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500-Watt Fiber Coupled Blue Laser System Welding Results

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Abstract

This paper will present the welding results from a 500-Watt fiber coupled blue laser system. The system is based on 200-Watt blue laser modules that are coupled to a 400-μm optical fiber. The optical fiber is terminated with QBH connectors which allows the easy adaption to most welding heads. The test results with this laser using a 2:1 welding head (215-μm spot) showed a substantial improvement in welding speed or penetration over previous results obtained with a prototype free-space coupled system. The prototype free-space system was tested at a 20-degree angle of incidence and the motion system was a FANUC 6-axis robot. The speed improvements for this system are attributed to three factors: 1) the improved beam uniformity, 2) the ability to process at normal incidence, and 3) the use of a precision 3-axis gantry system. A summary of the improved welding results will be presented.

Keywords: Welding; Copper; Blue; Laser

1. Introduction

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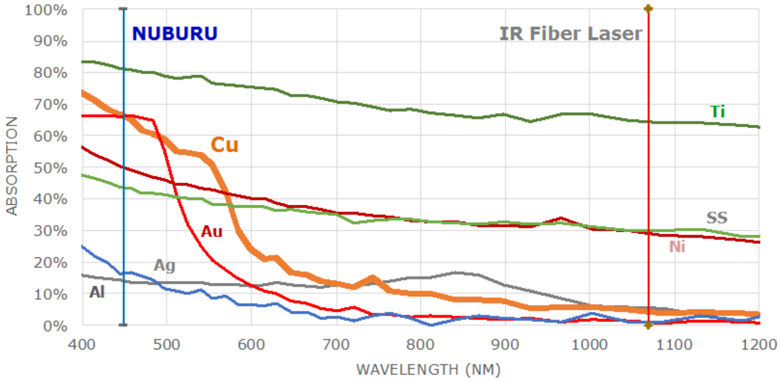

Fig. 1. Absorption characteristics of metals at room temperature.[1]

The manufacturing of battery cells, battery packs, electronics and automotive components/assemblies all require a method to reliability weld copper at a high speed and with no spatter or defects in the weld. The 500-Watt fiber coupled blue laser system developed by NUBURU Inc. is the answer to this demand. Spatter-free and defect-free welds can easily be accomplished with this system due to the high absorptivity of the blue laser light by the copper, gold, or aluminum materials. This contrasts with the low absorption characteristics of these metals at the infrared wavelengths Figure 1. The high absorptivity means that a lower power is required to initiate the welding process, and since the power does not need to be controlled and the beam does not need to be wobbled during the welding process, the weld monitoring system is greatly simplified. This means a lower capital cost for the installation since a less complicated welding head is all that is needed to weld the materials. The welding head used in these tests is shown in Figure 2, where the beam can be scaled 1:1 or 2:1 to achieve a spot size of 400 μm or 215 μm. The input to the head is a standard QBH connector, there is a protective window at the base along with an air knife for keeping welding fumes from contaminating the window. The welding head was designed by NUBURU and has an optional weld monitor which fits between the upper half and lower half of the square lens holder at the bottom of the head. Earlier tests with the 500-Watt prototype were conducted with free space coupling from the laser to the workpiece. As will be reported in this presentation, the 500-Watt system (Figure 3) used in these tests was fiber coupled. The homogenization of the spot due to the 5-meter-long optical fiber combined with the ability to process at zero degrees resulted in a substantial improvement in welding speeds and penetration depth.

2. 500-Watt Laser System Tests

The 500-Watt product developed by NUBURU is CE certified and operates from 208V single phase power. The system power can be controlled either through the ethernet interface or by a simple 0-10V analog signal. The system is 24" (61 cm) wide by 20" (51 cm) tall by 39" (99 cm) deep. The output of the laser is an industry standard QBH cable that is 400 μm in diameter and exits the back of the laser unit. All user interfaces are on the back side of the unit including the power hookup, the water hookup and the electrical interfaces. The cooling requirements for the system are a water / glycol mix in the system for corrosion protection and when the chiller is located remotely in a freezing environment. There are no special requirements for the water other than the filter recommended for the system.

Fig. 3. 500-Watt fiber coupled blue laser system (AO-500).

Fig. 2. BlueWeld™ processing head without the weld monitor.

