

Microstructural analysis of laser micro-welds between copper and aluminum

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Abstract Currently used ultrasonic welded joints for assembly and packaging of Li-Ion batteries have reliability concerns for automotive applications, as the battery is subjected to vibration and other mechanical loads. The sealing of the battery can is very critical for safety. Due to battery weld failures in recent years, the postal service has put ban on shipping Li-ion batteries via regular mail. A laser based alternative joining technology has the potential to offer robust, fast and cost-effective processing of Li-Ion batteries. Before the technology can be fully implemented, it is imperative to understand the effects of various process parameters on the robustness of the weld. In the present analysis, a preliminary study is performed to understand the effect of laser scanning speed on the micro-structural and physical characteristics of the materials in the weld area that ultimately affect the bond quality. Samples are created by welding aluminum and copper in lap shear configuration using a continuous wave fiber laser. Two sets of samples are created using a laser power of 225 W; however, the scanning speeds are 300 and 400 mm/s. Scanning electron microscopy and energy dispersive spectroscopy are performed in the weld area to understand the microstructural and physical characteristics of the joint that may have been affected by the processing parameters.

1 Introduction

In a rechargeable lithium-ion battery, lithium ions move from the negative electrode to the positive electrode during discharge, and back when charging. Li-ion batteries use Li intercalation compounds such as graphite as the negative electrode (anode) and lithium cobalt oxide (LiCoO_2) as the positive electrode (cathode) material. While the negative electrode materials are deposited on a copper foil, the positive electrode materials are coated on aluminum foils. A thin polymeric separator typically made from polyethylene/polypropylene with about 25 μm thickness is then sandwiched between the two electrodes and either wound inside a cylindrical metal can or in prismatic metal cans or soft pouches. Organic solvent-based electrolytes are then added to activate the cells and then subjected to so-called formation and cycling protocols (Fig. 1). To meet electrochemical requirements, most metal components in the cell are either made of copper or aluminum. The assembly of Li-Ion batteries includes a variety of joining operations of copper and aluminum parts. For example, both anode (Cu foils) and cathode (Al foils) of the electrode package must be joined to anode lead and cathode lead tabs, respectively, that protrude out of the cell cases. It is important to note here that Li-ion batteries require a moisture free environment and hence they need hermetically sealed cases. The hermetic sealing of the housing requires joining of metals such as aluminum as well. A battery pack consists of cells that are connected in series, requiring sometimes parallel connections, via busbars that require joining of aluminum and copper.

Currently, ultrasonic welding is mostly used to join copper and aluminum or aluminum and aluminum for both the internal connections between the foils and the tabs of the cell as well as for connecting cells externally to make

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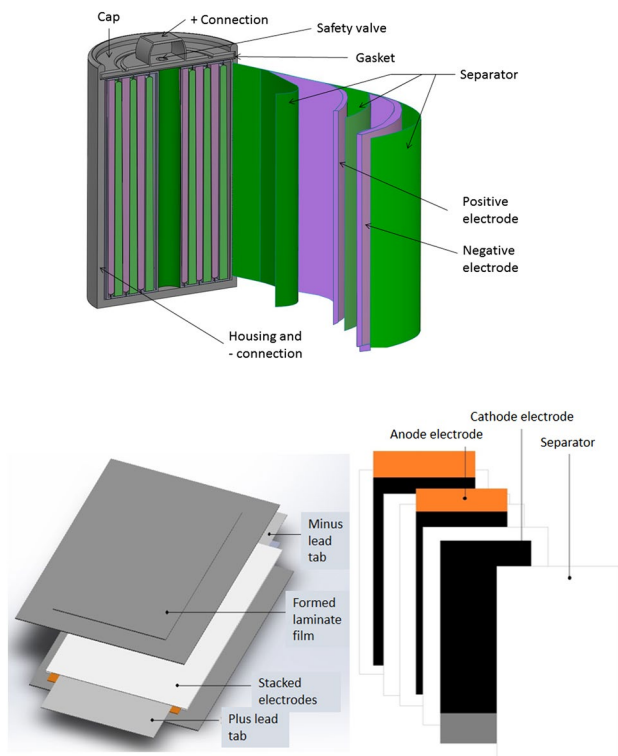


