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Laser welding of e-mobility materials with variable beam profile lasers and pulse shaping

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Abstract

Most of the big automakers around the world are focused on electric vehicles. The battery technology used in these vehicles is lithium-ion batteries because they are smaller and lighter than existing automobile batteries. Batteries used in electric cars are built from a variety of materials, and one of the primary materials is copper.

The use of Variable Beam Profile (VBP) lasers for welding e-mobility materials is demonstrated. The VBP laser uses a dual beam outlet to produce a central point surrounded by another concentric ring of laser light. The use of VBP lasers results in more stable and consistent welding during welding.

This paper highlights welding results achieved with a VBP fibre laser, and power ranging from 6kW to 12kW (different beam qualities) on e-mobility materials and weld joints including dissimilar joints between copper and aluminium-based alloys. The VBP laser results are compared to those obtained via, for instance: pulse shaping of traditional single-beam lasers.

Keywords: Variable beam profile laser; welding; copper; aluminium-based alloy; dissimilar material joints and pulse shaping

1. Introduction

Various types of batteries are used in a range of e-mobility applications, including automobiles, buses, trucks, off-road vehicles, ships, ferries, and other seagoing vessels. The lithium-ion batteries used in e-mobility applications are manufactured from a combination of different materials and one of the leading materials is copper; the most significant driver is the electric vehicles expected to drive copper demand figure 1. All types of electric vehicles (EVs) require a great deal of copper and use a lot more copper than conventional vehicles equipped with internal combustion engines, the International Copper Association (ICA).

- Internal combustion engine: 23 kg of copper.
- Hybrid electric vehicle (HEV): 40 kg of copper.
- Plug-in hybrid electric vehicle (PHEV): 60 kg of copper.
- Battery electric vehicle (BEV): 83 kg of copper.
- Hybrid electric bus (Ebus HEV): 89 kg of copper.
- Battery-powered electric bus (Ebus BEV): 224–369 kg of copper (depending on the size of the battery).

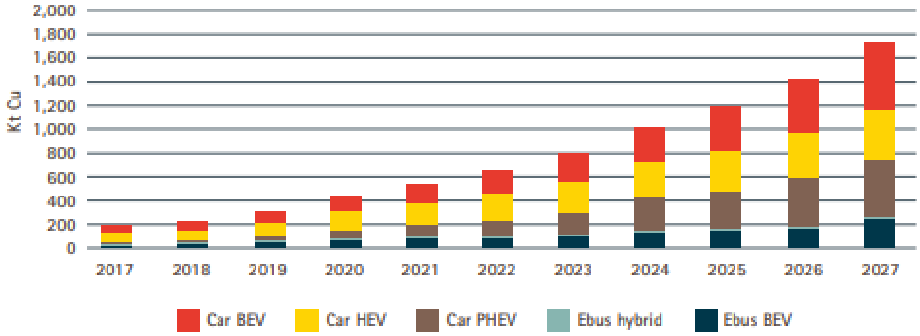


Fig.1. Electric vehicle copper demand (Ref. International Copper Association)

Copper possesses several desirable electrical, thermal, mechanical, and cost characteristics compared to other metals, which is why it is used throughout EVs. Its desirable properties also make it challenging to weld with traditional laser sources like fibre, disk etc., regarding the weld quality, i.e., porosity, inconsistent welds, and poor surface quality. The weld quality is essential because it needs to operate safely and reliably for the whole life cycle stipulated by the vehicle manufacturer, which is at least ten years. As a result, high-power, solid-state green and most recently blue lasers have emerged as a possible alternative for copper welding because these wavelengths are more strongly absorbed by that metal. But both green and blue lasers respectively possess several practical limitations which ultimately result in higher cost of ownership.

Three different types of lithium-ion batteries are used in electrical mobility applications figure 2. The components used to transport electricity inside a lithium-ion battery are aluminum alloys and pure copper. The thickness of these materials varies based on the type of battery, as illustrated in figure 2. The final welding steps in the cell assembly are the sealing of the can seals, which creates a barrier for the internal electrolyte and the welding of the material tabs to negative and positive terminals. It also makes the electrical contacts for the package. Materials include stainless steels, alloys based on aluminum and magnesium alloys figure 3.

