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An extended process window for copper welding with a tailored beam-shaping based on Multi-Plane Light Conversion

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Abstract

Copper is a popular material in electric engines due to its high electrical and thermal conductivity. However, welding copper can be difficult because of its low absorptivity of the laser energy at 1µm and high thermal conductivity. In this study, we introduce a new approach of copper laser welding using a Multi-Plane Light Conversion (MPLC) beam shaper which stabilizes the melt pool.

A high-speed x-ray imaging was used to evaluate the geometry of capillary and the occurrence of pores during the process showing that no pores are present for a wider set of parameters compared to a single-fiber process. According to X-rays and macrographics the developed system allows for deep penetration welding of depths of up to 2.8mm at 8kW and 3m/min, as well as welding up to 25m/min at 8kW. The system allows for defect-free welding at lower and higher speeds compared to dual-core fiber and single-fiber systems.

Keywords: Laser; Welding; Copper; E-mobility; MPLC; beam shaping; Busbars; X-Ray; pores; spatters; laser head

1. Introduction

The demand for copper welding has surged with the rise of the e-mobility market, primarily due to its extensive use as an electrical conductor. However, copper welding presents challenges because of its high reflectivity at the conventional infrared laser's wavelength (1 µm), resulting in limited energy for initiating the keyhole. At room temperature, copper absorbs only 5% of energy, but energy absorption increases during the liquid phase once the keyhole is initiated. Additionally, copper's high thermal conductivity makes welding unstable, leading to the appearance of various weld defects such as porosity, which can hinder electrical conductivity, spatter, causing potential short circuits, and cracks, negatively impacting mechanical performance. Considering the high cost of copper, it becomes imperative to avoid faulty parts. To achieve good electrical conductivity and component longevity, copper welds must be free from pores and spatter, necessitating the use of laser shaping. In this paper, we will explore an innovative method for laser beam shaping, leveraging Multi-Plane Light Conversion technology. We will delve into the details of the developed beam-shaping systems and the resulting process outcomes obtained with these systems.

2. Determining the optimal configuration with the Institut Maupertuis

2.1. Test Method

At the Institut Maupertuis, the MPLC Beam shaper laser head proved its relevance by being utilized to weld 10 mm thick Cu-ETP copper samples, employing argon shielding gas. The setup included an 8kW laser with a 100 µm diameter fiber, fitted with a beam shaping laser-head. This entire assembly was mounted on a 6-axis robot arm. To prevent equipment damage caused by reflections, the laser head was tilted. (Refer to figure 1).

