Copper Welding with High-Brightness Fiber Lasers

Process stabilization by high dynamic beam deflection

Michael Grupp and Nils Reinermann

The consumer electronics and automotive industry are the driving forces for an increased use of copper in industrial processes and products. With the development of new battery technologies and higher battery capacities, the demands to the joining technologies are increasing. While soldering is still the state of the art for low power applications in consumer electronics, it is necessary to apply welding technology whenever high currents have to be transmitted, or high and dynamic loads stress the joints. The e-mobility sector is especially driving this trend and the automotive industry and its suppliers are looking for robust and efficient processes for high volume production in electrical power storage and transmission line applications.

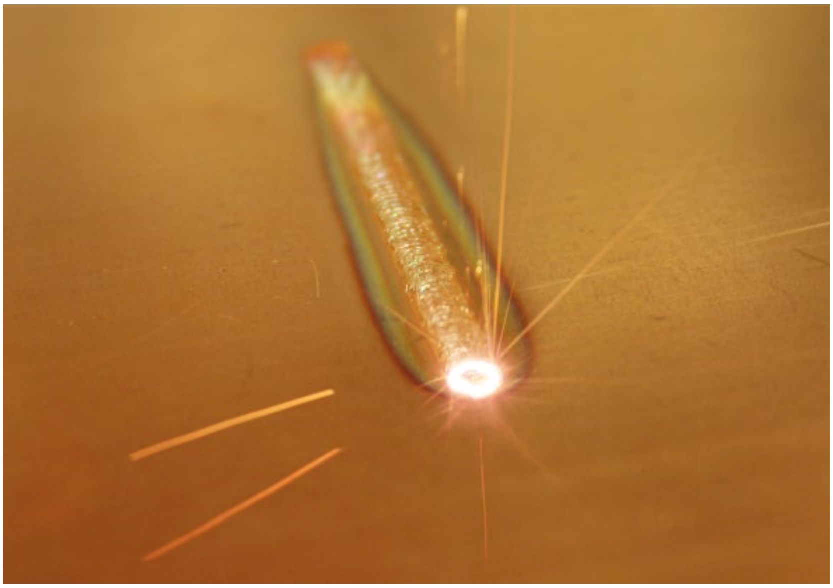

Fig. 1 Defect-free copper welding by high speed beam deflection

Historically, laser technology was limited when welding copper and copper alloys due to the physical properties of the material. Nowadays, with the availability of high power, high brightness fiber lasers these limits can be overcome and with new and adapted processing technologies stable and defect free joints can be achieved in a highly efficient welding process.

Challenge of copper welding with NIR lasers

The challenge of laser welding copper is related to two major physical properties of the material: low absorption for most industrial high power laser types and high heat conduction during the process. It is known that with decreasing wavelength the copper absorption increases. This means, that lasers in the visible band (e.g. green 532 nm) would have enormous benefits for copper welding, but these lasers are either not available yet or not industrially proven in the power range which is required for most welding applications. The absorption with infrared lasers is problematic in the solid state of the material. If the material gets molten or even evaporated by deep penetration welding, the absorption increases significantly. While solid copper has an absorption grade of < 4 %, copper vapor (keyhole welding) absorbs more than 60 %, see table 1. This absorption issue can be overcome by a very high power density, which allows very fast melting and evaporation of the copper and consequently increased absorption. Evaluation using high speed video show that after less than 1 ms a stable process is established. For a continuous wave (cw) weld operation, this hurdle has to be overcome just once at the beginning of the weld. After the

State	Absorption (%)
Solid	4
Fluid	10
Keyhole	> 60

Table 1 Absorption of NIR laser radiation for copper in different states

Company

IPG Laser
Burbach, Germany

IPG Laser GmbH is a 100 % daughter company of US-based IPG Photonics Corp., Oxford (MA). IPG Photonics is the world's leading provider of high power fiber lasers and fiber amplifiers for materials processing, telecommunications, medical and other advanced applications. With more than 1200 employees IPG Laser GmbH develops and produces in Germany lasers for a wide range of applications with its three main product lines of industrial low, mid and high power fiber lasers. IPG is the unique provider of high power single mode fiber lasers of more than 1 kW laser power. IPG has a worldwide network of sales, service and applications centers to provide best customer support and solutions.

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Fig. 2 High power single mode Lasers: air-cooled YLR-1000-SM rack (left) and 3-kW YLS-3000-SM system (right).

