Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 56 (2014) 750 – 758

Physics Procedia

8th International Conference on Photonic Technologies LANE 2014

Tailored Beam Shaping for Laser Spot Joining of Highly Conductive Thin Foils

Kerstin Funck[a,]*, Ralf Nett[a], Andreas Ostendorf[a]

[a]*Laser Application Technology, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum,Germany*

Abstract

Laser spot joining of thin metallic foils in the order of 100 micrometer and below has a number of interesting applications in electronic industry. However, high thermal conductivity and thermal expansion of common materials largely prohibit spot joints with a sufficiently large contact area needed to satisfy mechanical and electrical requirements. Of the numerous possibilities to positively influence the process of such joints we investigate using a pulsed Nd:YAG laser to generate spot joints of thin foils in combination with a beam shaping optic to tailor the temperature profile during laser spot joining of thin foils. This allows for increased contact area, stabilized process behavior and offers the potential for joining ultra thin foils far below 100 µm. Different configurations are examined, results are presented and discussed, mainly in terms of their general impact on the micro joining process.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: Laser spot welding; thin foils; beam shaping; aluminum

1. Introduction

Joining of highly conductive materials such as aluminum and copper is a key application in the electronic industry. With increasing miniaturization joining of thin foils (in the range of 100 µm and below) has a rising demand and is of particular interest in consumer electronics, solar cell and battery manufacture. Here, electrical

* Corresponding author. Tel.: +49-234-32-23915 .
E-mail address: kowalick@lat.rub.de

1875-3892
Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2014.08.082

contacts with low electrical resistance and sufficient mechanical strength of the joints need to be produced with high precision and great reliability.

Laser spot joints have some significant advantages for the aforementioned applications: they allow precise local contacting and introduce only a small amount of energy. This minimizes the thermal load and avoids damage of neighboring structures. For optimal electrical and mechanical properties joint dimensions need to be large enough to reduce resistance and increase strength. Hence, for thin foils the lateral dimension of spot joints become much larger than typical foil thicknesses resulting in aspect ratios well below one which is quite unusual for most laser joining applications. The most common laser system for small scale (micro) application is still the Nd:YAG laser.

The challenges associated with laser spot joining of highly conductive thin foils fall into three major categories: process dynamics, material properties and aspect ratio. Spot joints, by nature, are characterized by a high dynamic with high heating and cooling rates and a temperature profile that never reaches a steady state. Yet, it is precisely these parameters as well as convection behavior which determine the quality of spot welds [1]. To positively influence the process in recent years, studies deal with the influence and manipulation of surface tension gradients e.g. by changing composition and orientation of process gases [2,3,4]. Good results could also be achieved using temporal pulse modulation to control the final microstructure, to overcome brittle phases as well as low laser coupling efficiency [5,6]. In most laser joining applications the light is focused to a point or circle using a fiber to guide the laser light. Using a multimode fiber coupled to the laser and imaging the facet of the fiber onto the sample gives a fairly homogeneous circular intensity distribution often called a top-hat or, if particularly homogeneous, a flat-top profile.

For very thin foils and small aspect ratios energy transport mostly occurs in the radial direction of the substrate. As electronic materials generally have high thermal conductivities this results in a very high lateral heat transport leading to a bell shaped temperature profile in spite of a spatially homogenous laser spot intensity distribution. For aluminum with an high thermal conductivity the temperature profile exaggerates rapidly over time as the degree of laser absorption rises with the increasing temperature of the material [7]. This increases the absorbed energy in the central parts of a laser spot which are already hotter and heats up the center even quicker. As a result, the melting point in the spot center is quickly reached. Due to very small melt volume of foils with thicknesses below 100 µm as well as tolerances in the air gap between foils (for overlap joints) there is a very fine line between acceptable joints and holes.

We have found that for an Nd:YAG laser system with millisecond pulses and comparably large top-hat focus (> 200 µm diameter) a pulse modulation alone does not suffice to stabilize the process. A solution could be the application of rapid control systems involving process observation of temperature and/or melt pool size. With typical processing times of a few milliseconds this appears to be very complex and challenging. Kawahito et al. have demonstrated a similar control based on evaluation of the reflected laser intensity [8].