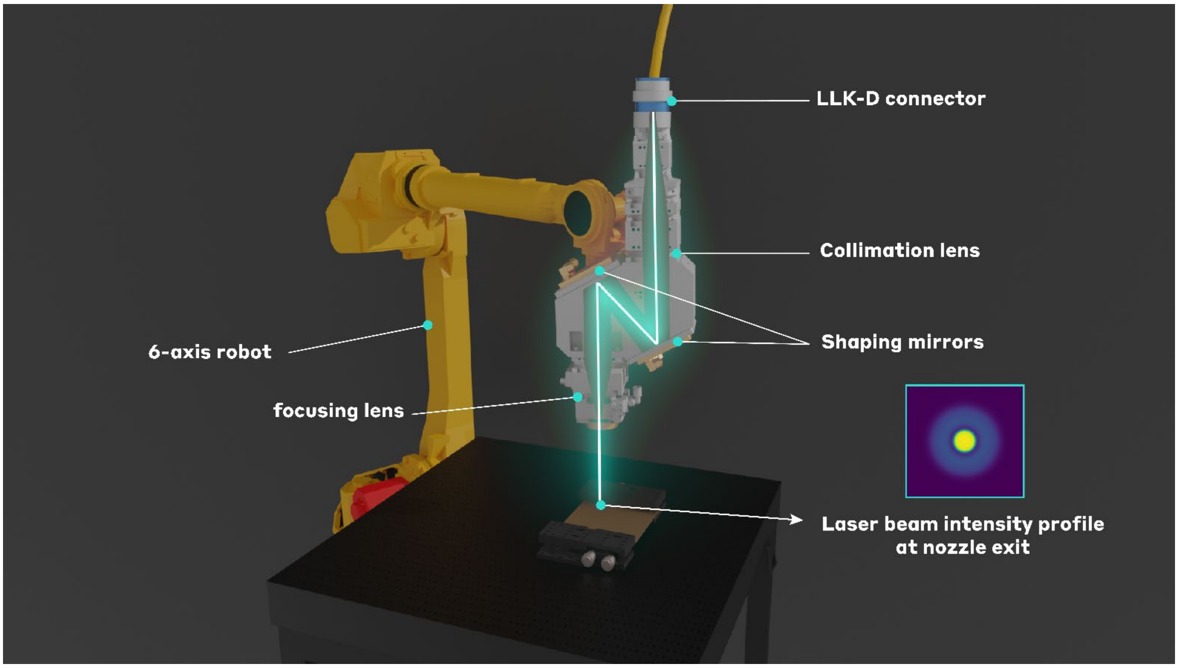


Fig. 1. Diagram of the Industrial Assembly

The primary objective was to assess the quality of the shaped laser beam profile, leading to a series of initial optical tests. Process tests were then conducted to explore different power ratios in between the spot and the ring, as well as varying beam dimensions. The four configurations tested are detailed in the Table 1 below:

Table 1. Table with the different configurations tested.

	"Small"	"Large"
Ratio: 30/70	**Configuration 1** Ø100 µm spot - 30 mW/cm² Ø400 µm ring	**Configuration 4** Ø125 µm spot - 20 mW/cm² Ø500 µm ring
Ratio: 50/50	**Configuration 3** Ø100 µm spot - 50 mW/cm² Ø400 µm ring	**Configuration 2** Ø125 µm spot - 30 mW/cm² Ø500 µm ring

2.2. Results

Of the four configurations tested, configuration 2 has provided the best results:

- It created more consistent welds.
- It produced weld beads with good penetration.
- It was the only solution that gave 100% compliant weld beads for penetrations of between 0.4 mm and 2.8 mm.

Fig. 2. Weld bead on the surface, 3 m/min - 8 kW – Configuration 2

This solution has been compared with conventional Brightline dual-core laser technology using a 5×5 test matrix. The aim was to identify the best process parameters and establish the process window, evaluating five power values ranging from 4 kW to 8 kW, along with five robot speed values varying from 3 to 15 m/min. The first criteria used for evaluating the results were weld bead stability and/or penetration.

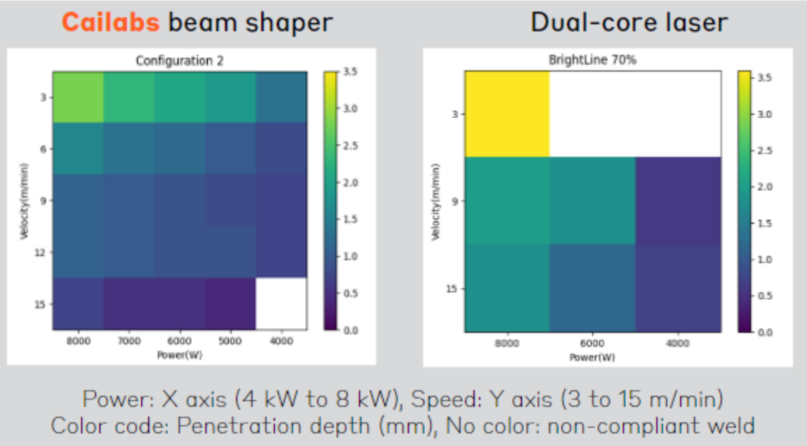


Fig. 3. Process Windows for the Cailabs head (left) and dual-core laser (right)

The color gradient in the visual representation indicates the penetration depth, and absence of color denotes non-compliant welds. Using the MPLC technology widened the process window by 1.25 times compared to other methods. For this specific sample, the optimal configuration involved welding at 3 m/min and 8 kW, which yielded a penetration depth of 2.8 mm without any pores or spatter in the weld. These tests conclusively demonstrate the compatibility of the MPLC Beam shaper with high-power industrial robot arms.

