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Single mode fiber laser micro joining of dissimilar metals: A comparative study

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Abstract

In the past few years the need for micro joining of dissimilar metal combinations increased drastically. Especially consumer electronic products and lithium-ion battery packs are demanding applications in the market environment of Manz. There are many potential process approaches to overcome the current limitations in terms of connection strength ,durability and heat management. Due to this wealth of variants Manz engineers compared two promising strategies capable of thin sheet joining. As initial material combinations 1000 series aluminum and unalloyed copper to low-alloyed steel were welded in an overlap configuration. The process results were qualified by cross-section analysis, penetration depth consistency and peel off strength. Finally the collected results were compared in respect to process duration, connected area, peel off strength and commercial aspects.

Keywords: Dissimilar metal; laser welding; Copper; Aluminum; Steel; Micro joining; Single mode fiber laser

1. Introduction

The efforts made in the field of dissimilar metal welding for electronic application increased drastically. A typical application of interest in the business segment of Manz AG is the joining of cylinder cells like 18650 or 21700 format Lithium Ion Batteries. These cell types are widely used in automotive, stationary and power tool products. Module sizes range from less than 10 to multiple hundreds. Due to economic reasons and the good accessibility of these cell types a significant number of the products named above utilize these standardized cells. The number of cells and the wiring within a module or pack define its electrical properties. A common approach to realize the interconnection within a module is the usage of flexible circuit boards or thin metal sheet connector plates. This allows the realization of complex and flexible wiring structures within a minimum of installation space.

In order to minimize the energy loss and heat generation due to the specific ohmic resistance of the circuit board material the common attempt is to either increase the transverse section or to decrease the

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specific ohmic resistance. As a result of this copper and aluminum begin to replace low alloyed nickel coated steel (e.g. Hilan™ or Hilumin™) as traditionally used current collector material and a rising request for increased sheet thicknesses can be observed.

Currently a state of the art process to join 18650 and 21700 cells is resistance welding. This process utilizes the specific ohmic and contact resistance of the current collector and the cell envelope material to create a firmly bonded connection between the current collector and the cell pole. By the usage of materials with low specific ohmic resistance this process begins to reach its boundaries. A second process approach is wire bonding. The downsides are relatively high cycle times with small transverse sections compared to resistance welding.

This work follows an alternative process approach which is laser welding and will show the capabilities using the example of 250µm thick copper as a current collector material welded to 18650 cells in an overlap joint configuration.

In order to be cost competitive within a resistance welding dominated competitor environment, Manz engineers developed two alternative welding processes with distinct advantages. The assessment criteria used are:

- peel off strength
- Process stability versus focal position shift
- Connection rate (mm²/s of welded interface)

The distinct laser sources used to realize the two process approaches are described in Table 1.

Table 1. Laser source parameters

Parameter	Laser source A	Laser source B
Laser type	Ytterbium YAG fiber laser	Ytterbium YAG fiber laser
Nominal wave length [nm]	1070	1064
Beam quality (M²)	<1,09	<1,42
Operation mode	Continuous wave	pulsed
Maximum average output power [W]	1000	100
Nominal pulse duration (FWHM) [ns]	Continuous wave	120
Nominal pulse repetition rate [kHz]	Continuous wave	100
Calculated focus diameter [µm]	27	46

2. Experimental work

Laser welding of copper at wavelengths of 1064nm or 1070nm respectively can be critical and a high intensity within the laser focus needs to be achieved to retain a stable in coupling and welding process. As it can be seen in Table 1 both laser sources deliver a fairly good beam quality. This allows the generation of relatively small focus diameters. Laser source A is a continuous wave fiber laser with an maximum average output power of 1000W. Laser source B delivers just 100W of maximum output power but due to the pulsed operation mode and short pulse duration a high pulse peak power can be achieved. This enables the realization of two completely different processes approaches which are described in the following section.

Both lasers were positioned via a 2D galvanometer scanner and focused by a F-Theta flat field lens. The principle optical setup is illustrated in figure 1. The welds were performed in an overlap configuration whereby the bottom joint partner was the minus pole of a 18650 cell.