In contrast to these approaches, we propose using beam shaping to manipulate the laser spot intensity profile (e.g. a ring shaped intensity distribution) as a means to improve process stability. While ring shaped intensity profiles or fast scanning are sometimes used to created ring shaped joints [9], we have not seen the application of such intensity profiles in order to deal with the thermal management of highly conductive material in laser spot joining. Choosing ring diameter and ring width appropriately it is possible to generate a more homogeneous temperature profile or even a temperature dip in the center. However, a more homogenous temperature profile may reduce Marangoni convection. Resulting effects on the joining process will be discussed subsequently.

2. Motivation for laser beam shaping

Focusing a laser spot with a top-hat intensity distribution on the surface of a sample, as is typically done, results in a washed-out temperature profile as is schematically shown in Fig. 1. For thin foils which are smaller than the thermal diffusion length δ_{therm}, heat transport occurs predominantly in the radial direction. For typical pulse durations of τ = 3 milliseconds the thermal diffusion length [6] in aluminum is larger than 1 mm and is calculated using

$$\delta_{therm} = \sqrt{4 \cdot \kappa \cdot \tau} \tag{1}$$

Here, κ is the thermal diffusivity which for aluminum amounts to 98.8e-6 m^2/s.

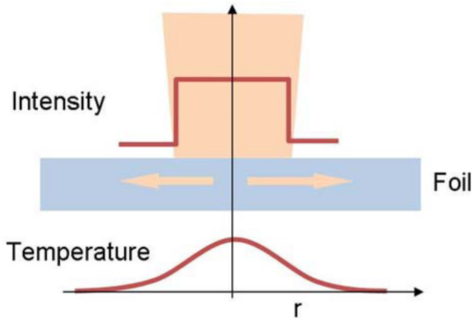

Fig. 1. Intensity distribution and resulting temperature profile for top-hat laser spot processing.

The temperature profile as qualitatively shown in Fig. 1 is subject to laser pulse energy, laser absorption and thermal properties of the material. For aluminum the absorptivity of laser pulses shows a strong dependence on the temperature of the material as is depicted in Fig. 2 (a). In particular, crossing the melting point of aluminum the absorptivity is more than doubled with respect to ambient temperature absorptivity.

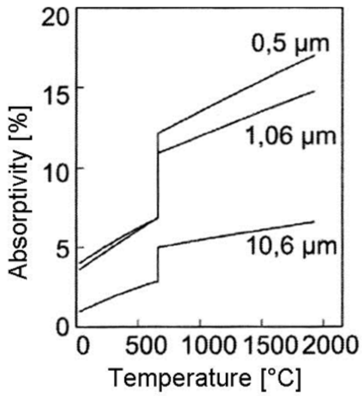

Fig. 2. (a) Absorptivity of aluminum for different temperatures and laser wavelengths [6].

Taking the effect of increasing laser absorption with rising temperature into account the temperature profile which develops in the material will change over time. Starting with an initial temperature profile the absorption will be magnified in the center of the spot where temperatures are already high. As a consequence, the temperature in the center of the spot will rise even more, as more energy is absorbed, while the outer regions of the laser spot absorb less.

The more pronounced central peak could explain why it is so difficult to realize laser spot joints in thin foils of aluminum. With relatively low absorption, the process starts slowly but accelerates rapidly. It is thus very difficult to determine a pulse duration which ends the process just at the right point in time. The situation is complicated even further as small differences in surface conditions (impureness, roughness, oxydic layer,etc.) require different process times. It is then almost impossible to find a fixed pulse duration which yields a robust joining process. This is visualized in Fig 3.

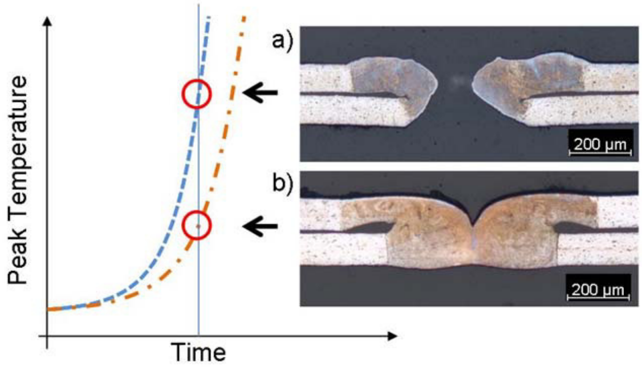

Fig. 3. Effect of perturbations on peak temperature with (a) high peak temperature and (b) smaller peak temperature.

