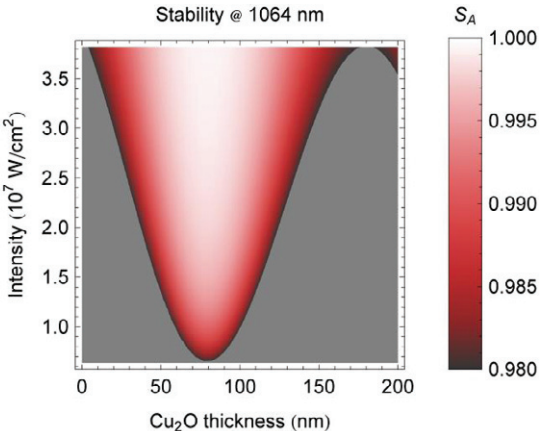

Fig. 3: Stability coefficient S_A for copper welding with 1064 nm radiation as a function of Cu_2O thickness and laser intensity. Gray area depicts $S_A < 0.98$ (pulse duration $\tau = 1\ ms$).

While welding with 532 nm radiation shows very high values of S_A for all shown oxide layer thickness and laser intensity combinations, welding with 1064 nm radiation shows distinct stability oscillations over increasing oxide layer thickness. If the oxide layer thickness is below 50 nm, as with native oxide layers, the stability is significantly low. Confirming empirical knowledge, increased laser intensity shows increased stability. However, increasing laser intensity is also known to lead to melt expulsion and drilling behavior.

As a consequence, it seems reasonable to avoid oxide removal measures as weld preparation, like polishing, wet etching or plasma etching. Here, ambient oxygen could quickly cause oxide formations in the 10 nm thickness range. Instead, oxide layers could potentially enhance spot welding stability, if their formation is properly controlled.

4. Welding concept and experimental setup

The key concept for enhancing laser spot welding stability is reliably controlling the initial absorptivity by controlling the oxide layer thickness. For this, an additional short laser pulse (prepulse) is used prior to welding. The prepulse irradiates the copper surface, reliably setting uniform starting conditions for the subsequent laser welding process (Figure 4).

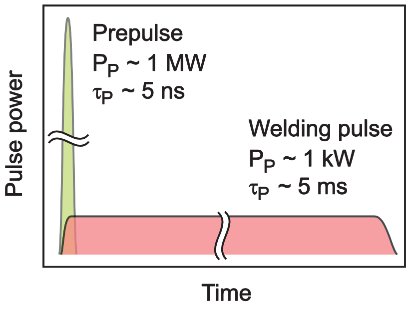

Fig. 4: Concept of prepulse welding

The duration of the prepulse is in the nanosecond regime. Typical pulse energies and pulse powers are in the order of 1 mJ and 1 MW respectively. Compared to the subsequent welding pulse, the prepulse features far less energy yet a far higher pulse power.

The laser sources used in the scope of this paper are shown in Table 1:

Table 1: Laser sources and used parameters for prepulsing and welding.

	Rofin Powerline SHG	neoLASE Prepulse Prototype	LASAG SLS-200 CL16
Purpose	Prepulsing, energy variation	Prepulsing, designated system	Spot welding
Wavelength	532 nm	526 nm	1064 nm
Pulse energy	0.05-0.25 mJ	0.6 mJ	0.5-10 J
Spot size	40 µm	40-70 µm	122 µm

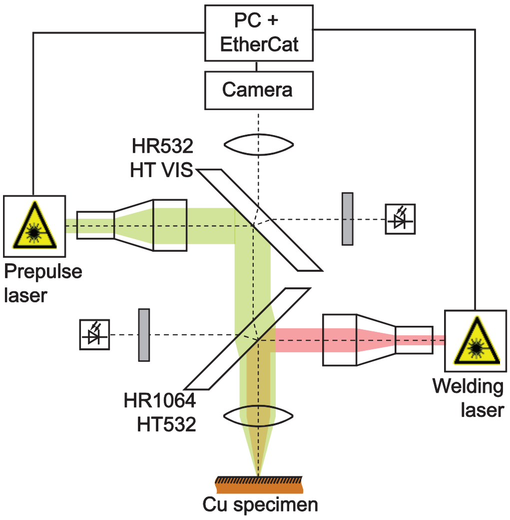

Fig. 5: Sketch of experimental setup for radiation combination and synchronization of two lasers.