Prismatic cell, Al/Al, Cu/Cu and Al/Cu lap joints, Sub-mm, and thicker materials (1-2mm)

Cylindrical cells, Sub-mm thicknesses, Commonly Ni-plated Cu to Ni-plated steel lap joint corrosion, also improves coupling of IR radiation.

Pouch cells, Similar sub-mm thicknesses Multiple stacks possible Commonly Al/Al, Cu/Cu and Al/Cu lap joints

Fig.2. Types of lithium-ion batteries and types of materials/weld joints used to build the batteries.

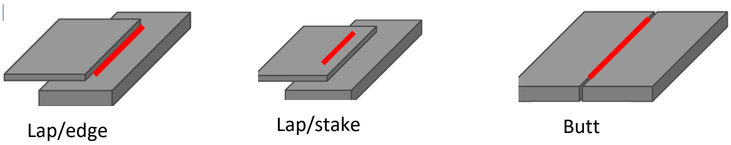


Fig.3.Type of joints for battery cases, Al, Mg alloys and stainless steel, 1-5mm thick

The boom in E-mobility manufacturing is the main factor driving a significant increase in development of new laser sources to weld difficult within the battery pack, i.e.

- heat-sensitive material
- Highly reflectively and crack sensitive materials like aluminum, copper, and high strength steel
- Joining of dissimilar materials

Successful welding of these materials requires laser source capable of producing high average power to meet the necessary production throughput rates and to produce full penetration welds when welding thicker parts. The laser should also precisely control the way that laser power is distributed in terms of heating and cooling at the work surface over time.

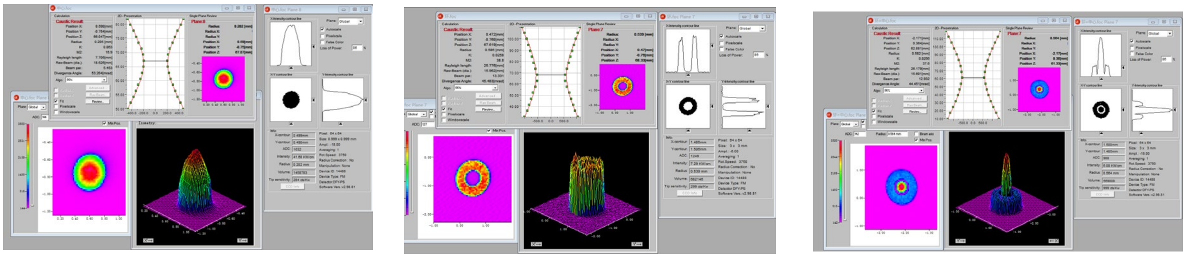
The VBP laser uses dual beam output to produce a central spot, surrounded by another concentric ring of laser light. The power in both the center and ring spots can be independently controlled and this enables very careful control over the melt pool dynamics modulated. The result is that the welding process is more stable and maintains consistently during welding, regardless of surface variations in the work piece, thus overcoming the limitations experienced with traditional fibre lasers.

This paper highlights welding results achieved with a 6+6kW VBP fiber laser with e-mobility materials and weld joints including dissimilar joints between copper and aluminum-based alloys. Work was also carried out with traditional high power fiber lasers with continuous and pulsed outputs to develop pulse shapes to produce crack and porosity free welds and some of the results will be also discussed in this paper.