The schematic diagram in Fig. 3 (a) shows the peak temperature (e.g. in the center of the laser spot) as a function of elapsed time during a laser pulse. As explained before, the temperature rises with increasing duration and the temperature rise is progressive due to increasing absorption. Considering two independent spot joints, the temperature curves may vary due to environmental perturbations such as oxidation for example. Hence, one of the peak temperature curves is shifted horizontally. For a laser pulse of the same length (indicated by the vertical line in the diagram) very different peak temperatures result.

In the extreme case this can make the difference between burning a hole and achieving a stale joint as shown in Fig. 3 (a) for two overlap joints. While in one case no connection between the foils is achieved, a prominent central dip can be observed in the second case. Even though the two foils are joined together, this is not a good joint as mechanical strength is greatly reduced.

With quickly rising temperatures a stable process can only be realized by sophisticated process control or by changing the temperature profile inside the material. This can be done optically by altering the intensity distribution of the laser pulse from a top-hat distribution to a ring shape distribution as illustrated in Fig. 4. The resulting temperature profile can be influenced by changing the ring diameter and may even have a small central dip.

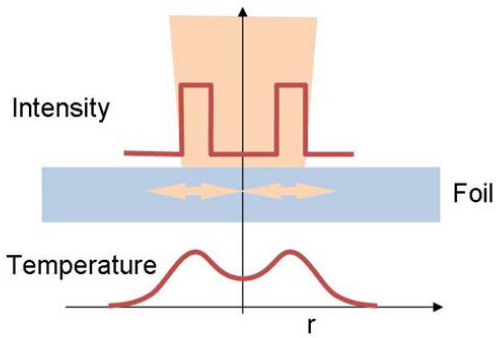

Fig. 4. Intensity distribution and resulting temperature profile for ring laser spot processing.

Using beam shaping to solve this problem avoids a complicated process control to stop heating the material within fractions of a millisecond and has the advantage that additional pulse modulation is still possible. One of the open questions, however, will be how the different temperature profile effects melt pool dynamics and how this impacts joint properties and joining of hybrid materials.

3. Laser system with beam shaping optics

3.1. Experiment setup and material

The experiments which follow are conducted with a modified Nd:YAG laser (LASAG SLS 200CL16) with a maximum average laser power of 25 W and pulse modulation possibility. The system is equipped with a flat-top fiber of 200 µm diameter. The beam shaping optics which is used is placed right behind the fiber. In order to avoid direct back reflections the optical setup is mounted at an angle such that the laser beam exhibits and incident angle of less than 15 degrees.

The materials used are thin foils/sheets of EN AW-1050A aluminum with a purity of 99.5% and SE-CU F20 copper.

In order to study the effects of beam shaping on the joining process of thin aluminum foils it is necessary to avoid some of the process variation causing difficulties. The variation that has the largest impact is a variable air gap between foils. These are very difficult to control and are furthermore influenced by the process itself when the air heats up and increases the gap between two thin foils in an overlap situation as well due to high thermal expansion of aluminum. Sophisticated clamping devices are employed for overlap welds in order to minimize the effect.

To avoid the problem altogether and study melt pool dynamics in more detail some experiments are conducted using single sheets of greater thickness which simulate a situation with no air gap. The thickness (500 µm) of these samples is chosen to be well below the thermal diffusion length of aluminum for characteristic pulse durations of a few milliseconds.

All welding trials are performed under standard atmospheric conditions. This may results in pores. However, it is reported that gas composition and orientation may also influence convection behavior. At this point we try to isolate convection arising by the beam shaping optic.

3.2. Design and development of beam shaping optics

The experimental setup which is used to investigate the influence of a ring shaped intensity distribution on material processing needs to satisfy the following requirements to facilitate in depth investigations of the associated effects on material processing:

- Variable ring size
- Variable width/thickness of the ring
- Correction for two wavelengths
- Robust and easy alignment
- Mostly off-the-shelf components

The variability in ring size (diameter) and width of the ring is important to find a set of suitable processing parameters and to evaluate the different effects on processing which are expected. Color correction is desired for this ring optic to work with a Nd:YAG Laser at its primary and frequency doubled wavelength in order to allow processing of different materials in further investigations. Color correction also helps during the alignment of the system as the focus deviation for the two processing wavelengths and the red pilot laser wavelength is reduced. It is hence of importance to have both colors create a ring of similar size for a given focus position. As this is an experimental setup, readily available components shall be used and the optics be robust and easy to align to work well even in a more rugged environment. Most importantly, the shape of the ring and its intensity distribution should remain constant during operation and not change unexpectedly.

