Spatter-Free Stable Conduction and Keyhole Welding of Copper with 275 Watt Blue Laser

Abstract

Laser welding of highly reflective materials such as copper has been problematic for infrared lasers due to the low initial energy absorption of the material during the welding process. This paper will report on the recent bead-on-plate test results using a 275 Watt CW 450 nm blue laser for welding copper foils up to 500 µm thick where the initial absorption is ~65%. Highly stable conduction mode welding of copper is observed over a wide processing window using the high power blue laser source. Stable, no spatter keyhole welding is also observed with complete penetration of the 500 µm thick copper foil. Both welding regimes exhibit highly stable weld puddles with minimal porosity and no gaps in the weld bead due to melt ejection. Processing of the parts can be done at a near orthogonal orientation due to the low reflected energy from the copper surface.

Keywords: Welding; Copper; Blue; Laser

1. Introduction

The growing market demand for batteries and electrical components is driving the need for improving the methods for welding copper. Current techniques, such as ultrasonic welding, produce wide bead widths and requires physical contact with the materials being welded resulting in variable bead width and quality issues. Similarly, welding copper with an infrared laser has proven difficult because of the very narrow processing window. Here the laser is initially driven to a very high power level to overcome the low absorption of the copper which is required to begin a key hole process. However, if the laser power is not rapidly reduced once the absorption peaks up, then a blow out of the weld occurs. In addition, the high peak laser power makes it difficult to control the vapor pressure of the keyhole and consequently, there is a significant amount of weld spatter across the surface being welded. These issues lead to multiple problems ranging from limiting battery power density to latent defects which affect the reliability of the final product. NUBURU has developed a new class of blue laser systems that are ideal for welding copper because of the high initial absorption level of the laser light (65% with blue compared to 5% with infared) which insures that the energy is efficiently coupled into the part being welded.[1] This paper will discuss the results of copper welding tests performed with a 450 nm laser source operating at 275 Watts.

2. Experimental

2.1. Laser System

The direct diode laser system used in these welding test consisted of two 450 nm laser modules operating at 150 Watts each (Figure 1). The two lasers are combined in free space to create a 200 µm spot at 275 Watts at the work surface. The beam parameter product for each laser is 20 mm-mrad resulting in a free space beam divergence of 2-mrad 95% power point, full width. The free space output beam is 20-mm x 20-mm for each laser. The two lasers are combined spatially using dielectric mirrors to form a composite beam. The composite beam is focused by a 100-mm focusing optic to a 200 -µm spot with 95% power content at full width. The control of the laser system is through an analog interface and a separate enable line. The output power of the laser is set with a 0-10V analog signal and is commanded on / off with a 24 V signal from the robot to turn the laser on/off.

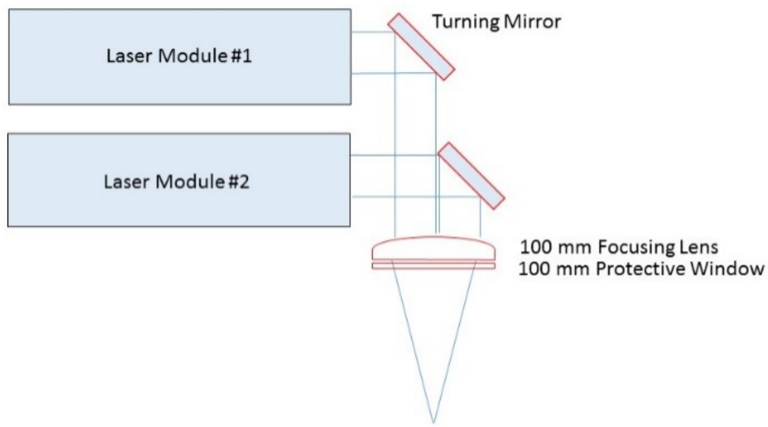

Fig 1. Free space laser system

2.2. Welding System

The welding system (Figure 3) used in this test consists of the blue laser system described above, a six-axis FANUC robot, and a stainless-steel welding fixture. The stainless-steel fixture that holds samples in place used two stainless steel wedge shaped clamps secured by a set of screws (Figure 2). The six-axis robot was used to translate the sample through the focused spot of the laser system to create the bead-on-plate shown in Figure 3. The tests were performed over a range of speeds from 0.06 m/min up to 9.6 m/min. The copper samples tested included foils and plates ranging in thickness from 8 µm to 500 µm. The tests performed included welding a simple bead on plate for the thicker samples to lap welding stacks of the 8 µm foils where the stack thickness was varied from 10 to 20 foils. An assist gas was delivered through a nozzle located just above the surface of the sample piece as well as through the slot underneath the sample to minimize the oxidation of the top and bottom surface of the sample. An air knife was positioned directly below the protective window of the system and compressed air was used to keep the window clean.