The welding tests were conducted at zero degrees incidence to the surface in a gantry system manufactured for NUBURU Inc. by Formalloy. This system can contain a fully inert processing atmosphere and perform Laser Additive Manufacturing (LMD) test. Figure 4 shows the gantry system with a Laser Mech / Formally cladding head mounted in the system prior to performing copper deposition tests.

Fig. 4. Gantry system used for testing the welding characteristics of the blue laser system and BlueWeld™ processing head.

3. 500-Watt Laser System Design

The 500-Watt product (AO-500) is based on individual blue laser diodes and is designed to provide 500 Watts CW from a 400 µm-0.22 NA optical fiber. The system uses four 200-Watt modules through spatial and polarization beam combining to create the composite beam that is launched into the optical fiber. The optical and mechanical tolerancing of the system were designed in order to allow for field replacement of the laser modules or the fiber cable without realignment of the system. A diagram of the optical system is shown in Figure 5, each of the modules produces up to 200-Watts of output power from 4 OSRAM PLPM4 450 packages which are rated to operate at 50-Watts CW.

Each of the laser diodes in the package are first collimated in the fast axis by a high F# aspheric lens. The

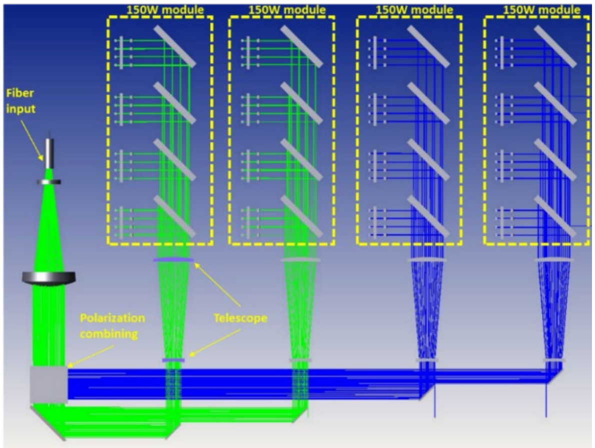

Fig. 5. Optical schematic of 500-Watt blue laser system (AO-500).

slow axis of each laser diode is then collimated individually with a slower F3 aspheric lens. The resulting beamlets are then combined in a series of patterned mirrors to fill up the space between each of the rows of the laser diodes in the package. These patterned mirror fold the beam 90 degrees to form a composite beam that is 5 beamlets wide by 16 beamlets high. This approach enables the system to achieve the highest brightness possible because there is no need to compensate for bar bow, or to give up brightness due to the packing factor on the bar.

The composite beams now have different divergences in the fast and slow axis. A 1:2.7x Galiean telescope is used to compress the fast axis of the composite beam to circularize the divergence out of the module. This beam compression allows a single focussing lens to create a neary circular spot on the face of the fiber and enable very high coupling efficiencies in excess of 90%.

After the beams have been compressed in the fast axis, they have a rectangular cross section and can be combined spatially to create a square cross section. A pair of shearing mirrors are used to spatially combine each pair of modules in the fast axis, which minimizes the distance between the beamlets from adjacent modules. These composite beams are then overlaped in polarization in a single cube with a waveplate integrated onto the cube for rotating the polarization of the incoming composite beamlets. The resulting beam is then focussed into the fiber with a single aspheric lens.

At this wavelength, the fibers have a transmission loss of nearly 1%/meter, consequently, when launching into an optical fiber, it is necessary to take the loss factor into consideration when calculating the effective coupling efficiency. The two early units that were built and tested achieved a 90% and 92% power transmission efficiency from the asphere to the exit of the 400 μm core fiber. When correcting for the fiber transmission losses, this corresponds to a launch efficiency of 95% and 97%, where the latter is the theoretical maximum. Because of this high coupling efficiency and the repeatability of the QBH connectors, test have confirmed that the fiber can be replaced in the field with little or no power penalty. Multiple connect and reconnect tests were performed with several different fibers to confirm the design.

Figure 6 shows the power vs. current curve for the first two units built, the first unit achieved over 650 Watts through the 400 μm fiber, while the second unit achieved 700 Watts through the same size fiber. Tests were also conducted plugging and unplugging the laser modules from the optical bed and confirmed the ability to replace the laser modules in the field.