Two options for the creation of a ring shaped intensity distribution are considered: intensity mapping and field mapping. If the fiber is imaged onto the sample a circular top-hat distribution results. In order to create a ring the imaging can be manipulated such that the intensity distribution at the fiber is rearranged when it appears on the sample. This is what we call intensity mapping. One way to achieve this is using an axicon, an optical element with a conical surface on one side which splits the light. Field mapping is different in that the far field distribution of the collimated beam is redirected such that more light is directed to the outside of the beam, e.g. using aspheres, and the light focused afterwards. This type of beam shaping depends on the far field distribution behind the fiber. This method is susceptible to variations in the far field distribution which is often a problem with fiber optics, e.g. when the fiber is bent. Varying distributions are a major disadvantage and difficult to control, thus intensity mapping is chosen for the experimental setup.

The developed optical system uses an axicon element and a pair of collimating and focusing lenses. The focusing and collimating lenses are designed to correct 1064 and 532 nm simultaneously. Moving one of the elements the ring size can be adjusted continuously. The following Fig. 5 shows the principal optical layout of the system creating a ring focus.

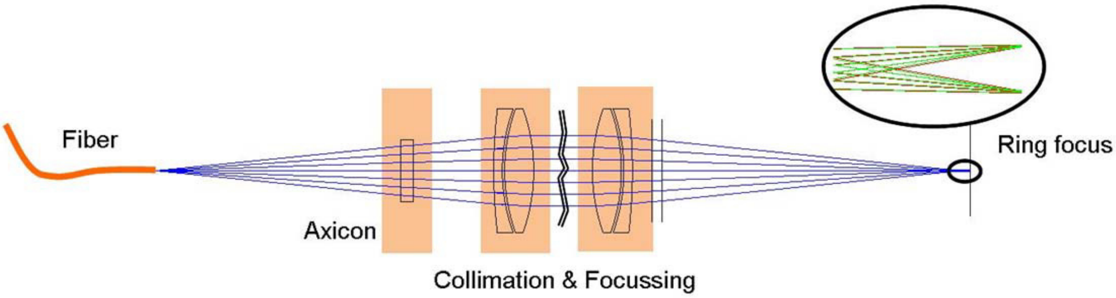

Fig. 5. Principal layout of the ring optics system.

With a fiber diameter of 200 µm ring diameters between a few hundred microns and over a millimeter can be realized. The width of the ring solely depends on the fiber diameter and the focal length of the system. Here, the width of the ring is equivalent to the fiber diameter (200 µm). Different fibers can be used to adjust the ring width and the focal length of the system can be adapted by adding an extra lens without sacrificing the color correcting properties too much. Alignment of the system is mainly performed by adjusting the angle of the fiber mounting. This alignment has a large influence on the symmetry of the ring which is of utmost importance for the joining process. The final setup is shown in the Fig. 6 (a) and is realized using mostly off-the-shelf components for mechanical and optical parts.

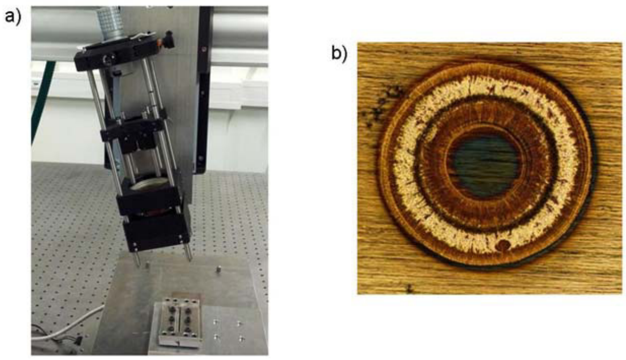

Fig. 6. (a) Picture of the laser focusing unit; (b) Ring distribution demonstrated on steel sample.

Working at very low power the ring shape nicely manifests itself on a sample as shown in Fig. 6 (b). This was used during alignment to determine the optimal position of the laser fiber and to find the best focus position. It also shows very nicely how the temperature profile develops with a larger heat affected zone on the inside of the ring.

4. Experimental results and discussion

Using the described equipment with the beam shaping ring optics, a series of joining experiments with aluminum foils down to 30 µm thickness are carried out. In contrast to the top-hat intensity distribution, foils can be joined together. However, currently results are not consistently reproducible. Fig. 7 exemplarily depicts an overlap spot weld in a 100/30 µm configuration. The top view shows a fairly smooth and symmetrical surface structure. The size of the molten area in the back view reveals an extensive bonding between the two foils. This is very favorable in terms of electrical and mechanical properties.