2. Experimental details

2.1 Variable beam profile laser

The welding tests were conducted on pure copper and a 6061 T6 -aluminum alloy with a EverFoton 6000/6000W variable beam profile fiber laser equipped with 100 and 600µm fibres for the core and ring respectively. The beam profiles for the core and ring are displayed in figure 4. Laser beam terminated at High-YAG welding head equipped with 200mm focal length lens. The core, ring and welding speed laser parameters were adjusted to produce welds with consistent top bead and under bead with minimal spatter. The focus position was variable, and it was determined that the best weld quality was when the focus was 1.5mm above the material's surface. More specifically, this was the best compromise between pentation and weld quality. The laser produces deeper weld penetration if it focuses directly on the material's surface. However, the quality of the weld surface and the resulting splatters are insufficient for typical mobility applications. A 10mm diameter pipe supplied the gas shielding for the upper weld bead. In all cases, nitrogen (10-15 l/min) was applied to the shielding.



Core only

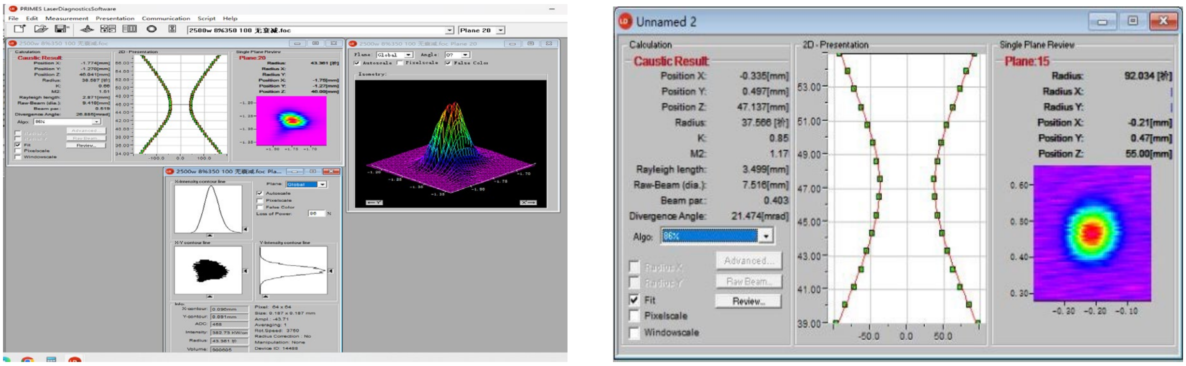
Ring only

Core + ring

Fig.4. Beam profile of 6+6kW VBP laser, core size 100µm with 6kW maximum average power, ring size 600µm with maximum average power 6kW

2.2 Pulse shaping

Welding tests with temporal beam shaping were performed with EverFoton low-power continuous wave (CW) and quasi-continuous wave (QCW) fiber lasers. The beam profiles of the two lasers are shown in figure 5. These tests were carried out on sub- mm thicknesses of copper and aluminium based alloys used in cylindrical and pouch cells. Pulse shaping allows the penetration depth of the weld to be optimised without distorting thin sections and splashes. This technique also permits the welding of different combinations of difficult materials by combining the best of keyhole and heat conduction welding.



Caustic Result
Position X: -1.774[mm]
Position Y: -1.270[mm]
Position Z: 46.041[mm]
Radius: 38.587 [illegible]
K: 0.66
M2: 1.51
Rayleigh length: 2.871[mm]
Raw-Beam (dia.): 9.410[mm]
Beam par.: 0.519
Divergence Angle: 26.886[mrad]
Algo: 86%
☐ Radius X
☐ Radius Y
☑ Fit
☐ Pixelscale
☐ Windowscale

Plane:20
Radius: 43.361 [illegible]
Radius X:
Radius Y:
Position X: -1.75[mm]
Position Y: -1.27[mm]
Position Z: 46.00[mm]

Plane: Global
☑ Autoscale
☐ Pixelscale
☐ False Color
Loss of Power: 86 %

Info:
X-contour: 0.096mm
Y-contour: 0.091mm
ADC: 468
Intensity: 382.73 KW/cm
Radius: 43.361
Volume: 900605
Pixel: 64 x 64
Size: 0.187 x 0.187 mm
Ampl.: -43.71
Averaging: 1
Rot.Speed: 3750
Radius Correction : No
Manipulation: None
Device ID: 14488