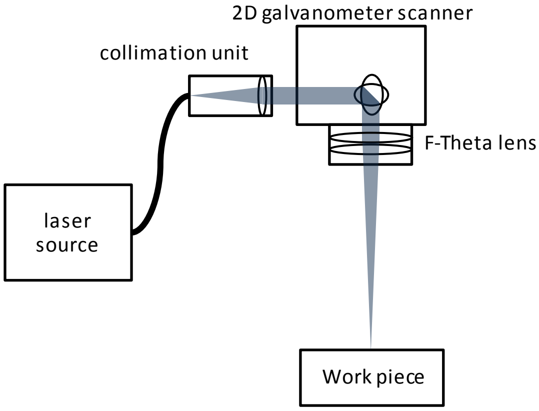

Fig. 1. Schematic illustration of the principal experimental setup

2.1. High frequency spatial modulation laser welding

Spatial modulation welding, also known as wobble welding, typically utilizes 2D galvanometer scanners to modulate the position of the laser focus in the working plane. The properties of the spatial modulation can be described by four parameters (figure 2):

- Modulation frequency (f_m)
- Modulation Amplitude (A_m)
- Modulation geometry (e.g. circle, sine, "8")
- Macro path feed rate (v_s)

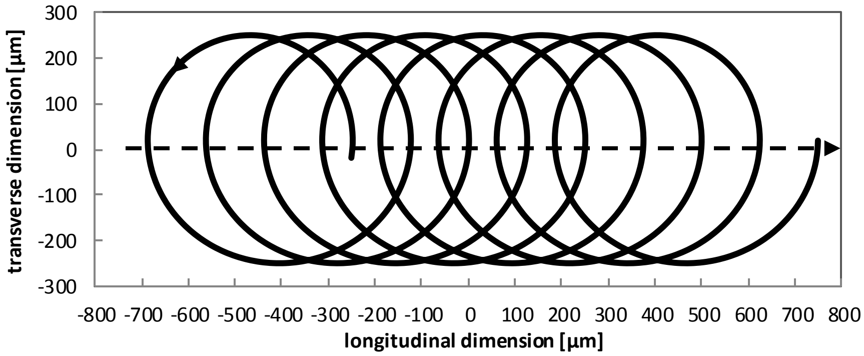

Fig. 2. Example of a circular modulation path with 0,8mm length at A_m=250µm; v_f=1050mm/s.. The dashed arrow illustrates the macro path movement (v_s) and the solid line the movement of the laser focus (v_f).

Due to the limited space available on a 18650 cell pole and to achieve a directional independent peel strength, the macro path in this experiments was designed as a closed circle. An example of a weld (d_M=1,4mm) performed with the modulation parameters described in figure 2 is presented in figure 3.

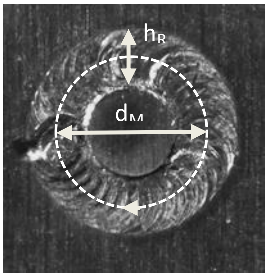

Fig. 3. Top view of a wobble laser weld performed copper and a 18650 cell in an overlap joint configuration. A_m=250µm; v_f=1050mm/s; P_L=360W. The dashed circle represents the macro path diameter of the circular weld (d_M=1,4mm). h_R represents the ring with and equals twice the modulation amplitude A_m.

In order to adjust the connected transverse section (A_w) the circle diameter d_M was increased. This leads to an increasing A_w and process duration T_w per weld. These two process properties can be calculated from equation (1) and (2). Figure 4 shows the relation between d_M at constant h_R and the resulting peel force in a 90° peel off test with a test speed of 10mm/s.

$$A_w = 2 \cdot \pi \cdot A_m \tag{1}$$

$$T_w = \pi \cdot d_M / v_S \tag{2}$$

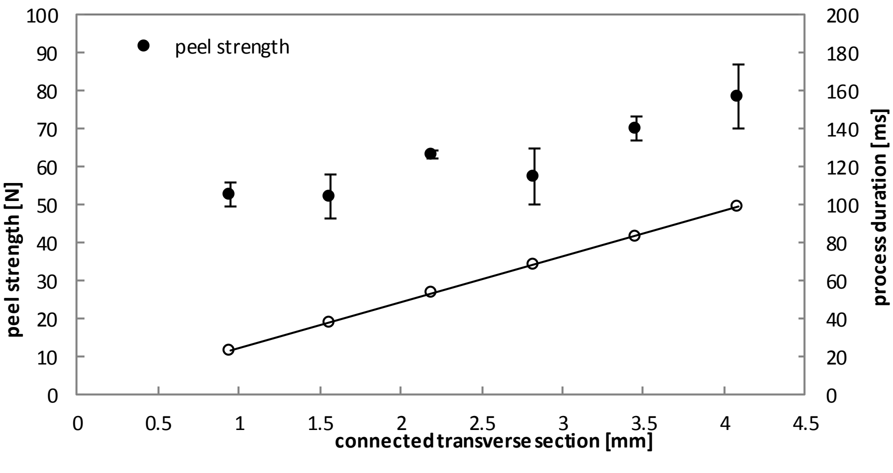

Fig. 4. Filled dots: peel strength (F_{peel}) versus connected transverse section at A_m=250µm; v_f=1050mm/s; P_L=360W; white dots: corresponding process duration versus connected transverse section.