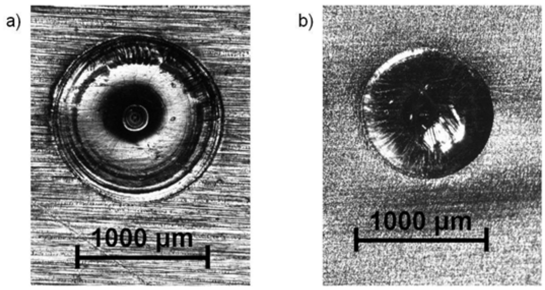

Fig. 7. Spot weld cross sections of 100 and 30 µm thick aluminum foils (a) top view; (b) bottom view (7.9 J, 3 ms).

In order to better understand the principles of using a ring shaped intensity distribution for laser spot joining additional experiments are conducted with single foils of larger thickness (500 µm). The following spot joints were all conducted using the same laser parameters (7.9 J and 3 ms pulse duration). Temporal pulse shaping was not conducted in order to not affect convection behavior induced by ring optic. All samples in Fig. 9 are color etched.

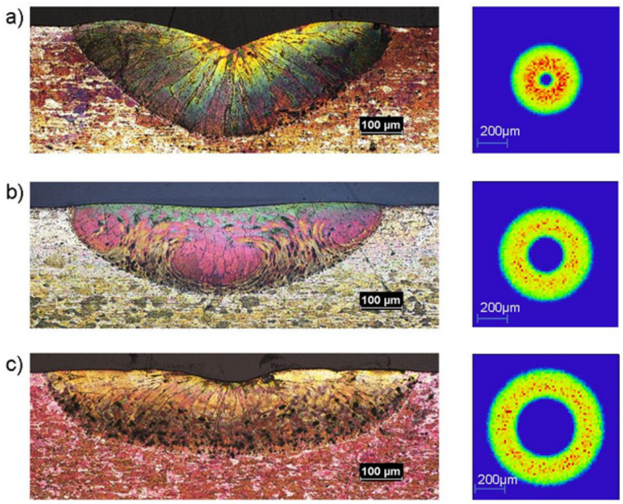

Fig. 8. Spot joint cross sections for different ring sizes alongside with corresponding Zemax® simulations, approximate outer ring diameter (a) 450 µm; (b) 600 µm; (c) 800 µm.

Varying the ring size, three distinctive cases can be identified. For very small ring sizes the situation is still very similar to a top-hat intensity distribution and the temperature profile still shows a central peak. Cross sections of an aluminum foil processed under these kinds of conditions exhibit a steep central dip comparable to the results shown earlier in Fig. 3 with long grains growing straight towards the surface (see Fig. 8 (a)). The strong and uniform grain growth indicates a slow cooling period without disturbing melt pool dynamics.

For medium ring sizes (Fig. 8 (b)) the situation changes and cross sections show that the central dip which showed up in the first phase is reduced. The reduced dip clearly demonstrates the positive effect of a more homogeneous temperature profile as is expected from theoretical considerations. In addition, a dynamic material transport must have occurred. Material from the bottom of the welt pool is flowing upward and circling inwards and is frozen in by the solidification process. As a result grain sizes are somewhat smaller. An explanation for the material flow structures that are observed in the cross sections could be a change in material convection but in our opinion cannot be explained by classical Marangoni convection. Further investigations are necessary to find a concise explanation.

Increasing the ring size even further results in very flat melt pools (Fig. 8 (c)) and the material transport phenomenon observed before disappears. This third case goes along with straight grain sizes. An explanation for the missing material transport could be that the ring diameter is now so large and the processing times so short that regions on opposite sides of the ring do not affect each other. Comparing the diameter of the joints in the three different cases, it can be concluded that despite large changes in the ring diameter joint diameters do not vary by the same amount. This could be due to heat dissipation into the central region as the same pulse energy is used for every case.

Convection behavior as it can be seen in Fig. 8 (b) is of great interest using dissimilar material. When joining dissimilar materials often brittle intermetallics are formed. The challenge becomes even greater for combinations of aluminum and copper with aluminum on the top. In addition to the absorption characteristics and resulting difficulties as detailed before copper has such a high thermal conductivity and higher melting point than aluminum that using a top-hat intensity distribution it is very difficult to reach a melting state of both materials and achieve real welding with an appropriate mechanical strength. First experiments are conducted to better visualize the convection behavior and also show that for a combination of copper and aluminum the materials can be mixed up using a medium ring size (fig. 9).