The QBH connector is a robust soluton for this wavelength and power. Significant long term testing has been performed both at the diode level and the system level. Figure 7 shows the long term test results for one of the modules being operated at its rated power of 150 Watts for over 1800 hours. This unit has

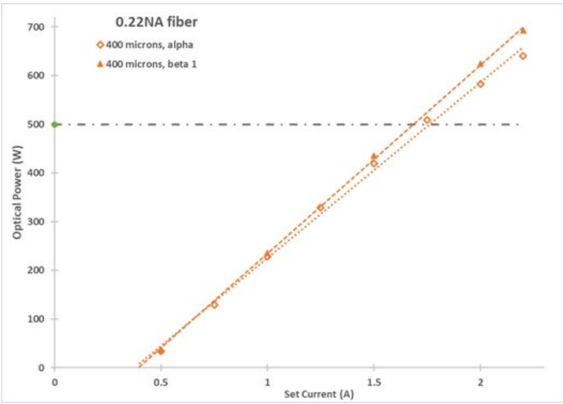

Fig. 6. Power vs. current curves showing the first Alpha unit produced 650 Watts out of the fiber and the first Beta unit produced 700 Watts.

demonstrated a power degradation rate of < -1%/khr over the duration of the test. The goal for the AO-500 design is to provide sufficient power margin for the system to be able to operate at 500 Watts of output power for a duration of 20,000 hours. With a 1%/khr degradation rate, the sytem has to have at least 100 Watts of additional power margin to meet this goal. Based on the results shown in Figure 6, the system is capable of meeting the 20,000 hour lifetime goal.

4. Copper Welding

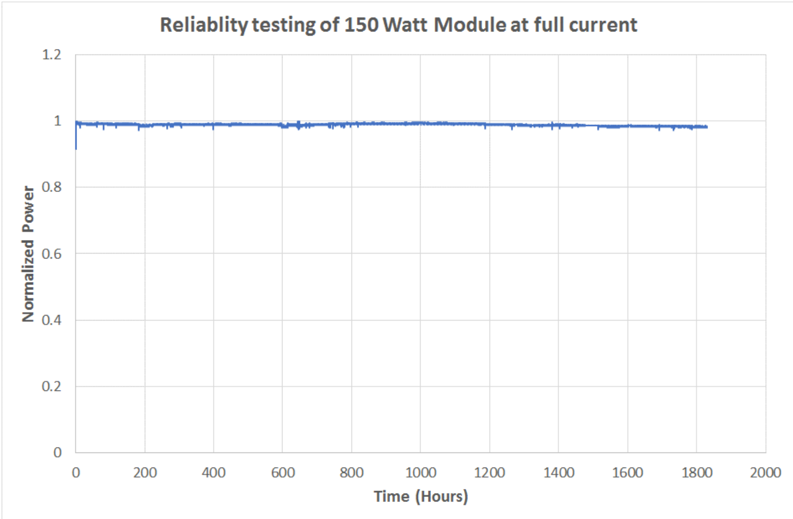

Fig. 7. Long term testing of 150-Watt modules at full rated power for >1800 hours demonstrating <-1%/khr degradation rate.

Welding copper with an infrared laser can be challenging due to the low absorption (~5%), high thermal conductivity, and low viscosity of the molten copper. The keyhole can become highly unstable resulting in the ejection of large amounts of copper in the form of spatter across the surface of the parts being welded, as well as high porosity in the weld joint. Methods have been employed to stabilize the weld puddle such as modulating the laser power, wobbling techniques, using multiple beams to open-up the keyhole, elongating the keyhole to enable the gases to escape and mixing a green laser with an IR laser. Even though these approaches improve welds to some extent, the fundamental problem of laser absorptivity and the instabilities it leads to result in a substantial amount of spatter on the part when using an IR laser. The process is simpler and more controllable when using a blue laser system because of the high absorption (~65%) of the copper at this wavelength.[2] The test results presented in the following subsections illustrate the various advantages for welding applications resulting from the 12x higher energy coupling of blue laser systems.