Caustic Result
Position X: -0.335[mm]
Position Y: 0.497[mm]
Position Z: 47.137[mm]
Radius: 37.566 [illegible]
K: 0.85
M2: 1.17
Rayleigh length: 3.499[mm]
Raw-Beam (dia.): 7.516[mm]
Beam par.: 0.403
Divergence Angle: 21.474[mrad]
Algo: 86%
☐ Radius X
☐ Radius Y
☑ Fit
☐ Pixelscale
☐ Windowscale

Plane:15
Radius: 92.034 [illegible]
Radius X:
Radius Y:
Position X: -0.21[mm]
Position Y: 0.47[mm]
Position Z: 55.00[mm]

SM 2kW CW laser

SM 150/1500W QCW laser

Fig.5. Beam profiles of low power SM CW & QCW fiber lasers

3. Results & discussion

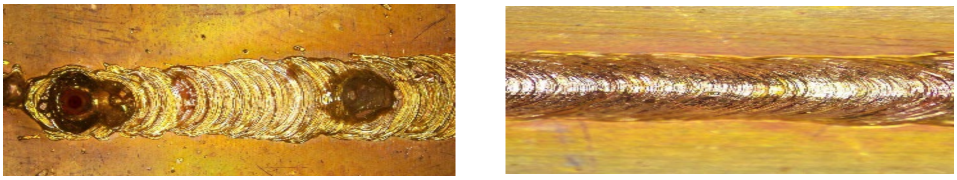
3.1 VBP laser

A series of welding tests for copper, aluminium, and dissimilar materials (Al Cu) were performed using an EverFoton 6 kW variable beam profile fiber laser. The average power in the core and in the ring was adjusted along with the welding speed to produce welds with consistent top bead and under bead with minimal spatter in the range of different material thicknesses for the material tested. Some of the findings are emphasized in subsequent sections.

- Pure copper

The results show that welding pure copper with a standard high power (6kW) CW fiber laser, the welding process was volatile regarding inconsistent weld penetration but more importantly, the formation of melt ejections, figure 6a. When laser welding copper with a specific feed rate, the tip of the keyhole begins to bend against the welding direction and a vapor bubble is formed, Heider A et al, 2013. The formation of the drop is due to increased absorption and vaporization caused by the bending of the keyhole. This bubble pushes against the liquid material in direction of the sample surface, which leads to swelling of the weld seam surface until the pressure created by the drop is higher than the surface tension of the melt pool. After passing this critical point, almost the whole molten material is ejected. To reduce the melt ejections, stabilization of the keyhole during the welding process is critical.

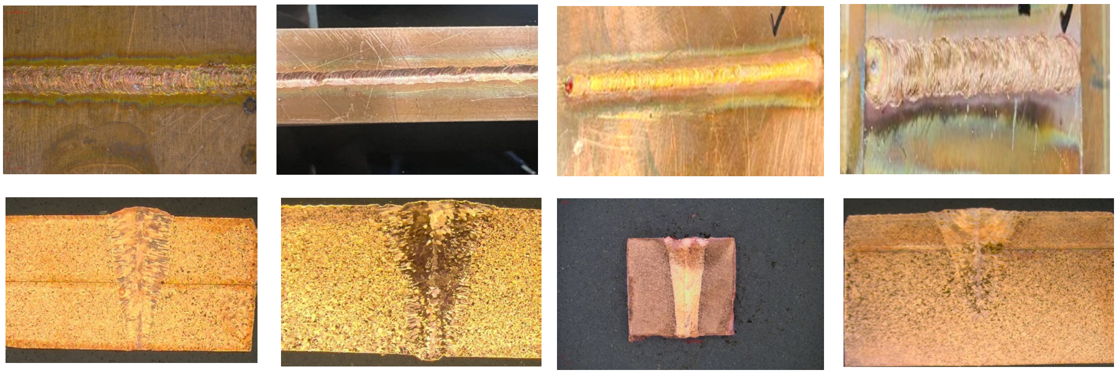
The welding tests carried out a VBP laser show that high intensity, high power centre beam is needed to provide the energy required to readily melt the material, while the ring beam helps stabilize the keyhole. The result is that the welding process is initiated and maintained consistently without formation of metal ejections, figure 6b regardless of surface variations in the work piece, thus overcoming the limitations experienced with traditional fibre lasers. The welding performance was very consistent with the range of material thicknesses and weld joint configurations respectively, as shown in figure 7.