Fig. 1 (top) Cylindrical Li-Ion battery, (bottom) prismatic (planar) Li-Ion battery

battery packs using busbars. Ultrasonic welded joints tend to have reliability concerns for automotive applications as the battery is subjected to vibration and other mechanical loads. It may be mentioned here that the sealing of battery can be very critical for safety. Due to many such failures in recent years, the postal service has put ban on shipping Li-ion batteries via regular mail. Recently, the failure of lithium-ion batteries is responsible for the grounding of Boeing's 787 Dreamliner in the US and Japan, after two separate incidents (<http://www.electronicnews.com.au/news/lithium-ion-battery-failure-at-centre-of-787-groun>). To improve reliability, the battery manufacturers are using a combination of ultrasonic and laser welding of Al and Cu that results in an increase of overall cost.

Li-ion cells especially of the planar or plate type often require welding of foils and tabs of differing number and thickness. Development of weld joints having high integrity and reliability using ultrasonic welding is rather a time-consuming and tedious process that involves optimization of amplitude, time and pressure, for example. The work is doubly challenging when it involves welding of parts having considerably differing thicknesses. For example, while the tabs that protrude outside of the cell are approximately 200 μm thick, the individual foils inside the cells are about 10–20 μm thick. Welding foils of such dissimilar thickness

requires careful adjustment of the weld variables which are quite different for Al/Al and Cu/Cu as well as for Al/Cu. Lack of high fidelity testing methodology to check weld quality prior to field deployment of the batteries, especially in vehicles, is a quite risky scenario. One failure mode that has been observed thus far is the occurrence of the so-called cold-welds; insufficient weld joint that fails under mechanical stress during vehicle operation. What is needed is an inexpensive, rapid and highly reliable welding process.

To increase reliability and reduce cost, it will be beneficial to explore alternative joining techniques. The use of lasers in manufacturing has been increased recently due to the numerous advantages and benefits they provide. They are currently used for cutting, drilling, surface treatment and welding of different types of materials for a wide range of applications. Lasers can efficiently and economically convert electromagnetic light into heat that could be applied precisely at specific and small spots. They provide a reproducible localized heating at elevated precision and high execution speed without the need for applying high pressure. Thus, a joint at the micro level, can be created with low heat input and small heat affected zone compared to soldering, and no post bonding shrinkage compared to chemical adhesives. The flexibility in controlling the heat generated by laser decreases the possibilities of distortion in the work piece compared to conventional welding, which makes it very convenient for welding of sensitive materials. Due to all the benefits and advantages mentioned a wide range of materials can be welded by laser, even the alloys that are normally difficult to weld by conventional welding. This has opened the door for welding of dissimilar or similar materials for hybrid systems (Kreimeyer et al. 2005; Olowinsky et al. 2002).

In this paper, we created several copper/aluminum specimens by lap joining them using laser at different process parameters such as scanning speed and power. Micro-structural and physical characterization of the joining region was performed using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDAX) to understand the effect of process parameters on the bond integrity.

2 Laser microjoining experiments

The three major parameters that have been shown to affect the joint the most (based on our previous experience) are laser intensity, beam scanning speed, and pulse rate (for pulsed laser.) Since a cw laser was used to create the bond, the third process parameter that is pulse rate is removed from the parameter list. The laser intensity and scanning velocity will certainly affect the fusion zone size and temperature distribution within the fusion zone. Thus, it is intuitive that these parameters will affect the bond reliability.