4.1 Processing Results with Breadboard Laser

The high absorption (Figure 1) of copper at 450 nm allows both conduction and keyhole welds to be achieved by varying the optical power and/or the welding speed (Figure 8). The metallographic cross sections presented in Figure 8 show bead on plate welding tests on a series of different thickness copper

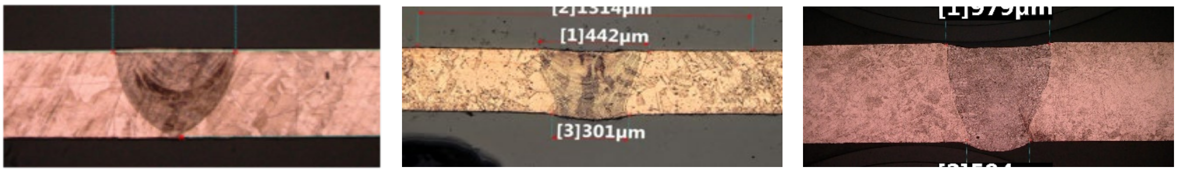

Fig. 8. Welding of copper sheet of different thicknesses: (left) 254 µm thick, welded at 275W; (center) 500 µm thick, welded at 500W; (right) 1 mm thick, welded at 600W.

materials. The thinnest material welded is a 254 μm thick sheet of Electrolytic Tough Pitch (ETP) copper on the far left. This sample was welded with 275 Watts of power using the breadboard 500-Watt laser system. The breadboard laser system was free space coupled to the part being welded and was capable of operating at up to 700 Watts CW. The middle picture is a 500 μm thick sample that was a transition keyhole-conduction mode weld at 500 Watts and the right-hand picture is of a 1 mm thick Oxygen Free Copper (OFC) sample keyhole welded with 600 Watts of laser power. All welds that were performed showed the same features, no spatter and no porosity as well as a wide processing window.

Lap welding tests as well as butt welding tests were also conducted with the 500-Watt breadboard laser, the results are shown in Figure 9 for a copper-zinc alloy. The picture on the left is for 2 sheets of 200 μm thick copper-zinc welded at 500 Watts in the keyhole mode. The cross-sections clearly show no porosity in the weld and no spatter attached to the top side of the plate. The objective of this first weld was to demonstrate the ability to do a full penetration of the top layer and partial penetration of the lower layer. The picture in the center is the same material, but now welded with a full penetration weld. The tilt of the weld puddle can be attributed to the 20 degree off axis welding angle used in the processing of the copper with the breadboard set up. The final picture is a full penetration butt weld of the same two sheets of copper-zinc, there is no evidence of porosity or spatter in the cross section.

Fig. 9. Lap welds of 2 sheets of 200 μm thick copper, at 500W and 230 μm beam diameter. (left) partial penetration; (center) full penetration. (right) butt weld of the same sheets.

4.2 Processing Results with AO-500

A significant number of welding characterization tests were performed using the 500-Watt optical breadboard. The differences between the breadboard and the product are numerous. The breadboard was built on an optical bench with free standing optical components and the spot was prone to drifting. Since the breadboard was a free space delivery system the test samples were tilted at 20 degrees during the welding process to avoid back reflections into the laser modules. The AO-500, however, is fiber coupled using an industry standard QBH connector that is capable of withstanding full back reflections from the part. When welding copper in the conduction mode this can be up to 35% of the incident power. The initial tests with the breadboard were conducted with a 400 μm spot size while the tests with the AO-500 were conducted with both a 215 μm spot size.

NUBURU developed the BlueWeld™ processing head shown in Figure 1 to test the impact the smaller spot size would have on the penetration depth and welding speed of copper. The Blue Weld processing head can be configured as a 1:1 head with a 400 μm spot size and a 170 mm stand-off distance or as a 2:1 head with a 215 μm spot size and a 65 mm stand-off distance. Given the quiescent nature of the weld puddle when welding copper, the 65 mm standoff distance is sufficient to minimize the contamination of the protective window during welding. The spot for the welding head is shown in Figure 10, it measures approximately 215 μm. This welding head also has an optional on-axis weld monitor and an illumination system to allow monitoring of the weld puddle relative to the seam to be welded. The camera used is a MAKO U-051 and can capture up to 2131 frames per second. An image of the keyhole captured at 1048 fps is shown in Figure 11, at this speed, any spatter process can be easily seen.