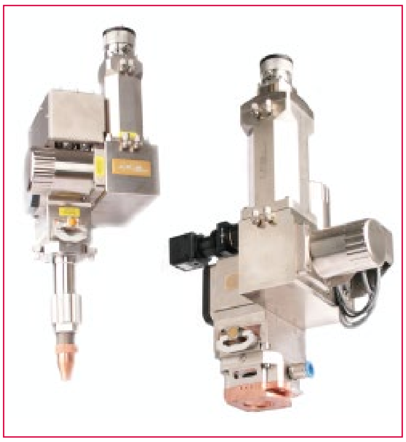

Fig. 4 IPG wobble head FLW D30/D50

keyhole welding process is established, a constant high absorption is given. However, for pulsed operations, this has to be overcome at the beginning of each pulse.

The required high power density can easily be created by using single-mode fiber lasers. These lasers have superior beam quality and focusing abilities compared to other solid-state lasers. IPG Laser is able to deliver high power single-mode lasers with up to 10 kW power, and high brightness multimode lasers exceeding 10 kW, in a robust, industrially proven design. With these single-mode fiber lasers and low-mode high-brightness lasers, it is possible to reach intensities higher than 10^8 W/cm² and achieve reliable in-coupling even with power of a few hundred watts. Compared to common multimode lasers with comparable power the intensity is up to fifty times higher, see Tab. 2. IPG Laser provides single-mode YLR series fiber laser in compact 19” racks from 100 up to 1000 W, and furthermore YLS series

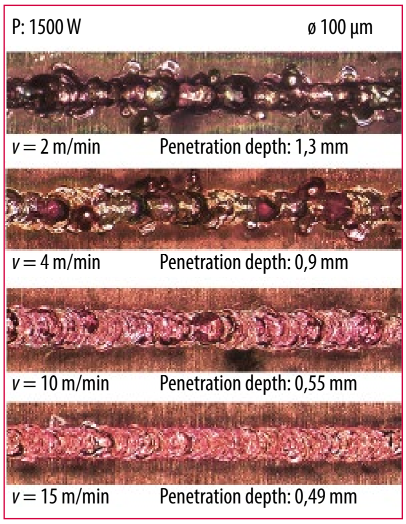

Fig. 3 Influence of process speed on weld quality and penetration depth.

systems up to 10 kW (Fig. 2). Both series feature an overall efficiency of 40 %.

Another issue in the copper welding process is instability when welding at low speed [1]. For a welding speed of less than 5 m/min, we typically face problems with weld instabilities such as spatter, blowholes and irregular weld seam surfaces. With increasing speed, these instabilities disappear and the process stabilizes. In the range of 5 to 15 m/min, the quality reaches an acceptable level. Above 15 m/min, the weld seams are mainly free of defects (Fig. 3). This means that the best weld parameters are in a range where conventional motion systems such as robots reach a limit. Besides this, penetration depth decreases with increasing speed and the weld gets very narrow. This has to be compensated with more laser power which generates higher capital investment for the system technology. New process investigations have shown that this can be avoided and the process can be stabilized not just by increased speed in the welding direction but also by a dynamic positioning by means of a beam deflector [2]. This so-called wobble technique allows stable welds at relatively low welding speeds and insignificantly reduced penetration depth. With this wobble technique it is possible to achieve high quality copper welds up to 1.5 mm welding depth with only 1 kW power from a single-mode fiber laser. Welding depth as a function of the welding speed can be easily controlled without being restricted by the weld quality. The same technique

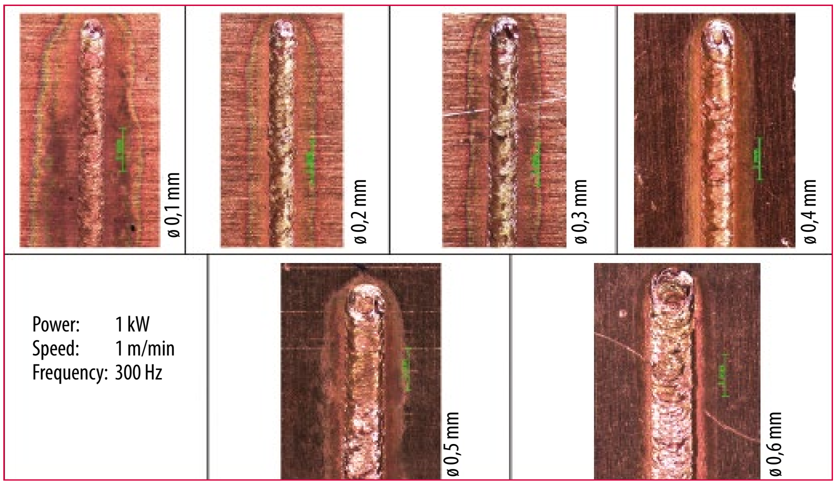

Fig. 5 Influence of the amplitude on the weld width and quality

Fiber diameter	Spot diameter (@Optics 2:1)	Laser power	Intensity
14 µm	28 µm	1 kW	160 MW/cm²
50 µm	100 µm	1 kW	13 MW/cm²
100 µm	200 µm	1 kW	3.2 MW/cm²

