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Closed loop control for laser micro spot welding using fast pyrometer systems

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Abstract

Laser micro spot welding offers temperature resistant high strength contacts without filler material. However, due to varying surface absorption properties of copper, the welding quality shows poor reproducibility.

To stabilize the process we set up a power control for laser micro spot welding of copper. It consists of a high speed pyrometer and an external micro controller. The subject of the investigations is to apply a constant energy amount using conduction welding to increase the process stability. Using the closed loop control, the standard deviation of pull force for overlap welds is reduced from 3.3N to 1.3N.

Keywords: process sensing and controlling; pyrometers; copper; joining; micro spot welding

1. Introduction

The stimulation of renewable energy systems like solar technology and the constant demands for optimized electronic components (haptics, flexibility, size, resistance etc.) out of automotive and entertainment industry lead to market growth regardless of the economic crisis. For example the average annual market growth of flexible printed circuits (FPC) which are used in many automotive and consumer electronics is about 7% with rising tendency [1]. In these applications conventional joining techniques such as reflow-soldering or ultrasonic welding often reach their limits as they put the components under mechanical and thermal stress [1], [2]. The high joining temperatures used in lead free soldering also prohibit the application of cost-effective base materials like Polyethylenterephthalat (PET) in FPC production [1].

As a competing joining technique laser spot welding offers zero-force joining and locally and temporally well defined thermal input. The applied energy affects just a small area of the component particularly only the metal layer. Furthermore no filler material is needed so that the recycling process is simplified and the contact achieves the strength and thermal resistance of the base material. Although good welding results are obtained when welding steel

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there is still a backlog demand regarding process stability hence welding quality when welding copper alloys. These instabilities do particularly appear due to the high reflectivity and good thermal conductivity of copper [3], [4]. The thermal conductivity is about 26 times higher than the one of steel while the absorptance at the laser wavelength of 1064nm is up to 22 times lower [5], [6] and [7]. These facts necessitate a high energy density to create accumulation of heat and thus initiate the welding process. Nevertheless the absorptance shows a strong rise as melting is initiated. The laser power has to be reduced instantly to avoid boiling and thus spatter.

Furthermore the absorptance of copper varies depending on surface quality like oxidation, scratches or contamination (oil etc.) [8]. Due to this the time to melt ignition also varies. With constant laser parameters, a higher absorption at the beginning of the process leads to fast melting and higher temperatures at the pulses end. The heat often exceeds the evaporation temperature and the conduction welding process is transferred to deep penetration welding with increased melt pool dynamics which causes spatter and damage of the substrate. A high process stability will increase the acceptance for existing applications and bring laser spot micro welding into new application fields [9], [10]. The attempts to stabilize the process can be divided in beam guidance and closed loop controls based on optical measurements.

In so called SHADOW®-welding the laser beam is also guided over the work piece during one pulse by a scanner or a fast axis, to distribute the energy on a larger area. This reduces overheating of the melt pool and spatter [3], [11]. SHADOW® welding can help improving the process but this is a passive method which can not react to changing surface qualities or influence of interaction between welding points only separated by a small distance (e.g. debris). Conventional single spot welding enables better miniaturization compared to SHADOW®-welding and smaller pulse duration and therefore lower thermal stress to the substrate.

In order to react on varying surface qualities, closed loop controls of the laser power can prevent overheating. They predominantly use optical measurements to analyze process emissions. In order to use the signal for the control, its behavior must be in relation to the state of the process and the signal-noise-ratio (SNR) has to be high. Because of its strong SNR, recent studies detect the discontinuity of the reflected laser wavelength during the phase change when melting starts [12], [13], [14]. So far these systems could not reach a noticeable penetration in industrial applications. Another disadvantage is found in the principle of the control as it reacts to the initiation of melting. For high laser peak powers and small welding parts the response time of the laser might be to long and lead to spatter or destruction of the work piece.

To detect process phases before melting, pyrometers are used. We discuss the potential of fast online process control for micro spot laser welding using one-color and two-color pyrometers. A numerical simulation and empirical measurements help understanding the behavior of the control system. The quality of the produced welds was evaluated using tensile strength tests.