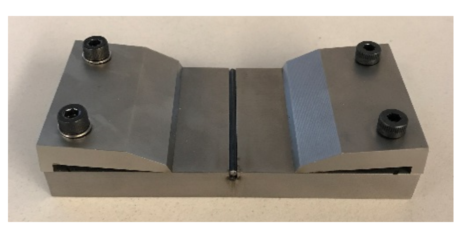

Fig 2. Stainless steel welding fixture

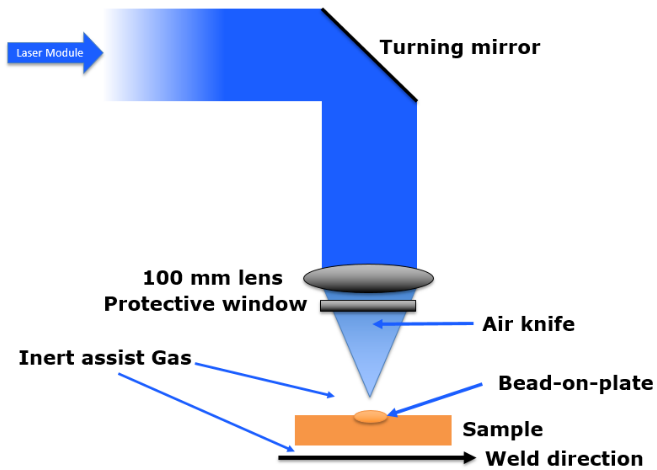

Fig 3. Welding system

3. Results

3.1. Bead-on-plate on 125 µm Copper

The first bead-on-plate tests were performed with 125 µm thick copper foils. The welding speed was varied from 0.6 m/min to 12 m/min with full penetration achieved up to 9 m/min at 275 Watts. Since the sample was fully penetrated, the top and bottom width of the beam on plate was measured with a Keyence digital microscope. The results of these measurements are shown in Figure 4.

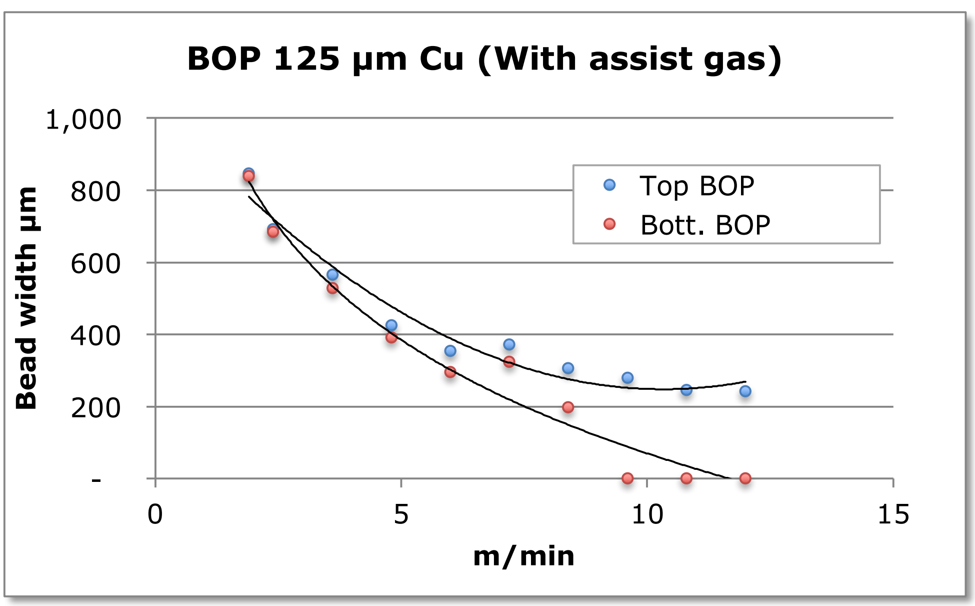

Fig 4. Bead-on-plate results for 125 µm Copper @ 275 Watts

Each sample was sectioned, polished and etched to reveal the microstructure of the weld bead. The images from the processed samples are shown in Figures 5a and 5b, where there is no trace of defects or porosity in the weld bead. The heat affected zone (HAZ) is also apparent in both the figures. The upper and lower surfaces of the weld were smooth and free of spatter or blow-through defects. This shows clearly that the high absorption of the blue laser light enables the efficient coupling of energy into the copper making the welding process stable and consistent over a wide processing window.