With increasing connected transverse section and circle diameter d_M respectively the peel force F_{peel} increases as well. Starting from F_{peel}=52N at A_w=1mm² up to F_{peel}=78N at A_w=4mm².In this experiment the process duration T_w increases accordingly from 23ms to 98ms for A_w=4mm². Figure 5 shows a cross sectional view of an overlap weld (250µm copper to the minus pole of a 18650 cell) with A_w=2,2mm².

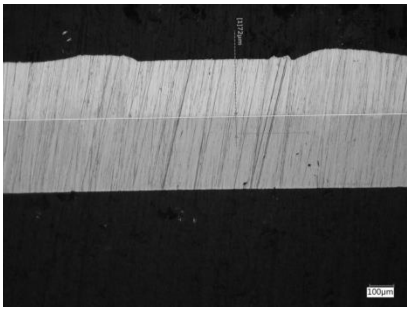

Fig. 5. Cross section of a wobble laser weld performed 250µm thick copper and a 18650 cell in an overlap joint configuration. F_m=666Hz; A_m=250µm; v_s=83mm/s; P_L=360W; A_w=2,2mm². The measured maximum welding depth is 72µm

In order to compare the stability of special modulation welding and short pulsed welding, a focal position variation in respect to the work piece surface was performed. The purpose of this experiment was to evaluate the robustness against product height variations and tolerances. A narrow process window would lead to an increased automation effort and impact the system costs and production yield rate significantly. The resulting peel strength plotted against the focal position of is represented by Figure 6. Increments of Δz=125µm were used.

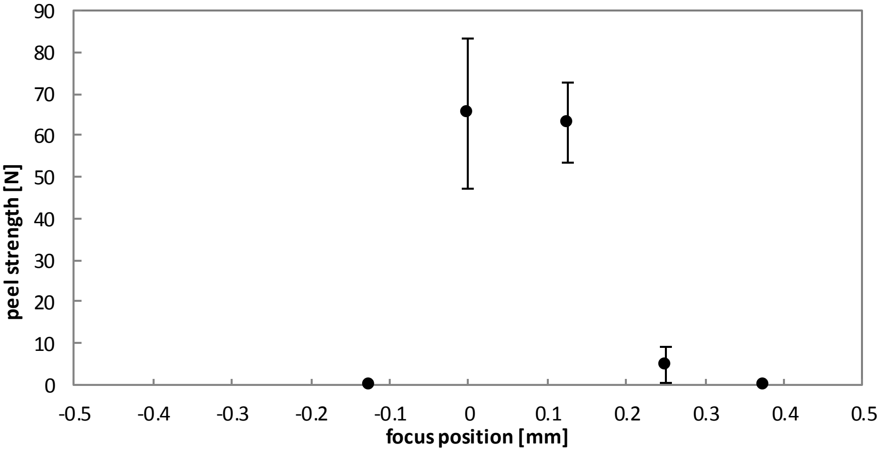

Fig. 6. Variation of the focal position in respect to the work piece surface on 250µm thick copper and a 18650 cell in an overlap joint configuration. A_m=250µm; v_f=1050mm/s; P_L=360W; A_w=2,2mm²

A slight shift of approximately 75µm compared to the adjusted working position can be observed. Never the less a shift of +/-200µm will cause a drop in peel strength to almost 0N.

2.2. Short pulsed laser welding

Short pulsed laser welding is a less common and novel approach to laser weld thin metal sheets in an overlap configuration. Due to the high short pulse duration of laser source B the intensity was by the factor of 2,8 higher than the intensity of laser source A at maximum output power. Therefore the high reflectivity of bare copper could be overcome and a stable in coupling was achieved.

In order to create a circular weld seam geometry an Archimedean spiral with varying inner and outer diameter was used. This spiral geometry can be described by three parameters:

- Inner diameter (D_i)
- Outer diameter (D_o)
- Spiral pitch (p_s)(radius increase after 360°)

An example of an Archimedian Spiral and the parameters named above are shown in figure 7.