(a) Weld made with traditional fiber laser, 6kW fitted with 100µm fiber, 4mm thick pure copper, 2.5m/min, inconsistent top bead with blow holes and spatter.

(b) Weld made with 6+6kW VBP laser, 4.5kW core, 1.5kW ring, 4mm thick pure copper, 2.5m/min, very consistent and spatter free weld.

Fig. 6. Weld quality comparison between traditional and VBP laser for pure copper welding, total power 6kW for both lasers



(a) 2+2mm overlap joint, 2.5m/min.

(b) 4mm butt joint, 2.7m/min.

(c) 6mm butt joint, 1.5m/min.

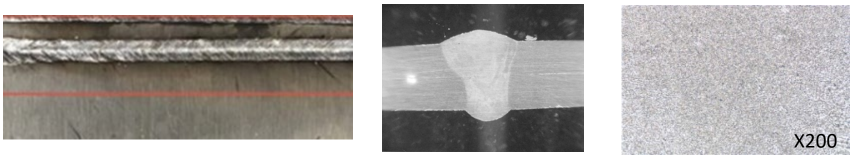
(d) 2+4mm overlap joint, 1.2m/min.

Fig.7. Copper welding, (a) 4.5+1.5kW, (b) 4.5+1.5kW, (c) 5.0+2.0kW, (d) 6.0+ 2.0kW

- Aluminium alloy

The major problems associated with laser welding of aluminium alloys, generally, are high surface reflectivity, high thermal conductivity, and volatilization of low boiling point constituents. These and other material challenges can lead to problems with welding and cracking of the heat affected area, degradation of mechanical properties and inconsistent welding performance. These problems are now overcome mainly with higher average powers, enhanced beam qualities producing a high-power density to produce a stable keyhole for welding. Although most aluminium alloys are considered weldable, some are likely to weld metal or crack in the heat affected area. This is especially true of aluminum alloy 6061, a heat-treated Al–Mg–Si–Cu alloy with high mechanical strength, due to its poor weldability and high crack susceptibility Tadamalle, et al. 2013, where cracking has been linked to the formation of Mg-Si precipitates. Unfortunately, this alloy also used in lithium-ion batteries, so having the right laser source and set parameters is essential to consistently produce good quality welds. Typically, the cracking can be reduced or eliminated by adding correct filler wire during laser welding, Naeem, 1999,2004 which lowers the freezing range of the weld metal and minimizes the tendency for solidification cracking. The major problems associated with laser welding of aluminum alloys, generally, are high surface reflectivity, high thermal conductivity, and volatilization of low boiling point constituents. These and other material challenges can lead to problems with welding and cracking of the heat affected area, degradation of mechanical properties and inconsistent welding performance. These problems are now largely overcome with higher average powers, enhanced beam qualities producing a high-power density to produce a stable keyhole for welding. Although most aluminium alloys are considered weldable, some are likely to weld metal or crack in the heat affected area. This is especially true of alloys in the 6xxx series, where cracking has been linked to the formation of Mg-Si precipitates. Unfortunately, this alloy is also used in lithium-ion batteries, so it is very important to have the right laser source and set parameters that can always produce good quality welds. Normally the cracking can be reduced or eliminated by addition of correct filler wire during laser welding, Naeem, 1999,2004 which reduces the freezing range of the weld metal and minimizes the tendency for solidification cracking.