Table 2 Intensity is dependence of spot diameter

can also be applied to high-brightness multimode lasers. Tests with a 6-kW fiber laser and a beam quality of 2 mm mrad have shown a high weld quality up to 5 mm penetration depth.

The high beam manipulation dynamics can be either created by conventional scanning heads or with new wobble heads which combine the advantages of a well-proven welding head with the dynamics of a scanning head. Two galvo-driven mirrors enable a flexible use of the various pre-programmed figures and shapes such as circles, lines or "figure of eight" forms, as well as free-programmable figures and shapes of a limited size. One of the main advantages is the use of standard focusing lenses which can withstand much higher power densities at lower focal shift compared to F-Theta lenses and the use of conventional crossjets and protective windows which reduces costs for consumables. These IPG wobble heads of the type FLWD50 and FLWD30 can be operated at wobble frequencies up to 1 kHz and can be easily integrated in all kind of handling and processing systems (Fig. 4). They can handle laser power of up to 12 kW.

Experimental results

For welding of complex paths with changing weld directions, circular wobble movement has shown best results. The resulting beam velocity can be easily controlled by the wobble frequency and wobble diameter $v_c = \pi D f$. In most cases, the weld velocity vector v_w which dynamically positions the circular beam velocity v_c, is negligible, as the beam velocity is much higher than the welding speed v_w. The frequency settings that are providing the best results are depending on the spot size, wobble diameter (and thus the circular speed v_c) and linear welding speed. Fig. 5 shows the weld seams surface for a constant welding speed, laser power and frequency but at different wobble diameters. The spot size was about 30 µm at a focal length f = 300 mm. The laser power was constant at P = 1 kW and the linear welding speed set to 1 m/min. Without a wobble movement, these parameters would lead to a very unstable process, i.e., overheated melt pool and blowholes. It can be seen that with increasing wobble diameter and consequently

Fig. 6 Wobbled welding of copper: simulated and real path of a single mode beam; spot size d = 30 µm, amplitude 600 µm.

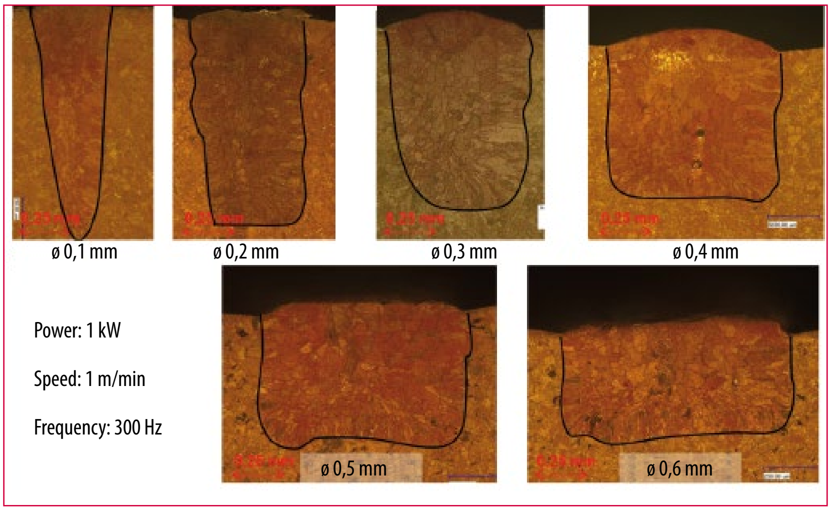

Fig. 7 Influence of the amplitude on the weld cross section.

increasing circular speed, the surface gets more and more stable. Dependent on the wobble parameters and the spot size, the beam and therefore the keyhole movement takes place in a common melt pool or on solid and re-solidified material. In both cases, stabilization takes place. Fig. 6 shows the surface of a weld together with the simulation of the movement. The very narrow weld bead of each single circular path can be seen together as a wide overall weld seam with overlapping circles. The surface occurs like as in a pulsed welding but with overlapping pulses.