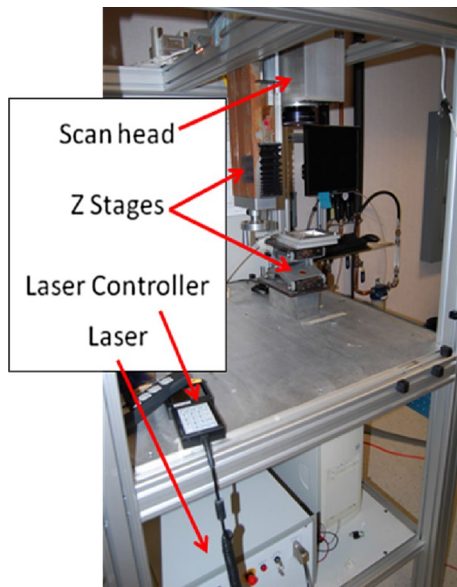


Fig. 2 Cw fiber laser

In this study, we fabricated the laser joints by varying only the laser beam scan speed. The beam scan speed defines the total power/energy input and can be varied within a reasonably wide range by means of external moving mirror optics or sample holder stage movement with respect to a fixed laser beam.

MLPC has varieties of laser systems; however, an in house built 500 W fiber laser (Fig. 2) was used to create welds for this study. The fiber laser is made by IPG and is model YLR-500-SM. The fiber laser is a continuous wave laser that has maximum average output of 500 W with a wavelength of 1,070 nm. The laser is integrated into a workstation with a Scanlabs scan head and manual z stages for placement. The scan head is capable of achieving line speeds greater than 500 mm/s.

Figure 3 shows an Al/Cu laser joining sample that is of interest to this project. Thicknesses of Al and Cu foils are 200 μm each.

3 Physical characterization

In general, mechanical testing provides the quantitative measure of joint strength and effect of process parameters on it. However, it is important to understand the mechanism for creating good welds, which can be revealed by SEM and electron dispersion energy dispersive analysis X-ray (EDAX) studies. It may be mentioned here that researchers have successfully utilized these methods before to characterize welds between various metals (Hailat et al. 2012; Chen et al. 1990). The tests were performed



Fig. 3 An Al/Cu laser joining sample viewed from Al side

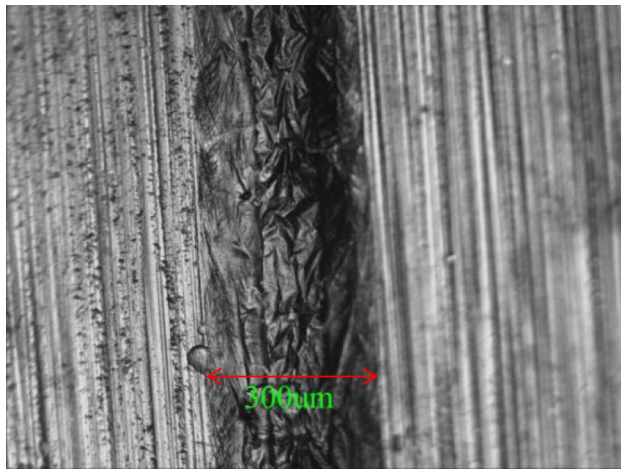
at WSU's Center for Nanoscale Multifunctional Materials (<http://www.cecs.wright.edu/nanocenter/>).

SEM of laser welded samples was used to obtain high-resolution images revealing micro-/nano-structural morphology of heat affected zone (HAZ). It may be mentioned here that the HAZ is defined as an area whose microstructure and properties are altered by the welding process. The EDAX analysis revealed the intermixing of Cu and Al in the weld region during welding. It was verified how various process parameters have resulted in improved bond strength.