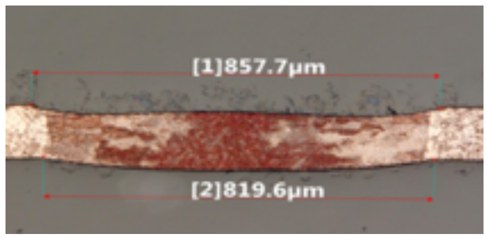

Fig 5a. Cross section results for 125 µm Copper @ 275

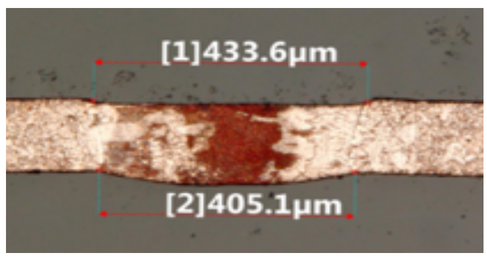

Fig 5b. Cross section results for 125 µm Copper @ 275

3.2. Bead-on-Plate on 254 µm Copper

The next series of tests focused on characterizing the penetration depth as a function of speed for the 254 µm thick foil. Full penetration was only achieved at the lower speeds (<0.6 m/min) in the keyhole welding mode (Figure 6). This mode was identified by the characteristic shape of the cross section, the observation of a hole in the middle of the bead while welding, and the vapor jet observed during the welding process. Even though the keyhole welding mode was observed, the weld puddle was very stable with no weld spatter observed on the surface of the foil after the weld was completed. At higher speeds the weld transitioned to a conduction mode weld again, with no evidence of spatter on the part. Figure 7a and 7b shows these results.

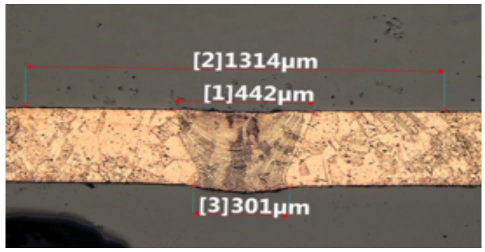

Fig 7a. Cross section results for 254 µm Copper @ 275 Watts, 0.3 m/min –

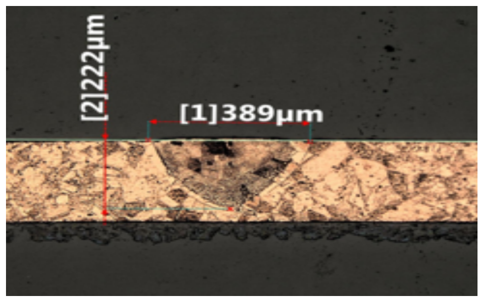

Fig 7b. Cross section results for 254 µm Copper @ 275 Watts, 0.6 m/min – conduction

3.3. Bead-on-Plate on 500 µm Copper

Tests were conducted at 275 Watts on a 500 µm thick copper plate (Figure 8). Full penetration was achieved at a speed of 0.1m/min with the keyhole mode welding regime. The test also showed that in both welding modes there was no spatter observed on the top surface of the plate. Figure 9a and 9b shows these results.