In Figure 5 a sketch of the experimental setup is shown. The main aim of the setup is to combine and provide relative adjustment of the laser spots of two laser sources. Also a PC with an EtherCAT bus is used as a common control system in order to enable synchronization of the two laser sources or a controlled timing delay. The shown setup is used for combining the neoLASE prototype laser and the LASAG welding laser. Prepulsing with the Rofin Powerline laser is performed separately.

5. Prepulse analyses

In order to examine the influence of the morphology of the prepulse irradiation on subsequent laser welding, experimental analyses are performed.

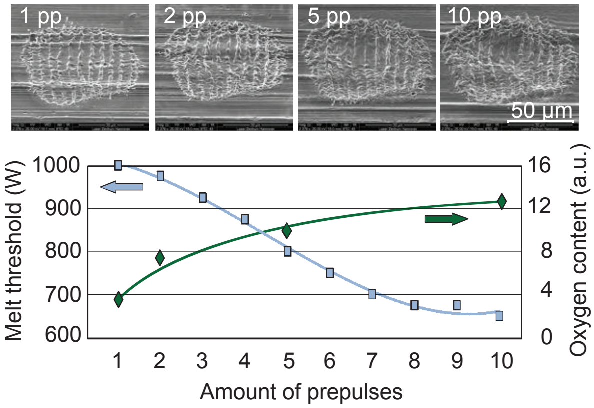

Fig. 6: SEM pictures of repeated prepulse irradiations on E-Cu58 (top), subsequent IR-laser melt threshold and oxygen content (bottom). (Prepulse parameters: $\lambda_{pp} = 526\,nm$, $E_{pp} = 0.6\,mJ$, $\tau_{pp} = 3\,ns$, $2w_0 = 70\,\mu m$. IR-laser: $\lambda_{IR} = 1064\,nm$, $\tau_{IR} = 1\,ms$.)

After surface irradiation with different amounts of prepulses, the minimum IR-laser power that is needed for initiating a phase change is acquired experimentally (melt threshold). Samples with a different amount of prepulse irradiations have also been examined with EDX. The results are shown in Figure 6.

The observed topography of the prepulse irradiation corresponds to the laser intensity distribution and does not seem to change significantly with an increasing amount of prepulse irradiations. However, for an increasing amount of prepulses a continuous melt threshold drop is observed, meaning that the prepulse effect is accumulating. Also, the EDX analyses of the prepulse irradiated samples show a continuous rise of the oxygen content. These new observations lead to the assumption that the topography is not dominantly responsible for the melt threshold drop. Instead, a correlation between oxygen content and melt threshold power is likely present.

It is confidently assumed that the increasing oxygen content observed is due to a superficial laser induced copper oxide formation. The oxide layers seem to increase IR-laser absorption.

In order to support the melt threshold investigations and explicitly identify the absorptivity change through prepulsing, calorimetric absorption measurements have been performed in accordance to ISO 11551:2003. Here, laser radiation is applied and the specimen temperature rise, which is less than 3 K, is evaluated (Figure 13).

Directly after polishing, all copper specimen feature 3 % absorptivity for 1064 nm radiation. After polishing and prepulse irradiation, the absorptivity is increased to approximately 30 %.

The results confirm a relationship between laser induced change of absorptivity and oxygen content.

6. Welding with laser prepulse

6.1. Melt initiation

The first noticeable observation when using prepulsing is that the weld spots become significantly more regular. In Figure 7 the results of spot welding attempts are shown without changing the welding laser parameters.

Prepulsing prior to spot welding seems to lead to regular weld spots. For better evaluation, this investigation is repeated for different IR laser parameters.

In Figure 8 the pulse power and the pulse duration of the welding laser are varied and the percentage S of successful melt initiation is depicted, based on 200 repetitions.