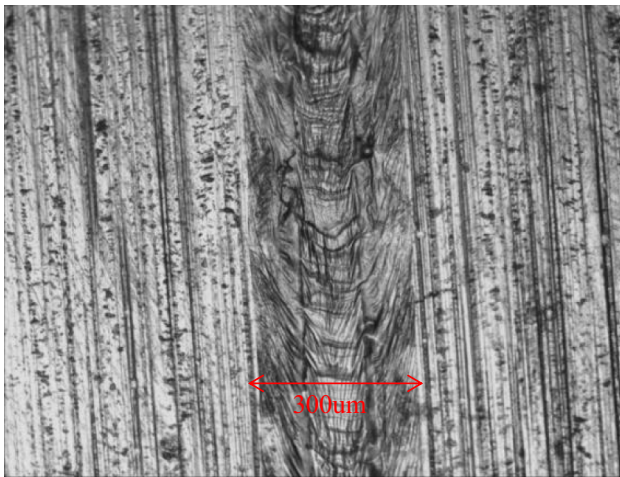
4 Results and discussions

As a preliminary study, we were successful to create line weld between Al and Cu. In this case, the laser was focused on the Al surface. Optical micrographs of such processed samples in the joint area when viewing from top are shown in Fig. 4. Both the samples were created using 225 W; however, scanning speeds were 300 mm/s (Fig. 4a) and 400 mm/s (Fig. 4b). The series of ripples that covers the entire track observed in Fig. 4 may be due to the surface tension gradients established during melting and of convective motion in the melt region (Pinto et al. 2003).

The width of the heat affected zone from Fig. 4 is observed to be approximately 300 μm . In other words, the scanning speed seems not to affect the heat affected zone (HAZ) as the samples are viewed from the Al side. This is due to the fact that the laser spot size and power are same for both the scanning speeds. Although the HAZ size may look similar from the top, it is clearly identified later through SEM and EDAX that the microstructure and composition in the keyhole regions are different.



(a) Scan speed of 300 mm/s

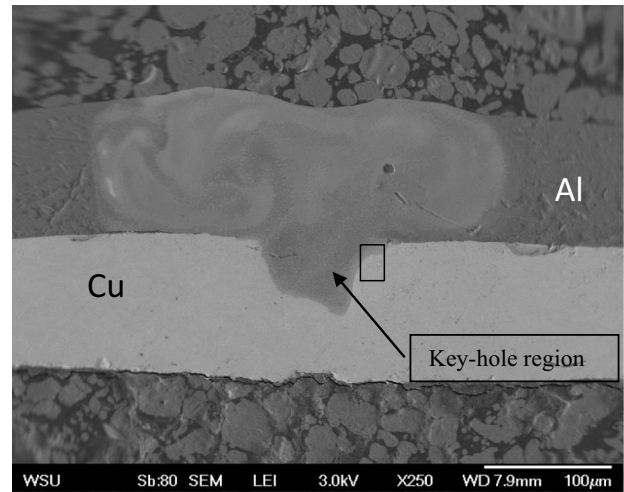


(b) Scan speed of 400 mm/s

Fig. 4 Laser welded Al/Cu sample viewed from top

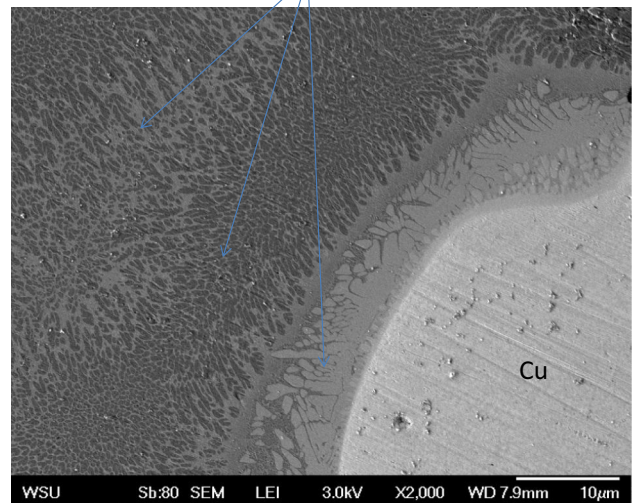
SEM micrographs of the cross sectional view near the joining area are shown in Figs. 5a and 6a, respectively for scanning speeds of 300 and 400 mm/s. From both the images, it is apparent that the width of the heat affected zone (HAZ) decreases in the depth direction. The HAZ width changes abruptly from Al to Cu resulting in a sharp key hole in copper. This abrupt change is attributed to the contact heat resistance at the interface and the Gaussian type intensity distribution of the fiber laser used in the experiment.