2. Experimental setup

The control loop includes a Nd:YAG-laser, an external real time controller, a pyrometer and the optical components to guide the laser beam and the process emissions. For the investigations a pulsed Nd:YAG-laser with a maximum peak power of 5kW and maximum pulse length of 20ms is used. The laser contains an internal control loop which measures the present laser power with a frequency of 20kHz, to keep the peak power at its preselected level. The laser is used to weld pure copper strips in dummy welds and overlap welding. A numerical simulation of the welding process is done to get a better understanding of the process behavior and the resulting heat distribution. For the numerical simulation of the process, the temperature dependent values were taken into account as there are the absorptance, density, specific heat and thermal conductivity of the copper. The laser focus which is 0.4mm in diameter is guided to the middle of the copper strips of 2mm widths and 20mm length. The thickness of the strips is 0.15mm for the dummy welds and two times 0.1mm for the overlap welds (figure 1). They are fixed on 20mm length using an aluminum clamping device with a 2mm aperture for the welding zone on top and bottom of the copper strips.

The laser radiation is guided to the work piece with a high reflective mirror (figure 2). The residual radiation is transmitted through the laser mirror. The near infrared process emissions above 1064nm are guided to the pyrometer via glass fiber which creates a measuring spot size of 0.5mm.

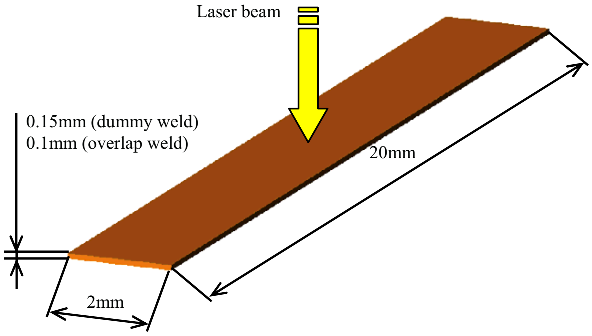

Fig. 1. Weld geometry copper strips

The pyrometer was developed by *Jencontrol GmbH* in cooperation with the LZH. It includes a notch filter at 1064nm to avoid any influence of back reflected laser light. A part of the process light is guided to fast photo diodes (rise time less than 50µs) with band pass filters (1550±24.5nm and 1620±24.5nm). The wavelengths were chosen with a minimal gap and small bandwidths so that the influence of the emissivity can be neglected when the ratio is generated (figure 2). The setup detects a lower temperature limit of 650°C.

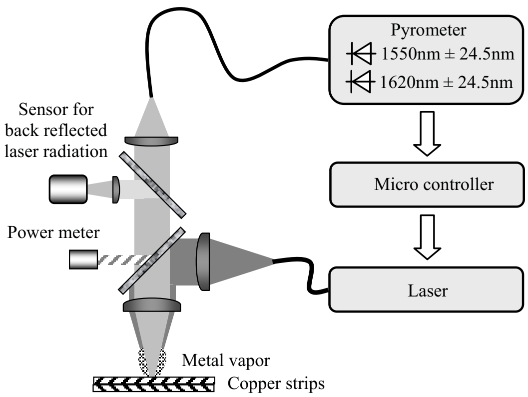

Fig. 2. Closed loop control setup

For a reliable process control, the signal to render the process status should have a high signal-noise-ratio and a direct relation to the process state. To evaluate the suitability for certain wavelengths of the process emissions we analyze the radiation at the pyrometer wavelengths and the reflected laser light. The response time of the laser source is measured, to define the parameters for the controller. The signals of the pyrometer are sent to a 16Bit real time (40MHz) micro controller where the correcting variable to control the laser source is calculated. The laser source contains an input to control the peak power and another one to instantly stop the process.

3. Experimental Results

The time and energy required for welding and the time segment from pulse start to initiation of melting is analyzed. With these values the external control loop is set up and tested in overlap welding. The welding results are evaluated by tensile strength tests.

3.1. Laser reaction time

To analyze the rise and fall time of the laser source for adjusting the external controller, a frequency modulator is used as signal input to the peak power control of the laser. The signals are analyzed for 3kw, 3.5kW, 4kW and 4.5kW with 40 measurements at each peak power value for a statistical evaluation. The time section from the controller signal to reduce the power to the reaction of the laser is tested (figure 3, response time). Figure 3 shows the signal input of the frequency modulator (P_i) and the reaction of the laser at 4kW peak power. The noise is caused by the internal control loop of the laser. The mean response time to an external signal is measured to 130µs. Due to the exponential character of the power signal, the fall time (90%-10%) increases with increasing peak power to values of over 0.8ms. The total laser delay results from a response time plus a fall time (100%-0%). With this time the additional energy which is applied to the work piece and thus the temperature rise remaining due to the delay of the Nd:YAG-laser is calculated. For example the total reaction time (signal input to 0% power) results in 23% additional energy amount for a peak power of 4kW and a laser pulse duration of 2ms.