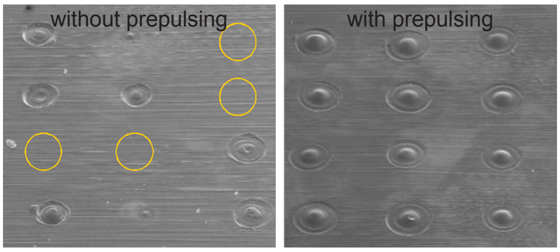

Fig.7: SEM images of spot welding results without (left) and with prepulsing (right). (Welding parameters: $\lambda_{IR} = 1064\,nm$, $E_{IR} = 2.4\,J$, $\tau_{IR} = 2\,ms$, prepulse parameters : $\lambda_{pp} = 526\,nm$, $E_{pp} = 0.6\,mJ$, $\tau_{pp} = 3\,ns$, $2w_0 = 40\,\mu m$)

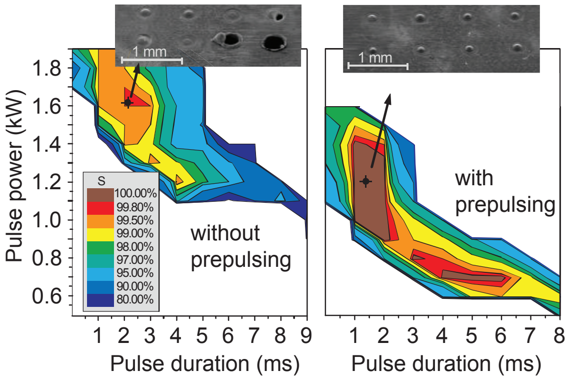

Fig. 8: Percentage S of melt initiation over 200 repetitions for different pulse durations and pulse powers of the IR welding laser, without prepulsing (left) and with prepulsing (right). (Prepulse parameters : $\lambda_{pp} = 526\,nm$, $E_{pp} = 0.6\,mJ$, $\tau_{pp} = 3\,ns$, $2w_0 = 40\,\mu m$)

Without prepulsing, combinations of pulse duration and pulse power are found where up to 99.8 % of the weld attempts lead to melt initiation. However, the whole process window with S>90% shows sporadic melt expulsion too, leading to drilling instead of welding.

With prepulsing, a large process window is acquired, where all spot welding attempts lead to melt initiation without observing drilling characteristics.

6.2. Spot weld diameters

The issues of energy coupling accuracy and reduced power requirements are investigated in further detail by evaluating the diameters of spot welds for different laser parameters (Figure 9). By using prepulsing the average spot weld diameter is increased and the standard deviation is decreased. For example, with the welding parameters P=1.3 kW and τ = 2 ms, the mean diameter is increased from 180 µm to 250 µm and the standard deviation is decreased from 100 µm to 15 µm when using prepulsing.

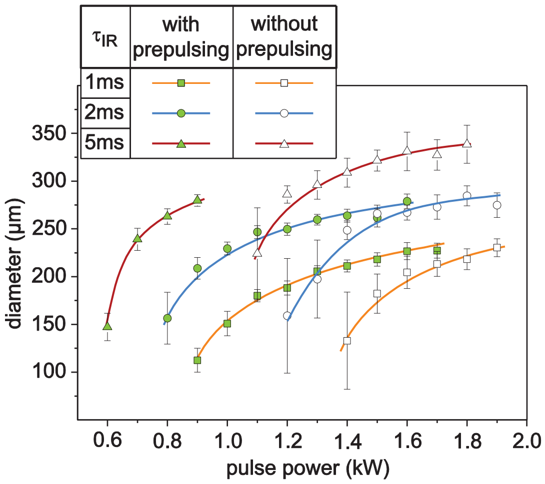

Fig. 9: Average diameters and standard deviations (60 repetitions) of spot welds on copper without prepulsing and with prepulsing for different laser parameters (E-Cu58, thickness 80µm, prepulse parameters : $\lambda_{pp} = 526\,nm$, $E_{pp} = 0.6\,mJ$, $\tau_{pp} = 3\,ns$, $2w_0 = 40\,\mu m$).