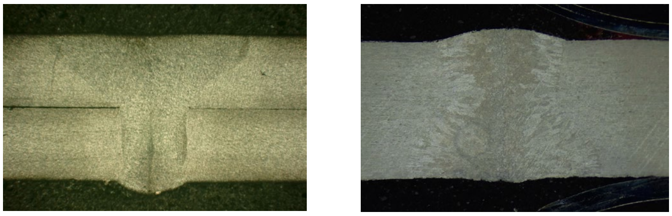
Work carried out with VBP laser has heightened the possibility of producing crack-free welds with optimized laser and processing parameters. Not only were the welds cracked free, but also there was no porosity which is also a big problem associated with these alloys during laser welding, figures 8 and 9.



Consistent topbead, no spatter or blowholes

Fusion zone, no solidification cracking

Fig. 8. 2mm thick 6061 T6 aluminium based alloy, butt joint, 3m/min, 1.5kW+2.5kW



2+2mm overlap joint, 2.5m/min, 1.5kW+2.5kW

6mm, butt joint, 2.0m/min, 2.0kW+1.5kW

Fig. 9. 6061 T6 aluminium based alloy

- Dissimilar joints (aluminium based alloy+ copper)

For joints of different materials, one of the most notorious combinations of welded metal, prone to cracks, is copper and aluminium, one of the most popular metallic combinations in lithium-ion batteries for electric mobility applications. The difference in the physical and chemical properties of copper and aluminium-based alloy during laser welding can often lead to the formation of brittle intermetallic phases, Naeem, et al, 2010, 2013, which are detrimental to the mechanical strength and ductility of the welded joints. This is unacceptable because the battery must operate safely and reliably for the entire life cycle stipulated by the manufacturer, and that's at least ten years.

Welding tests with copper and aluminum alloys demonstrated that they could be welded together in lap and butt joint configurations without weld defects. The VBP laser precisely controls the spatial distribution of output beam power, which consists of one central point, surrounded by another concentric ring of laser light. With this laser the energy in the center has been independently adjusted and modulated on demand to adapt the welding of dissimilar materials. This allows meticulous control of heat input and management of melt pool. The heating and cooling cycle reduces the tendency for Al/Cu seam cracking, figure 10.

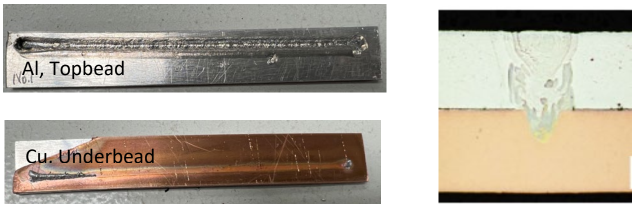
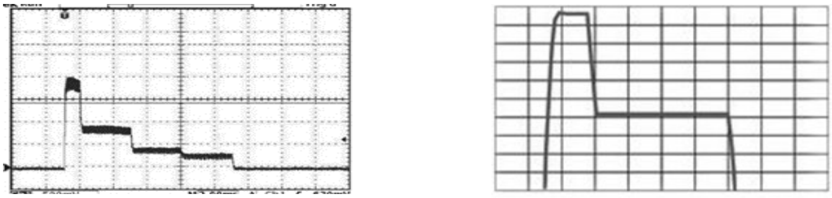


Fig. 9. Overlap joint between Al and Cu, partial penetration weld, reduced formation of intermetallics.

3.2 Pulse shaping

Laser welding requires the optimization of many parameters depending on the thermos- physical properties of the material, the environment, laser, and its process parameters i.e., peak power, pulse duration, pulse energy, pulse repetition rate, power density and temporal pulse shaping. A laser pulse is considered shaped when the power is varied during the pulse time. Development of the pulse shape depends strongly on what needs to be achieved by the laser weld, this can be a material type or combination which requires a controlled cooling down of the weld or a product tolerance that causes a gap between components that needs to be bridged or a material that has a temperature dependent laser light absorption. Typical pulse shapes, figure 10 for welding e-mobility materials include:



Ramp- down shape, for welding crack sensitive aluminium based alloy (6061) and for dissimilar materials (Al + Cu)

Enhanced spike, for welding very reflective materials with high conductivity (pure copper)

Fig. 10. Temporal pulse shapes used for welding e-mobility materials with low power CW & QCW lasers.