Figures 5b and 6b show the magnified microstructural images near keyhole boundaries for the samples created using the scanning speeds of 300 and 400 mm/s, respectively. The exact locations of the images are shown in Figs. 5a and 6a using rectangular boxes. It is clear from Fig. 5b that there are two distinct material phases present in the keyhole region. The material phases appear to be well



(a) Weld region

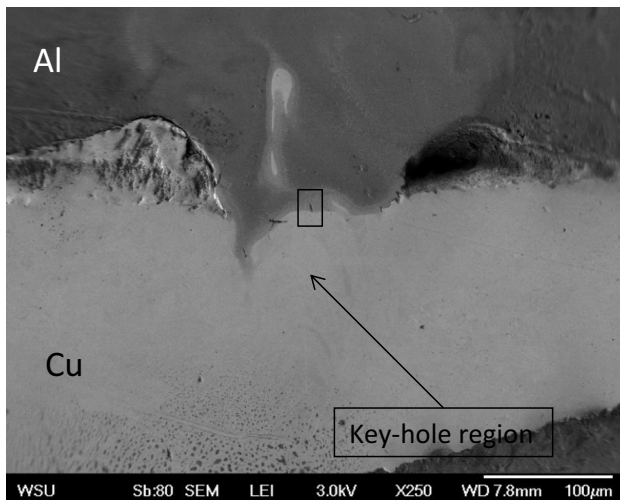
Presence of two distinct phases of materials



(b) Zoomed in view of the region shown by a rectangular box in (a)

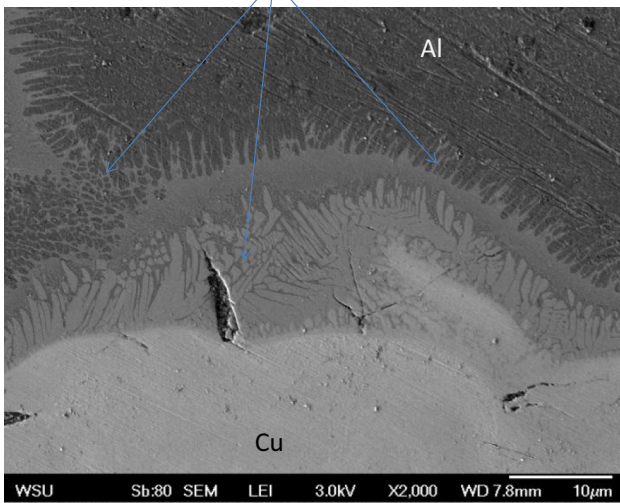
Fig. 5 SEM micrograph of cross section of a Cu/Al sample (300 mm/s)

dispersed and are present in the entire keyhole region. On the other hand, the samples created by using a scanning rate of 400 mm/s have completely different microstructure as evidenced in Fig. 6b. It is clear that the presence of two phases of materials is limited within a narrow band and the phase distribution appears not to be a uniform gradient as seen in Fig. 5b. So, although the heat affected regions have similar width as viewed from the Al side (Fig. 4), the microstructure and composition distribution are different because heat transfer and temperature distribution within HAZ are different due to different scan speeds (Mahmoud et al. 2007).



(a) Weld region

Presence of two distinct phases of materials



(b) Zoomed in view of the region shown by a rectangular box in (a)

Fig. 6 SEM micrograph of cross section of a Cu/Al sample (400 mm/s)

EDAX analyses of the cross sections of two samples created using 300 mm/s and 400 mm/s are shown in Figs. 7, 8 and 9, respectively. It may be mentioned here that the data has been collected only in the weld keyhole region.

The vertical and horizontal line scan EDAX data are presented in Figs. 7 and 8, respectively for samples created at 300 mm/s scan rate. It is clear from both the data plots that the relative wt% of Al and Cu is more uniform in the key-hole region away from the keyhole boundary. An increase in wt% of Cu is observed as the EDAX line moves closer to the key-hole boundary. This observation is also evidence in the SEM plot in Fig. 5(b).