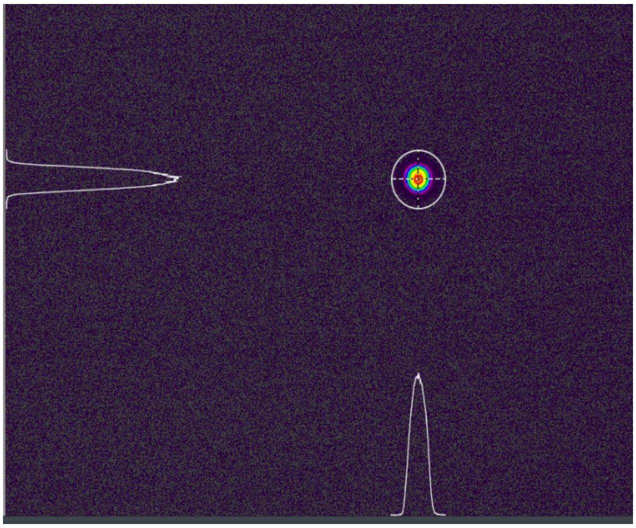

Fig. 10. The spot at the focal plane of the BlueWeld™ processing head measures approximately 215 μm.

The Blue Weld head was mounted in the gantry system shown in Figure 4 and an Argon cover gas is used to suppress the plume and to control the oxidation of the parts as they are welded. One of the key issues with welding copper is the high absorption in the plume that is created during both the keyhole welding process. Consequently, an Argon jet is required to control the plume and force it away from the incoming laser beam. If the plume is not suppressed, then the welding performance is substantially reduced. Various orientations of the Argon jet have been tested. The results presented today are for the Argon jet orientated at a 35-degree angle from the part and blowing the plume in the opposite direction of travel. The initial results of the tests comparing the breadboard's performance with a 400 μm spot size and to the AO-500 / BlueWeld™ head performance with a 215 μm spot size is shown in Figures 12 and 13.

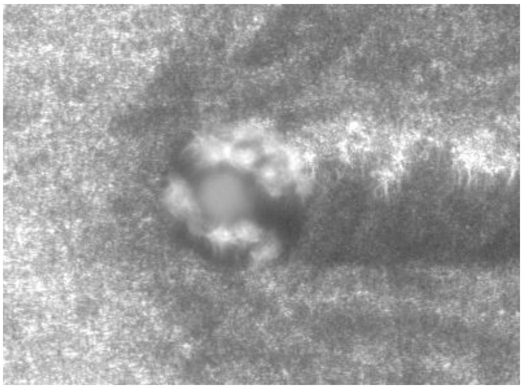

Fig. 11. High speed image of keyhole showing no spatter during the processing of ETP copper.

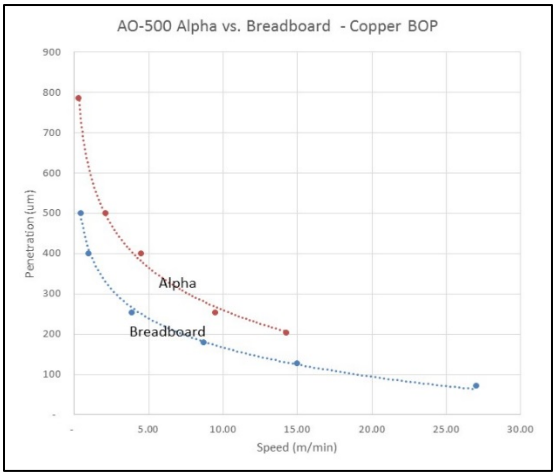

Fig. 12. Bead on plate test results for ETF copper comparing the breadboard with a 400 μm spot size and the AO-500 with a 215 μm spot size.

Figure 12 shows the improved penetration and processing speeds achieved in the bead on plate tests with ETP copper. The penetration depth increases by a factor of 1.6x for a given processing speed, while the processing speed for a given penetration depth increases by a factor of 1.6x as well. This improvement can be attributed mainly to the smaller spot size which enables the weld process to better overcome the thermal diffusivity of the copper material.

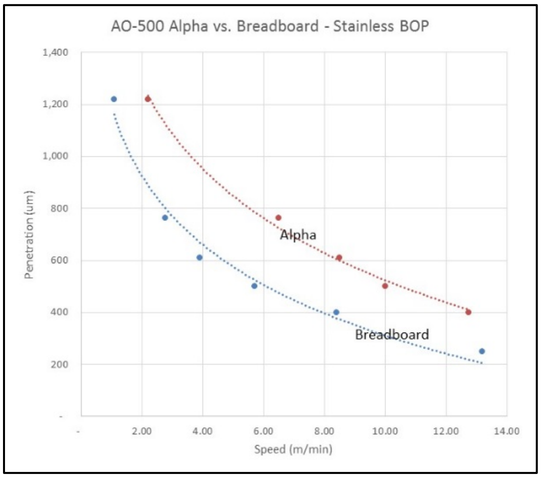

Fig. 13. Bead on plate tests on 304 stainless steel comparing the breadboard with a 400 μm spot size and the AO-500 with a 215 μm spot size.