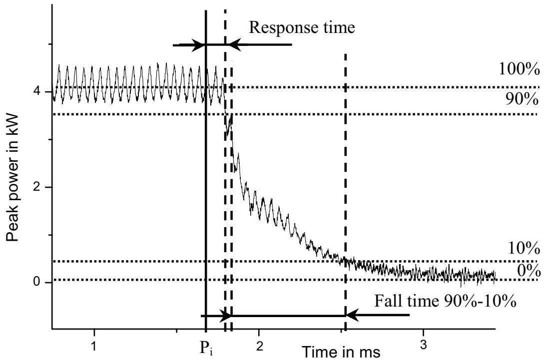

Fig. 3. Control signal and response of the pulsed Nd:YAG-laser

The signal to instantly stop the process is also analyzed and measured with a main response time of 30µs and fall times (100%-10%) of 100µs. This makes the resulting additional energy amount 10 times lower compared to the peak power control signal. For this reasons we choose a combination of the peak power input to control the laser and the stop signal to end the process after the required energy amount is applied to the work piece. Due to the internal control loop and the delay of the laser reduction the energy of each laser pulse varies depending on the laser peak power. As it is quite reproducible it can be estimated and taken into account to bring a constant energy amount to the work piece. This requires a constant process behavior. The behavior is analyzed regarding initiation of melting and resulting time and process sections.

3.2. Signal character of the pyrometer measurement and time sequence to melting initiation

To get empirical values of the time period Δt from the beginning of the laser pulse t_0 to the melting of the copper t_m, the pyrometer signal is analyzed as shown in figure 4. Additionally, the signal height h_m of the pyrometer signal at melting point is measured to get a fix point to adjust the threshold of the control loop below this point. The signals at each laser peak power are analyzed with 40 measurements for statistical evaluation and standard deviation. The analysis is done with blind welds on copper strips of 150µm thickness starting with a laser power of 4.5kW and 4ms pulse length. As the peak power is reduced the pulse length is increased to assure melting.

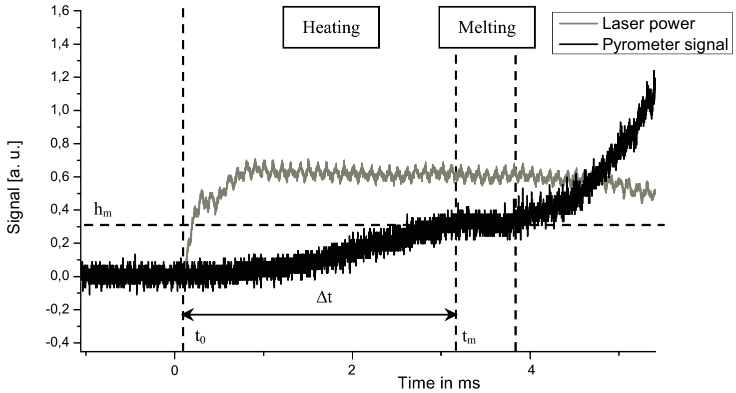

Fig. 4. Detection of melting time

In the phase of heating the pyrometer signal rises until the melting point is reached and the melting enthalpy has to be overcome. This time section is shown in the horizontal course of the pyrometer signal in figure 4. After the melting phase there is a fast rise of the signal until it reaches a section with typical high fluctuation caused by the rising metal vapor pressure, shielding of the signal and the fluctuation of the melt pool. As we use the control loop to keep the process in the conduction welding mode, these signal fluctuations are not reached.

Figure 5 shows the time sections Δt at different laser peak powers with their maximum, minimum and mean values. The standard deviation of Δt increases significantly to lower peak powers. As the melting point of copper (1083°C) is already reached after the average value of 1.7ms and the absorptance rises significantly after this point, a fast change of the signal and thus unstable process appears. The smallest standard deviation is measured for 4.5kW. But even at this high peak power Δt shows a high variation among 40 samples with 1.2ms for the fastest melting initiation and 2.1ms for the slowest one, which means a time difference of 0.9ms. Using the numerical simulation we calculate a temperature boost of 2000K for this time difference which would cause high evaporation rates without process control. To achieve a high reproducibility of the welding results a process control should be used. The smallest standard deviation in signal height when melting is initiated is also measured at a laser peak power of 4.5kW. If this value is taken as a threshold value high peak powers will improves the results of the control loop.