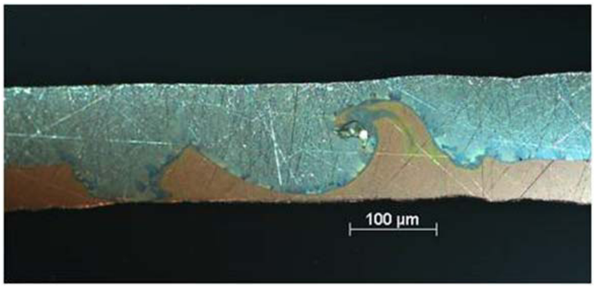

Fig. 9. Spot joint cross sections (not etched) spot welding aluminum (100 µm) to copper (50 µm) with aluminum on top (9J, 4ms).

Fig. 9 does not show a heat affected zone since no etching was carried out. Yet, it becomes apparent that in both configurations (Fig. 8 (a) and Fig. 9) a similar material flow is visible. Future investigations need to show how this affects the properties of the weld and how working gas (reducing pores) will have an influence on the convection behavior.

5. Conclusion

Joining thin foils of aluminum using a pulse-modulated Nd:YAG laser is challenging due to a small but rapidly increasing laser absorption. This induces a central temperature peak and results in a tendency to hole burning. It is demonstrated that additional degrees of freedom to manipulate the process can be generated by shaping the intensity distribution of the laser spot. A ring shaped intensity distribution which can create a more homogeneous temperature profile in the sample is generated with the help of an optical setup using an axicon element. First results show an enhancement of process window in terms of material thickness and material combination. The results reveal variations in melt pool convection and re-crystallization behavior with changing ring diameter which are not yet be fully explained. However, it seems evident from conducted experiments that a ring shaped intensity profile has positive influence on temperature distribution as well as convection behavior facilitating the joining of thin foils. Future work will include further investigation of overlap spot joints, additional pulse modulation as well as laser joining of different material combinations together with investigations on the effects of induced melt pool dynamics on weld properties.

Acknowledgements

Parts of the work were conducted under the Framework-7 Program (Ref. 260153). The authors would like to acknowledge the support.

References

[1] He, X., Fuerschbach, P. W., DebRoy, T., 2003. Heat transfer and fluid flow during laser spot welding of 304 stainless steel, Journal of Physics D: Applied Physics 36, pp. 1388-1398.

[2] Zhaoa, C.X., Kwakernaakb, C., Pana, Y., Richardsonb, I.M., Saldia, Z., Kenjeresc, S., Kleijnc, C.R., 2010. The effect of oxygen on transitional Marangoni flow in laser spot welding, Acta Materialia, Volume 58, Issue 19, pp. 6345–6357

[3] Prechtl, M., Schmidt, M., 2005. Laserstrahl-Kurzpulsschweißen von Metallfolien, Materialwissenschaft und Werkstofftechnik, Volume 36, Issue 5, pp. 226–231

[4] Ehlen, G., Ludwig, A., Sahm, P. R., 2005. Simulation of time-dependent pool shape during laser spot welding: Transient effects, Metallurgical and Materials Transactions A, Volume 34, Issue 12, pp. 2947-2961

[5] Weigl, M., Schmidt, M., 2009. Modulated laser spot welding of dissimilar copper-aluminum connections, Proceedings of 4M/ICOMM conference, pp. 211-214

[6] Holtz, R., 2004. Advanced laser micro welding by pulse control: new welding strategies with pulsed Nd:YAG lasers, *Proc. SPIE* 5662, doi:10.1117/12.596327

[7] Hügel, H., Graf, T. (eds.), 2009. Laser in der Fertigung – Strahlquellen, Systeme, Fertigungsverfahren (Lasers in the Production Process – Beam Sources, Systems, Manufacturing Processes), 2nd edition, GWV Verlag publishing house, Wiesbaden

[8] Kawahito, Y., Katayama, S., 2006. In-Process Monitoring and Adaptive Control during Pulsed YAG Laser Spot Welding of Aluminum Alloy Thin Sheets, JLMN-Journal of Laser Micro/Nanoengineering, Vol.1, No. 1, pp. 33-38.

[9] Olowinsky, A.; Klages, K.; Gedicke, J.; Gillner, A.; Poprawe, R., 2006. Shadow® - new applications in electronics and micromechanics, Congress proceedings. CD-ROM, Paper M805