3. Weld quality Analysis with the IFSW

3.1. Test Method

To gain insights into the melt pool behavior, a second set of tests was conducted at IFSW, using X-ray imaging with the IFSW (Institute for Joining and Welding). In this experiment, the MPLC laser head was employed to weld 100 mm x 30 mm x 4 mm Cu-ETP copper samples, using argon shielding gas. The setup comprised an 8 kW laser combined with a 100 µm diameter fiber, fitted with the beam shaping laser-head. Unlike the previous tests, this time, the head was configured to generate a 70% center and 30% ring profile, in order to widen the process window. The dimensions of the ring diameter (500 µm) and central spot (125 µm) remained the same as in the previous experiments.

A matrix of 3 x 7 tests, involving three power values and seven robot speed values, was examined using X-ray imaging. This analysis aimed to determine the capillary length and visualize the formation of pores and spatter. To facilitate X-ray imaging, an X-ray tube was positioned in front of the sample, while a camera was placed behind it. As a precautionary measure, the laser head was tilted to avoid any reflections that could potentially damage the equipment.

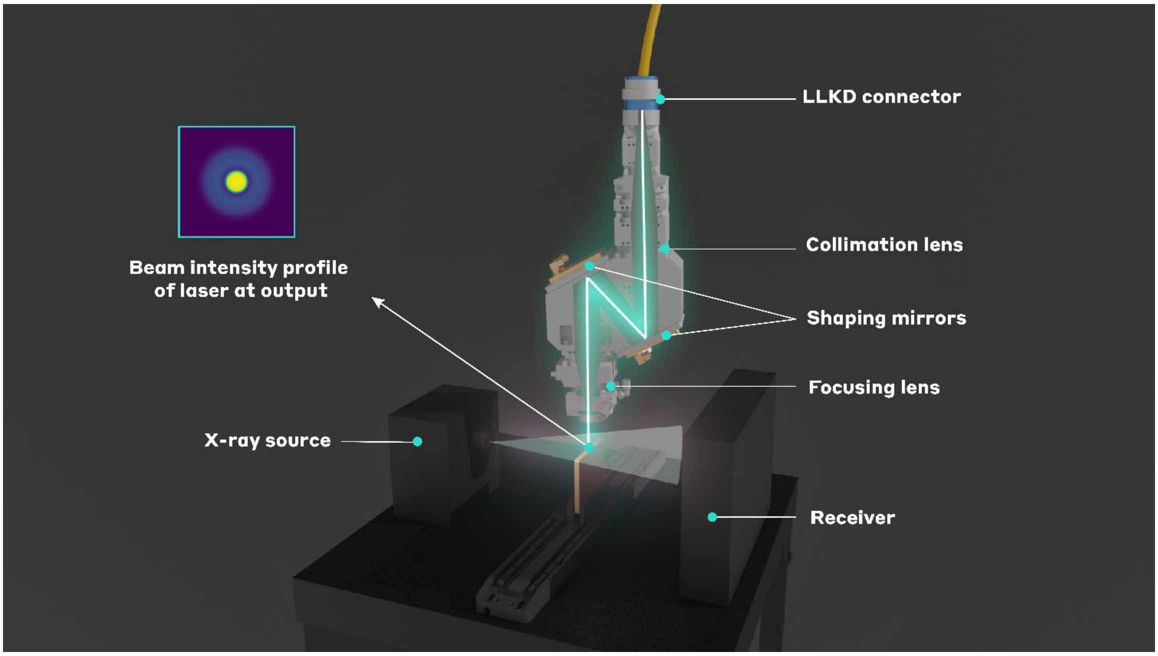


Fig. 4. Diagram of the Industrial Assembly

3.2. Results

X-ray analysis provided compelling evidence of the successful production of compliant copper solder joints without any presence of pores or spatter. The live images captured during the welding process (refer to Figure 5) showcased consistent capillary length and a typical copper weld profile. Subsequent post-processing analysis (Figure 6) further confirmed the absence of pores. Longitudinal macrographs in figure 7 were also examined, corroborating the lack of pores in the joints.