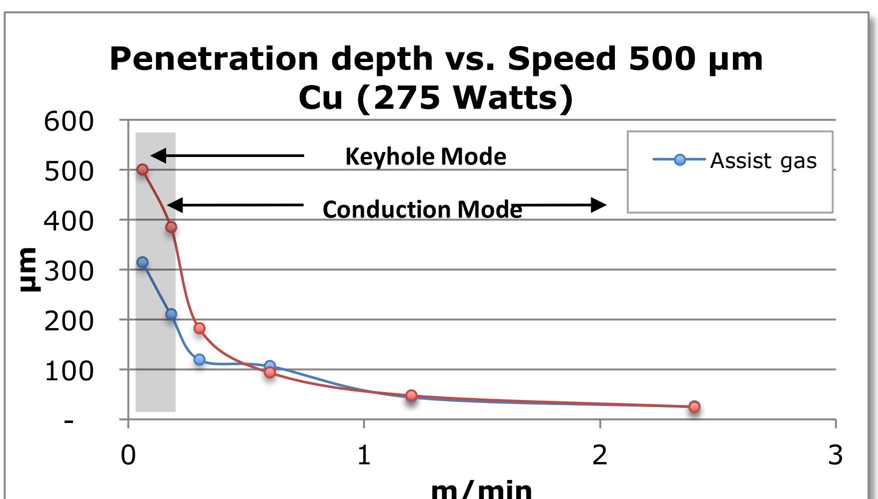

Fig 8. Bead-on-plate results for 500 µm Copper @ 275 Watts (with and without

Fig 9a. Cross section results for 500 µm Copper @ 275 Watts, 0.06 m/min –

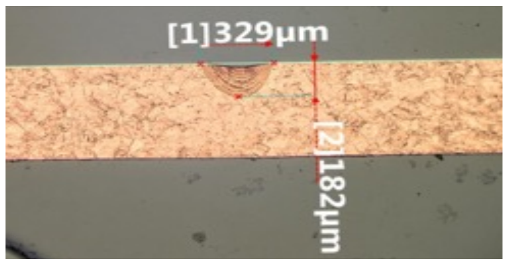

Fig 9b. Cross section results for 500 µm Copper @ 275 Watts, 0.3 m/min – conduction mode

3.4. Stacked Foil Testing with 8 µm Copper

One of the most important joining requirements in the manufacturing of a battery is the ability to weld stacks of copper foil ranging in thickness from 6 to 10 µm. A series of welding test were conducted using 8 µm thick copper foil with a stack height varying from 10 to 20 layers. The test using 10 layers of 8 µm thick foil produced a solid weld bead through all layers with no spatter on the surface, no blow-through holes and very limited porosity. This weld was performed with 130 Watts of laser power and the weld quality and porosity is highly dependent on how the foil stack was clamped. The weld was cross-sectioned to verify the quality of the weld, there is an indication of a small pore in the lower left corner, which can probably be eliminated with better fixturing (Figure 10a).

Additional tests were conducted with 20 layers of the same 8 µm thick oxygen-free copper foil using a laser power of 260 Watts. Again, the weld bead was cross-sectioned (Figure 10b) to examine the integrity of the weld, and very little porosity is observed which can most likely be eliminated with better fixturing and cover gas. The top and bottom surfaces exhibited a smooth, clean weld bead with no spatter or blow-through holes observed. Additional tests need to be performed on these foils, but the initial test results suggest a wide processing window with a strong dependence on the clamping means.

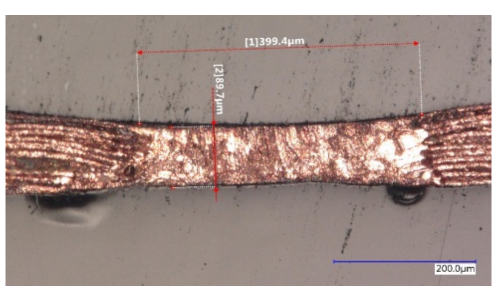

Fig 10a. 10 layers of 8 µm Copper foil, 130 Watts @ 0.72 m/min

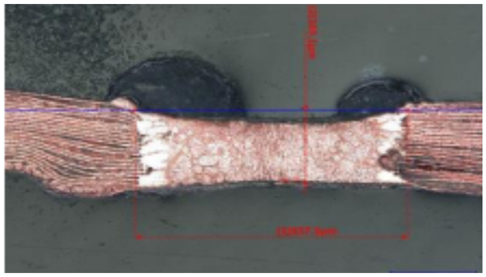

Fig 10b. 20 layers of 8 μm Copper foil, 260 Watts @

4. Summary & Conclusion

This paper has demonstrated the advantage of using a 450-nm laser for welding copper foils, copper plates and a stack of thin copper foils. The highly stable conduction and keyhole welding regimes show low spatter and porosity over a wide operating envelope. These spatter free processes will be very beneficial for the growing market demand of batteries and electrical component manufacturing. Higher power systems are in development at NUBURU and will show deeper penetration at higher speeds with wide processing windows making the blue laser system the clear system of choice for welding copper materials.

References

1. E. Spisz, A. Weigand, R. Bowman and J.Jack, “Solar Absorptances and Spectral Reflectances of 12 Metals for Temperatures Ranging from 300 to 500 K,” NASA Technical Note TN D-5353, Lewis Research Center, August 1969.