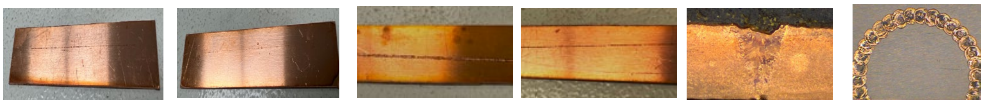
Figures 11-12 show examples of welds made with pulse shaping with materials with thin e-mobility materials (< 1.5mm). These materials are commonly used for pouch and cylindrical cells, respectively.

1mm 6061 T6 Al alloy, BOP, without pulse shape

1mm 6061 T6 Al alloy, BOP, with ramp-down pulse shape

Cu/Al spot welds

Fig. 11. Examples of ramp-down temporal pulse shape, material thicknesses <1.5mm



1mm pure copper, BOP, without pulse shape, no weld penetration

1mm pure copper, BOP, with enhanced spike pulse shape, full weld penetration

Pure copper battery terminals

Fig. 12. Examples of enhanced spike temporal pulse shape, material thickness <1.5mm, QCW laser

4. Summary

EverFoton carried out comprehensive testing programs on laser welding of electrical vehicle materials. These tests, which are currently in progress, covered a wide range of processing and laser parameters to study the weldability of aluminium alloys, pure copper, and dissimilar materials. The findings presented here for EV batteries demonstrated that.

4.1. VBP laser

These welding tests demonstrate that the EverFoton VBP high-brightness laser is convenient for various e-mobility materials, including copper and aluminium-based alloys. The results show that the weld penetration and process speed meet or exceed the required low-power electronic mobility applications and production requirements. The VBP laser avoids sensitivity to surface quality and process instability issues that have restricted the use of traditional fibre lasers for welding highly reflective materials (Cu & Al). To conclude, the VBP laser finally brings all the advantages associated with conventional fibre lasers, namely cost, reliability, and practical benefits have made these lasers the choice for several welding applications to the exacting task of e-mobility materials.

4.2. Temporal pulse shape

Welding tests carried out with pulse shaping have shown that it can help in increasing the weld penetration depth and eliminate weld carcking while maintaining a small pulse energy and reduced heat input, which is required for welding pouch and cylindrical cells because both cells are made with sub-mm thicknesses of aluminium-based alloys and pure copper. It also can provide for part conditioning before welding and postconditioning to reduce the cooling rate of the weld to reduce weld defects such as cracks, inclusions, and weld porosity.

References

The International Copper Association (ICA).

Heider. A , Stritt.P, Hess.A, Weber.R and Graf.T, “Process Stabilization at welding Copper by Laser Power Modulation“, Proceedings of

the Sixth International WLT Conference on Lasers in Manufacturing: LiM 2011, Amsterdam: Elsevier, 2011, pp. 81–87.Deep-Burn

Tadamalle. A.P, Reddy, Y.P., Ramjee. A, Influence of laser welding process parameters on weld pool geometry and duty cycle, Advances in Production Engineering & Management Journal, 215(15), 2013, 114-134.

Naeem. M, Aluminium Welding by lasers, a comparison of results with and without wire feed; Vehicle technology; The Journal of IBCAM; Volume IV (2); (1999)

Naeem. M, High Power Nd: YAG Laser Welding of Aluminium Alloys, Conference Proceeding; PICALEO 2004, Melbourne, Australia, April 19-21, 2004

Naeem. M, et al, Welding of dissimilar materials with 1kW fibre laser; Conference Proceeding ICALEO 2010, Anaheim, California, USA; September 26-30, 2010

Naeem. M, et al, Experimental Studies of Fiber Laser Welding of a Range of Dissimilar Material Combinations, Proceeding WLT-Conference on Lasers in Manufacturing 2015; Munich, June 2015