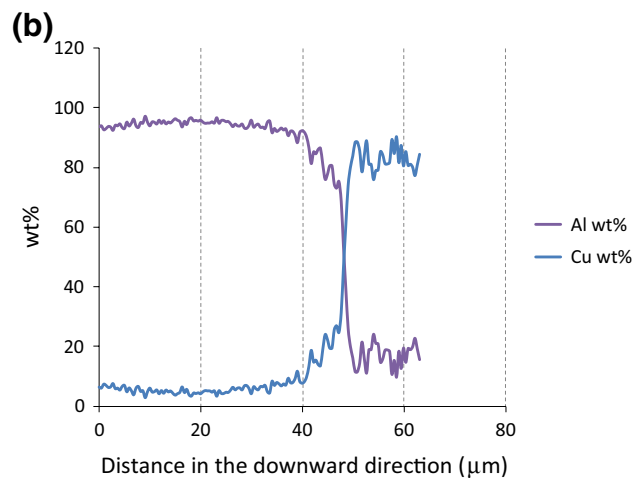
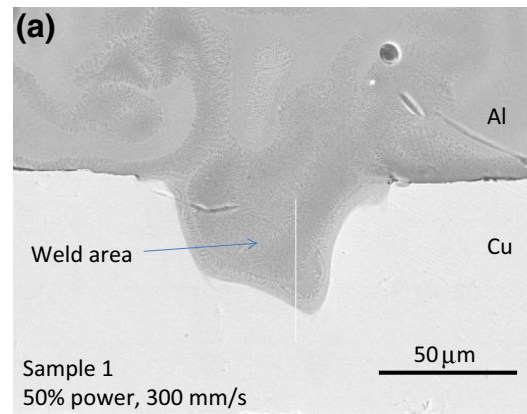


Fig. 7 EDAX analysis of a Cu/Al weld fabricated at MLPC a sample (scanning speed 300 mm/s)

The vertical line scan EDAX plot shown in Fig. 9 for 400 mm/s samples is completely different from Fig. 7. In this case, there are two distinct regions—the first region having high Al wt% while the second bottom region has high Cu wt% creating a material discontinuity in the key-hole. This is also clear from the SEM diagram shown in Fig. 6. This characteristic is due to the fact that since the sample was created at a higher scan rate, time needed for materials flow and mix during melting and solidification was not sufficient.

If the two process conditions are compared, it appears that the 300 mm/s scan speed provides continuous weld pool along the length of the weld. This results in creation of uniform Al and Cu rich regions that solidify and create robust joint. At 400 mm/s, it appears that the weld pool is unstable (ripple on top surface). This results in a very turbulent pool with a mixture of liquid and solid regions. This is obvious in Fig. 9 where both bands of Al are present 150 µm below the Cu surface resulting in a large variation Al and Cu composition. There is also a spout of Cu into the Al just to the left of EDAX line

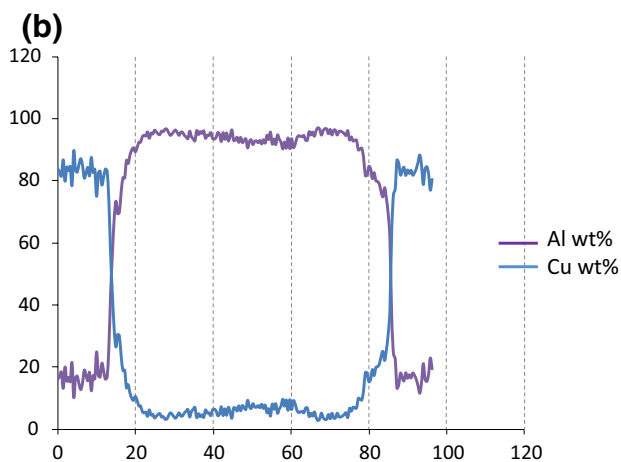
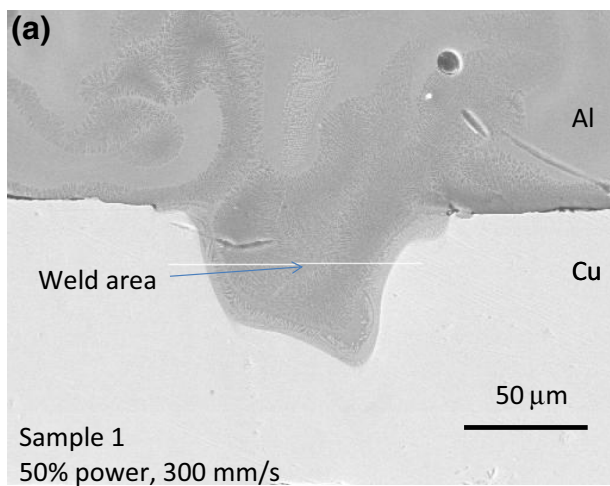