A similar result is observed in 304 stainless steel as shown in Figure 13. There are three major differences when comparing copper to SS. The absorptivity of the stainless is less than copper, (45% vs. 65%), the thermal conductivity of SS is much lower than copper and the melting temperature of SS is much higher than copper. As can be seen in Figure 13, the most important factor is the thermal conductivity. Copper's high thermal conductivity makes it an excellent heat sink, so it is difficult to overcome the thermal diffusivity of copper. Stainless steel on the other hand has about 1/28 the thermal conductivity of copper, so the heat that is deposited does not conduct away very fast and consequently the melting point of the stainless steel is achieved rapidly. Therefore, the penetration depths in stainless steel are much deeper than they are in copper for the same processing speed.

4.3 Welding Applications

Bead on plate tests are always helpful in understanding the characteristics of a welding method, but it is necessary to test the system's ability to perform real world welds in the area of batteries, electronics and automotive electronics. Figure 14 is two sheets of 500 μm OFC welded with 500 Watts of power and the 215 μm spot size. This weld configuration is typical for a bus bar application, where a group of batteries

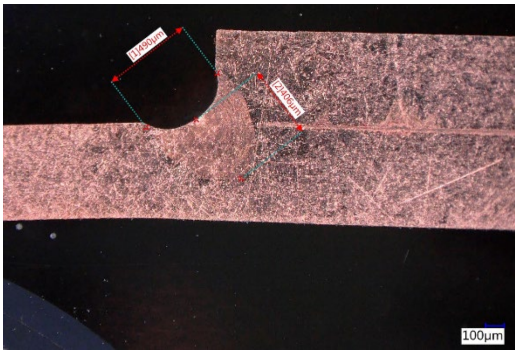

Fig. 14. Bus bar weld performed with the AO-500 and the Blue Weld processing head operating with a 215 μm spot size.

need to be welded together. The laser was positioned to be at a 45^{o} angle of incidence to the lower plate. The spot was focused evenly on the upper and the lower sheets to promote even melting of the two sheets. The two sheets were clamped together as close to the seam as possible before the laser was turned on. This weld was performed at 0.6 m/min and with 25 cfh of Nitrogen cover gas.

Fig. 15. Stack of 40 – 10 μm foils welded with the 500-Watt laser.

A test of the laser's ability to weld a stack of ETP copper foils was performed with up to 40-10μm foils. In this test, the weld was performed as a lap weld where all the sheets must be evenly melted without cutting through the upper layers. The clamping method used in this test is critical and requires a small bump under the weld position to provide a strong clamping force at the point of the weld. The weld is performed with a 215 μm spot size at a speed of 0.6 m/min. The key features in this picture are that the weld exhibited no porosity, no spatter and all layers are evenly welded together.

Additional testing with even a greater number of foils resulted in the successful welding of up to 70-8μm foils. This test, however, concentrated on welding the foils directly to a thick copper electrode. The resulting weld was also performed as an edge weld at a rate of 1.2 m/min instead of a lap weld. The results of this test are shown in Figure 16, the small porosity formed in the middle of the large weld bead is from the gap between two adjacent foils being larger than intended and as a result a small void was formed. Smaller voids at the interface to the large weld bead are the result of the simple welding fixture used to clamp the parts. The porosity can be minimized or eliminated with a more optimized fixture and process. This initial test however shows the feasibility of performing an edge weld on many foils simultaneously.

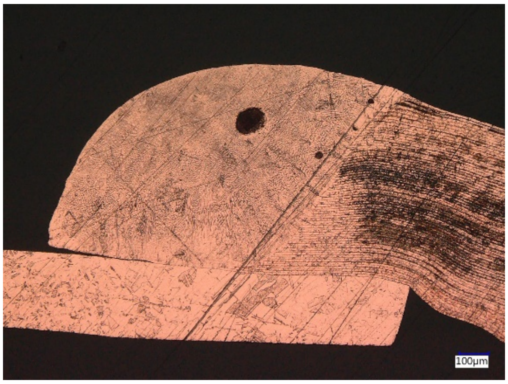

Fig. 16. Stack of 70 – 8 μm foils welded with the 500-Watt laser and a 215 μm spot size to a 254 μm thick electrode.