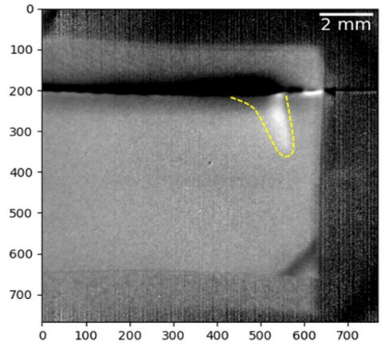
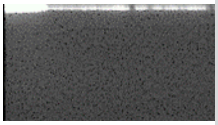


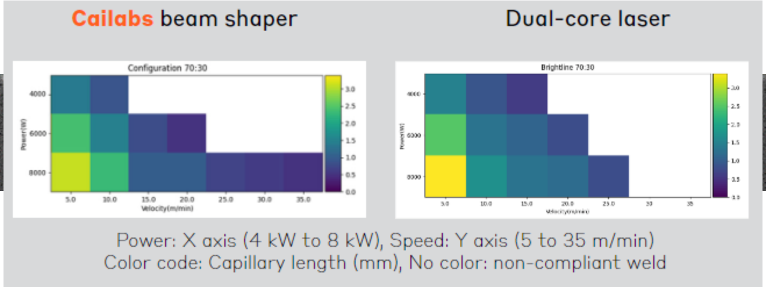
Fig. 5. In-process X-ray image, 15 m/min - 8 kW - 70/30 MPLC beam-shaper

Fig. 6. Post-process X-ray image, 25 m/min - 8 kW - 70/30 MPLC beam-shaper

Fig. 7. Longitudinal macrography, 25 m/min - 8 kW - 70/30 MPLC beam-shaper

To evaluate its effectiveness, we compared this solution with conventional Brightline dual-core technology. Our testing encompassed three power levels, ranging from 4 kW to 8 kW, combined with seven robot speed values spanning from 5 to 35 m/min. The results demonstrated that the MPLC laser head allowed welding at significantly higher speeds of up to 35 m/min, in contrast to just 25 m/min achievable with the dual-core head.





Power: X axis (4 kW to 8 kW), Speed: Y axis (5 to 35 m/min)
Color code: Capillary length (mm), No color: non-compliant weld

Fig. 8. Process window for the MPLC head (left) and dual-core laser (right)

The real-time X-ray imaging during the welding process facilitated the measurement of capillary length within the process window. Additionally, we were able to ascertain the repeatability of penetration depth in specific configurations. The outcome yielded a standard deviation of 0.2 mm among different samples under identical welding conditions.

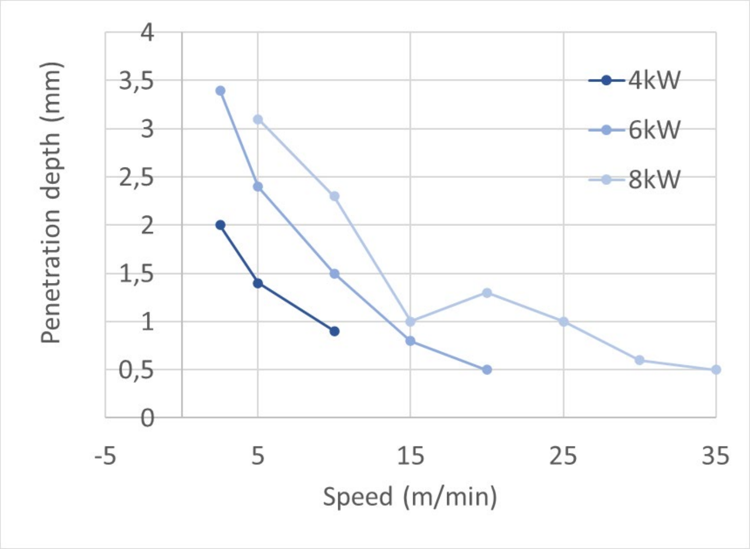


Fig. 9. Capillary length as a function of power and process speed for the MPLC head