Fig. 8 EDAX analysis of a Cu/Al weld fabricated at MLPC a sample (scanning speed 300 mm/s)

(Fig. 9a). It is thus concluded that the relative wt% of Cu and Al in keyhole is different for two samples created using different scanning speeds, hence it is expected that the bond strength will be different for two different samples. The created samples were also peeled manually. It was also observed that it was easier to peel samples created using 400 mm/s scan speed than those using 300 mm/s scan rate. Quantitative measurement of weld strength will be performed next and will be discussed in later publications.

5 Summary

Aluminum and copper were successfully welded by using a fiber laser of power 225 W (or 50 % of maximum power). The solubility of both metals was observed to be affected by scan rate; the distribution of aluminum in

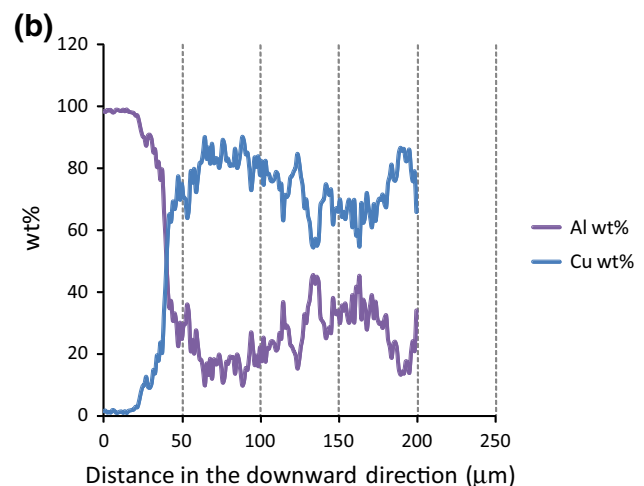
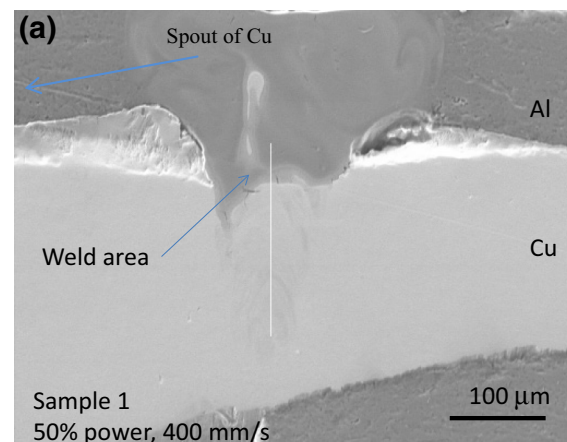


Fig. 9 EDAX analysis of a Cu/Al weld fabricated at MLPC (scanning speed 400 mm/s)

copper was more uniform for the samples created using a scan rate of 300 mm/s as evidenced from both SEM and EDAX analyses. It was expected that the samples created by 300 mm/s scan rate will have higher weld strength that was confirmed through qualitative weld strength observed from manual peeling of both types of samples.

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