A test with the 500-Watt laser was performed on a stack of mild steel and two copper sheets as shown in Figure 17. The mild steel is 300 μm thick and the two copper sheets are each 80 μm thick. The objective of this test was to weld through the mild steel and not fully penetrate the last copper sheet. Not penetrating the last sheet of copper is important for the long-term reliability of the better because the copper will not corrode when in contact with the electrolyte, but the steel will. This is a typical weld found in a cylindrical Li:ion battery at the base where the outer case must be attached to the inner copper electrodes. As can be seen from the picture, a controlled depth of penetration was achieved and because of the large process window it was very repeatable.

The stator in an electric motor has many electrical connections which need to be welded in order to complete the motor construction. The wires which connect each of the stator windings together is referred to as "hairpins". These hairpins are typically a 1 mm x 2 mm to 1 mm x 3 mm square wire that is standing on end exiting the stator. The hairpins are coated with an insulating material which can be removed readily with the blue laser operating in a pulsed mode prior to performing the weld (Figure 18). Using the 500-Watt

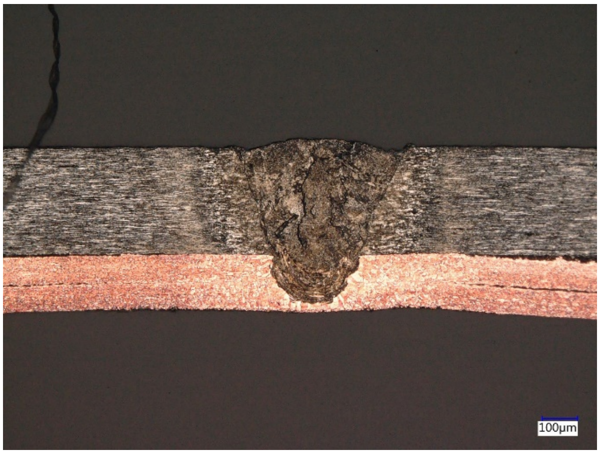

Fig. 17. Example of the partial penetration welding of a cylindrical battery cell case to the inner copper electrode with the 500-Watt laser

laser with a 215 µm spot size, a pair of 1 mm x 2 mm hairpins were welded in less than 0.35 seconds (Figure 19). The weld that is achieved shows no signs of spatter or porosity after cross sectioning. This weld must have these characteristics because spatter could damage the insulation of the adjacent hairpins leading to a short, while porosity would weaken the weld and result in a higher resistance than desired. In addition, since the weld is achieved in such a short time frame, there is no damage to the insulating layers leading into the stator assembly. Further process optimization should enable this weld to be performed in less than 0.15 seconds. Therefore, the 500-Watt blue laser is an ideal solution for achieving a strong, spatter free, porosity free weld of the hair pins.

Fig. 18. Stripping of the insulation on a 1.5 mm x 4 mm copper conductor using 150 Watts at 6 m/min.

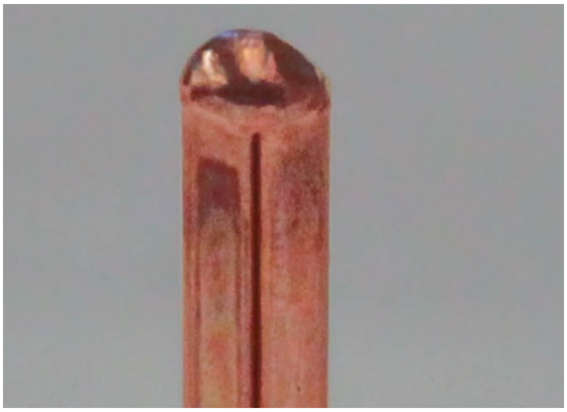

Fig. 19. Hairpins welded with the 500-Watt blue laser with no porosity or spatter.

5. Conclusions

The 500-Watt laser developed by NUBURU Inc. was developed for welding copper and copper alloys. The laser has been tested for its ability to perform many of the welds commonly found in batteries and electric vehicles. Test results on welding copper foils, thick copper materials, thin copper materials, dissimilar metals combining copper to steel and aluminum were all successful, demonstrating the unique ability to weld these materials with excellent weld quality, improved weld strength, no porosity and no spatter.

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