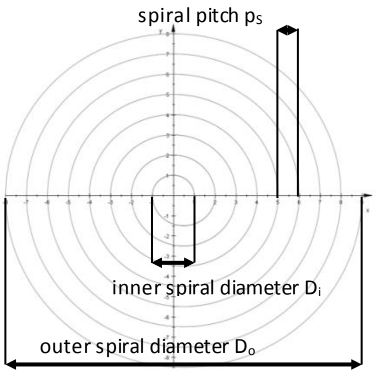

Fig. 7. Schematic illustration of an Archimedean spiral: inner spiral diameter (D_i); outer spiral diameter (D_o) and spiral pitch (p_S)

In order to adjust the connected transverse section, the ring width described by equation (3) was kept constant (w_R=0,08mm) and the outer or inner diameter was varied respectively. This leads to a linear relation of connected area A_w and process duration T_w. Figure 8 shows the peel test results at constant ring width w_R and increasing outer and inner spiral diameter respectively.

$$w_R = (D_o - D_i)/2 - p_S \tag{3}$$

The resulting connected transverse section can be calculated approximatively by equation (4).

$$A_w = \left({D_o}^2 - D_i^2 - 2p_S(D_o + D_i)\right) \cdot \pi/4 \tag{4}$$

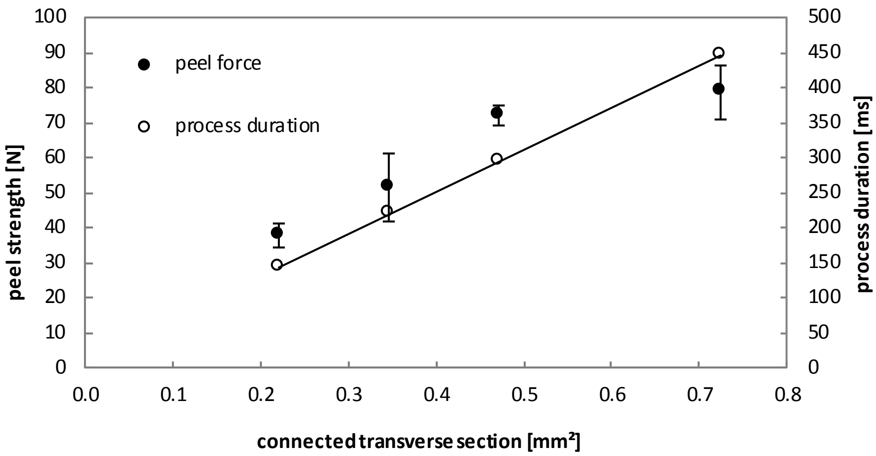

Fig. 8. Filled dots: peel strength (F_{peel}) versus connected transverse section (A_w) at p_S=40µm; v_s=60mm/s; P_L=100W; white dots: corresponding process duration plotted against connected transverse section. The vertical error bars represent the standard deviation of all measurements for each data point.

With increasing connected transverse section the process duration as well as the peel strength increases. Starting at 37N and increasing up to 78N for A_w=0,72mm².In Figure 9 an exemplary cross section of a weld with A_w=0,35mm² and F_{peel}=51N is illustrated.

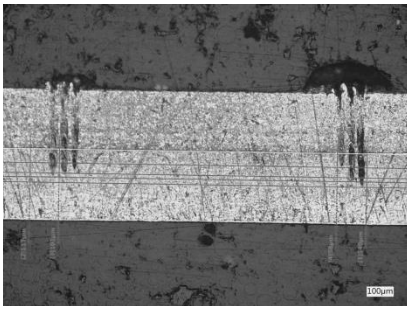

Fig. 9. Cross section of a short pulsed laser weld performed on 250µm thick copper and a 18650 cell in an overlap joint configuration at p_S=40µm; v_s=60mm/s; P_L=100W; A_w=0,35mm². The measured maximum welding depth is 117µm.

Short pulsed welding shows a relatively tolerant behavior towards focal position variations (figure 10). Within a window of +/-350µm a peel strength of >50N can be maintained at A_w=0,35mm².