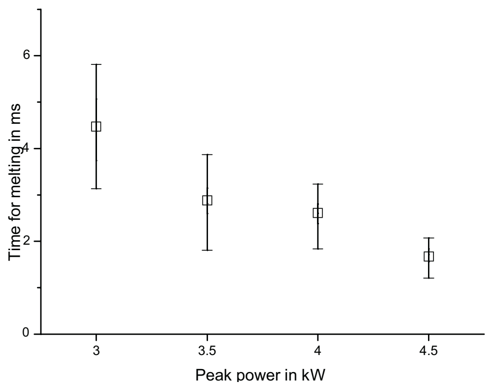

Fig. 5. Time section Δt pulse start t_0 to melting initiation t_m

3.3. Closed loop control with one-color pyrometer

As compensation to the variation in melting initiation, the pyrometer signal is used as actual value for the closed loop control to get a constant energy amount applied to the work piece. Using the set up shown in figure 1 a closed loop control is set up with a one-color pyrometer measurement and the combination of peak power control, limited remaining pulse duration and fast process abort. In our control loop we set a threshold for the pyrometer signal which is below the signal of the melting point. Due to changing absorptance the time from pulse start to this point varies. If the threshold is reached, the pyrometer signal is used as online control during the pulse. At the same time a counter is set to control the remaining pulse duration to get constant energy amounts applied to the work piece. The essential time for the remaining pulse duration depends on the laser and material parameters and has to be calculated using simulation or has to be empirically determined.

The process control is used for overlap welds of copper strips with 100µm thickness. A peak power of 4.5kW is set as start value until the preselected threshold value for the control is reached.

The welding quality is analyzed with tensile strength tests.

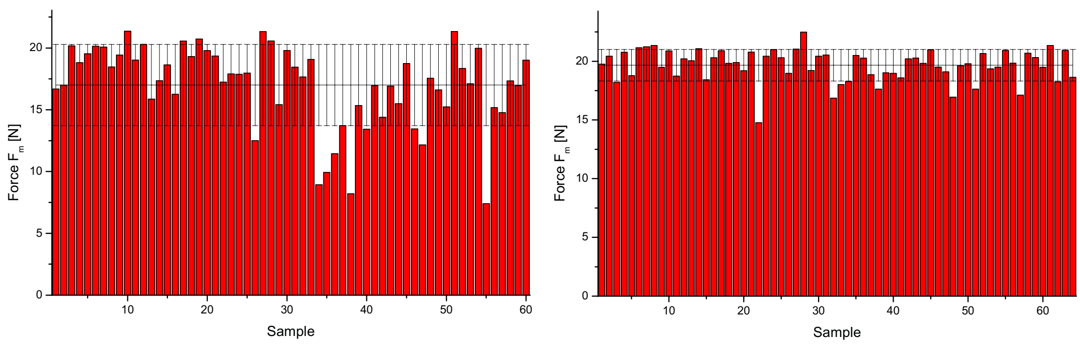

Fig. 6. Pull test without process control (left chart) und with process control (right chart)

The results of the tensile strength tests with and without process control are shown in figure 6. With control the standard deviation of the force was reduced from 3.3N to 1.3N, which means a reduction of more than 60%. These results show a significant quality improvement. As the signal heights at melting initiation still vary and thus influence the control loop the use of a ratio pyrometer will improve the signals as the changing emissivity has no influence on the pyrometer signal (temperature height) to the controller.

4. Conclusion and outlook

When welding copper strips with a pulsed Nd:YAG-laser without process control we recognize a high variance of the melting initiation which causes welding defects and thus poor reproducibility. A smaller standard deviation of the time is achieved at high peak power of the laser and short pulses which thus would cause less stress to the substrate material if electronic components are welded.

With the fast pyrometer process values below the melting temperature are detected. This enables to compensate the laser delay especially at high peak power and thus fast temperature rise of the melting pool.

Using it as a one-color pyrometer, we improved the process stability as we achieved more than 60% lower standard deviation in tensile strength for overlap welds of 100µm copper strips. Nevertheless, the signals taken by photodiodes at different wavelengths show a strong variance caused by changing emissivity or material layers. This fact complicates the adjustment of the process control to suitable thresholds. To withdraw this disadvantage and to be independent of changes in emissivity at lower laser power, ratio pyrometry is analyzed. In contrast to the control loop using one-color pyrometry the ratio pyrometer enables a control even at lower peak power with high variance of radiance. By measuring the temperature with the ratio pyrometer a direct determination of the process condition is realized. The possibility of temperature measurement within one laser pulse has already been analyzed and shows promising results even for small melting pools and thus little process emissions (e. g.welding of wires). The next step will be the integration of the ratio pyrometer within the control loop. With the measurement of a concrete direct process value it will also minimize adjustment times at different welding geometries and parts and improve the reproducibility of the welding results.

Acknowledgement

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