An additional advantage of the MPLC solution was its capacity to maintain its shape up to +4 mm from the best focus. In contrast, the conventional dual-core laser experienced degraded beam shaping from +2 mm after the best focus. The MPLC beam profile, on the other hand, remained well-preserved at +4 mm and beyond, with the central spot and ring shape simply increasing in size. This characteristic proves advantageous in certain processes, like hairpin welding, where fast robot arm movement speeds are required, and uncertainties exist concerning the exact position of the hairpins.

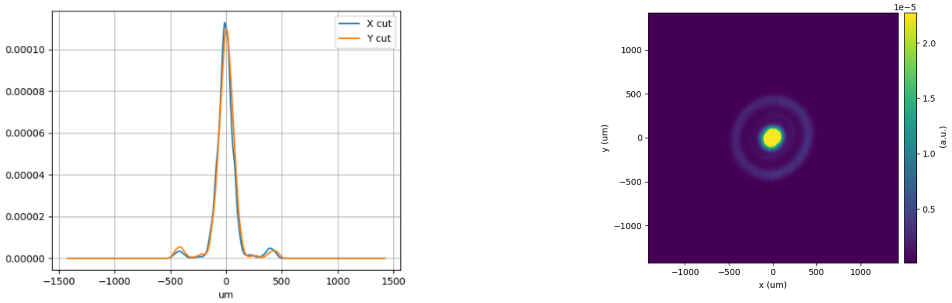


Fig. 10. Profile at +4 mm of the best focus, MPLC beam shaper 70% in the central spot

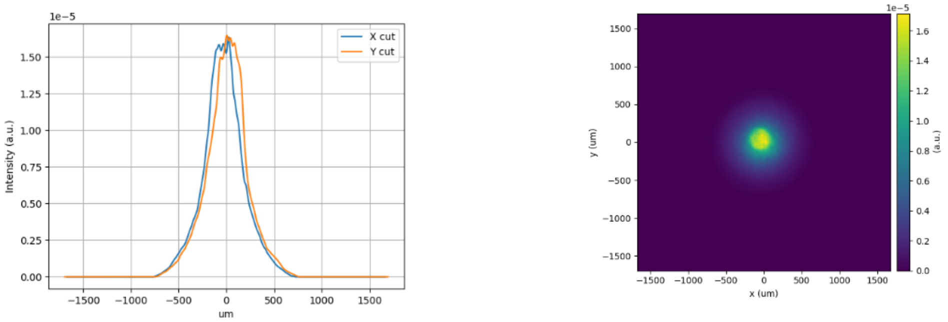


Fig. 11. Profile at +4 mm of the best focus, Dual-core laser 70% in the central spot

4. Conclusion

In conclusion, an innovative beam shaping system tailored specifically for e-mobility welding has been successfully developed. This cutting-edge system boasts several significant advantages that revolutionize the welding process:

- The beam shaping system is designed to provide a highly customized and precisely controlled beam shape, allowing for greater flexibility and efficiency in e-mobility welding applications.
- With an extended depth of field, the system ensures more consistent welding results across various material thicknesses and joint configurations, minimizing the need for frequent adjustments and enhancing overall productivity.
- Our beam shaping system ensures welds of exceptional quality, meeting and even surpassing industrial standards for copper welding.
- The system's versatility allows it to work effectively over a wide range of process windows, accommodating different materials, surface conditions, and welding parameters.
- The beam shaping system is designed to be compatible with a variety of industrial lasers, ensuring seamless integration into existing welding setups without requiring extensive modifications or investments in new equipment.

Overall, the beam shaping system represents a significant advancement in e-mobility welding technology, offering enhanced precision, productivity, and quality. Its ability to meet demanding industrial standards and adapt to various process conditions makes it an asset for manufacturers seeking to achieve efficient and reliable welding in the production of electric mobility components. Moreover, it is less expensive solution than those on the market.

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