With respect to spot weld diameters, when using prepulsing, the IR laser power can be reduced by up to 40 %.

A timing delay between prepulse and welding pulse in the order of several seconds up to one day does not seem to have a significant effect on the mean spot weld diameter and the standard deviation.

7. Discussion

Through prepulsing, both absorptivity increase and welding stability improvement are observed. Causality between these two observations is very likely, since the theoretically derived stability coefficient shows a monotone increase over absorptivity (Figure 10).

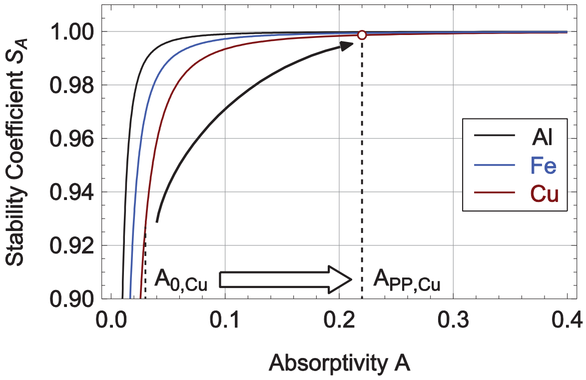

Fig. 10: Stability coefficient functions for different materials over absorptivity and influence of changing copper native absorptivity $A_{0,Cu}$ to a higher value $A_{PP,Cu}$ through prepulsing (welding parameters: $\lambda_{IR} = 1064\,nm$, $P_{IR} = 1500\,W$, $\tau_{IR} = 1\,ms$, $d_{IR} = 100\,\mu m$).

Taking into account the definition of the stability coefficient and the experimental results, the following causal relationships can be assumed:

- Small changes in native oxide layer thickness are causing large changes in absorptivity.
- Due to large changes in absorptivity the energy input during laser welding is varying significantly, causing poor welding process stability.
- Prepulsing is generating oxide layers with larger thickness compared to native oxide layers and/or with smaller thickness variations.
- Both larger oxide layer thickness and smaller thickness variations result in a smaller variation of absorptivity.
- Smaller change of absorptivity results in more consistent welding results.

8. Summary

Although oxide layers are generally considered disadvantageous for laser welding stability, we present a unique method where oxide layers are used as an asset for stability.

First, we define the stability coefficient S_A which evaluates process change, described by the melting time, on absorptivity change and which is a function of material and process properties. By modelling the oxide layer influence on the absorptivity, the laser spot welding stability as a function of oxide layers is derived.

The results are in accordance to empirical observations during laser spot welding of copper: Given a low absorptivity, native oxide layers which typically have thicknesses below 50 nm lead to poor spot welding stability. It also means that oxide removal measures prior to welding might not have the desired effect, if not performed reliably, strictly avoiding subsequent native oxidation.

As a consequence, instead of oxide removal measures, the key concept enhancing laser spot welding stability is controlling the initial absorptivity by controlling the initial oxide layer thickness. For this, an additional short pulsed laser is used prior to welding (prepulse). Thereby, the absorptivity is increased reliably. For example, a prepulse energy of $E_{pp} =$ 0.25 mJ and pulse duration of $\tau_{pp}=$ 5 ns increases the absorptivity of polished copper from 3 % to 30 %, improving the starting conditions for the subsequent laser welding process.

Copper spot welding with prepulsing shows the following advantages:

- In a wide parameter range all of the repetitions within the scope of this work lead to successful spot welds.
- The weld diameter variation is decreased to 2 %.
- The required laser power can be reduced by 20 % to 40 %.

The technique of prepulsing can be realized with any of the well-established spot welding IR lasers, only requiring an additional prepulsing laser source. The additional prepulsing laser only adds less than 20 % to the investment costs, which is acceptable given the shown stability improvement.

8.1. Outlook

Although spot welding stability is already achieved and the relevant mechanisms are understood, laser induced surface oxidation should be investigated further. The copper oxide thickness and composition will be analyzed with TEM, EBSD and AR-XPS for different prepulse laser parameters. The samples will also be characterized with absorptivity measurements.

Acknowledgements

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