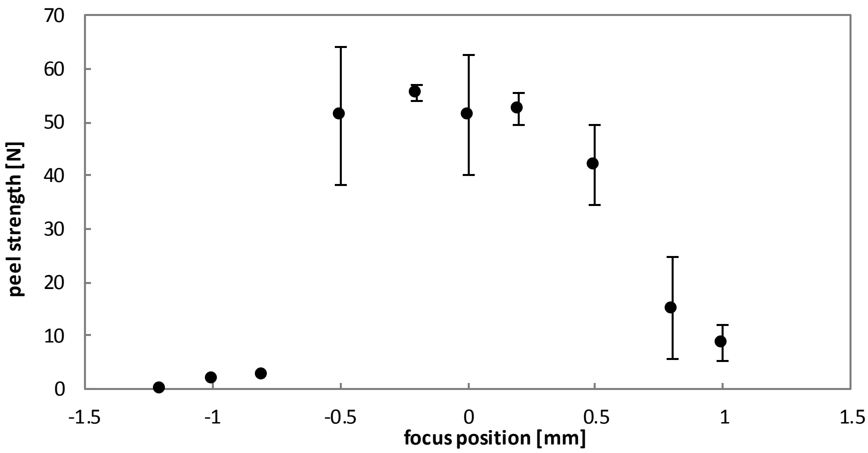

Fig. 10. Variation of the focal position in respect to the work piece surface on 250µm thick copper and a 18650 cell in an overlap joint configuration. p_S=40µm; v_s=60mm/s; P_L=100W; A_w=0,35mm²

2.3. Process comparison

Feasible criteria need to be defined to compare both process approaches. In general, joining of 18650 or 21700 cells within a module is driven by two major properties, among others.

- Mechanical strength
- Connected transverse section

A high mechanical strength is desired in order to create products that withstand mechanical forces in daily usage. Both processes showed their capability to create welds with high peel strength of up to 78N per weld. Short pulsed laser welding is capable to deliver these mechanical strength at 20% of the connected transverse section compared to spatial modulation welding (figure11). If only a very limited space is available for the actual weld itself this can beneficial.

In order to decrease the current carrying transverse section a maximum of connected area is needed. Both processes have a linear behavior of welded area A_w and process duration T_w. In order to compare both processes the connection rate $\dot{A}_w$ was chosen as a criteria. This can be calculated by equation (5) and describes the welded area per second.

$$\dot{A}_w = A_w / T_w \quad (5)$$

Spatial modulation welding has a significantly higher connection rate of $\dot{A}_w$=41,5mm²/s compared to short pulsed welding ($\dot{A}_w$= 1,6mm²/s). If a high throughput or a relatively large current carrying transverse section is needed spatial modulation welding can be beneficial.

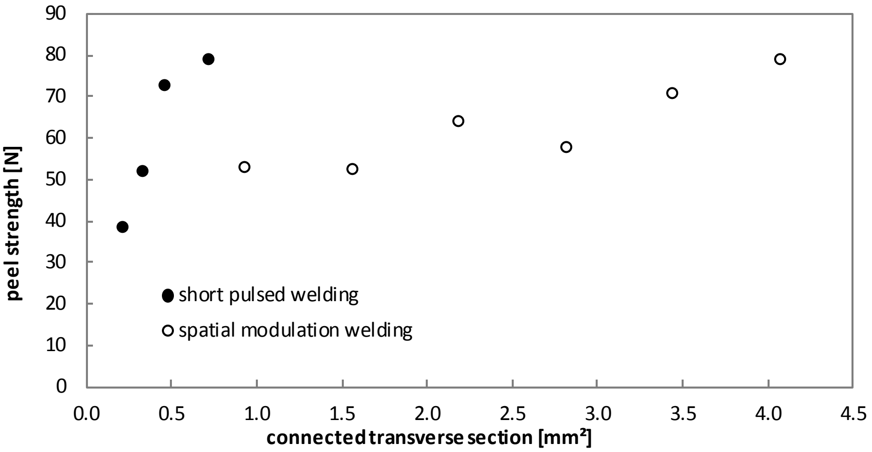

Fig. 11. Connected transverse section versus peel strength. Filled dots: short pulsed welding; white dots: spatial modulation welding

From an automation and OEM integrator standpoint of view process robustness against work piece tolerances is relevant as well. The cell types of interest are a widely available product, distributed by many vendors. Due to this, the tolerances of the product can be an issue in terms of z-height variation. Especially when they are assembled in modules with hundreds of cells. Considering this circumstance, the increased process window of short pulsed laser welding ($\Delta z \geq +/-350\mu m$) is a benefit compared to spatial modulation welding ($\Delta z \leq +/-100\mu m$).

3. Conclusion

This study shows that both approaches are capable of creating welds with high mechanical strength at competitive throughput compared to traditional processes like resistance welding and wire bonding. The distinct advantages of each process like increased connection rate, robustness against part tolerances or initial investment costs have to be considered individually to choose the appropriate process that will serve the needs of the actual application.