The cross sections of welds like these disclose another advantage of this technology: The wobble diameter can be used to tailor shapes of the weld cross section. A small wobble diameter leads to a typical V-shaped cross section of a laser weld, whereas bigger diameters allow shaping of the weld from a V-shape to a U-shape or very regular rectangle (Fig. 7). At constant energy input per unit length $E = P\, v_w$, the cross sectional area stays almost constant. This technique allows the adaptation of the weld seam cross section to suit the application requirements. For overlap welds for electrical contacts it is possible to increase the contacted area to reduce resistance and at the same time control welding depth and heat input. This control is required, e.g., in cell connectors for high power battery packs. In the joining of dissimilar materials such as copper and aluminum in an overlap configuration, it is possible to control the dilution of the materials by a controlled welding depth. By shallow melting of the lower sheet, the amount of molten material can be reduced to the minimum and the dilution can be controlled to reduce intermetallic phases.

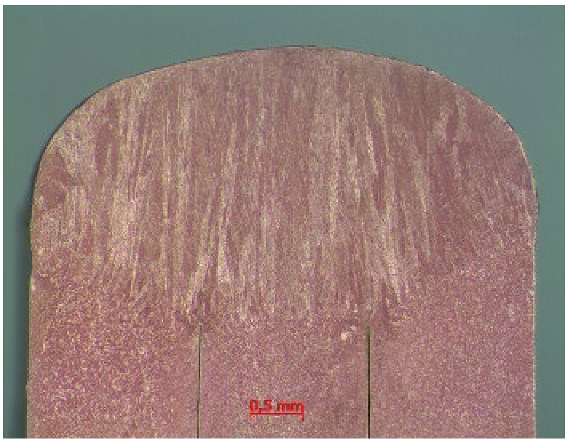

Fig. 8 Joint of three flat copper wires

Even without any movement of the processing head, static "spot" welds with high frequency beam movements can be processed. Overlap spot welds or welding of flat wire ends, e.g., for electric motors, can be achieved just by a high, repeatable movement of the beam with a small circle or a short line. Fig. 8 shows the cross section of weld of three wire ends, which get welded together by quasi-static welding.

Pulsed, continuous or both at once?

Long-pulsed fiber lasers with pulse durations of several milliseconds are available and were introduced to the market over the past few years. They have replaced conventional flash-lamp-pumped Nd:YAG lasers in a wide range of applications. These lasers are available as single-mode lasers with an average power of 250 W and a peak power up to 2.5 kW. The problems of pulsed welding of copper were mentioned earlier, i.e., the need to overcome the lack of absorption at the beginning of the pulse, and after this, the controlled energy input due to the sudden change of absorption and heat conduction is important. In the past, this was managed by special pulse shapes which had to be adapted to each power level and pulse duration.

When reducing spot size by means of a single-mode laser, we can bypass the lack of absorption, but at the same time, the concentrated energy input results on the one side to small and weak weld spots and on the other side to an overheating of the melt. The solution for this is as simple as the process described for continuous lasers. QCW lasers can be used with the same wobble technique. High frequency beam movement allows that during a relatively short time of the pulse the laser beam is moved over a relatively long distance. This means that during the pulse we have a quasi-continuous weld [3]. E.g., a 20 ms long pulse at 600 Hz wobble frequency creates a circular weld spot or short line consisting of twelve rotations of the beam. Adding pulse by pulse to a linear seam weld allows copper welding with high weld quality with a laser of very low average power and thus low investment costs. Solidification and re-melting from pulse to pulse takes place without weld defects, such as blow holes or intensive spatter or non-uniform penetration depth.

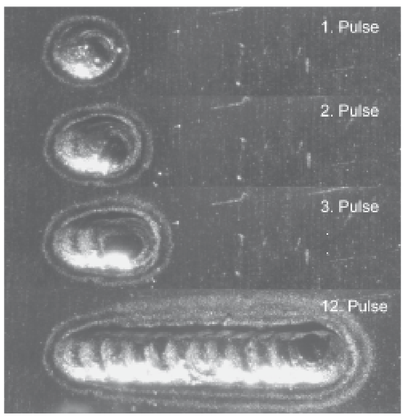

Fig. 9 Formation of a pulsed weld seam by "wobbled" pulses. Laser frequency f_p = 10 Hz, pulse duration t_p = 20 ms, wobble frequency f_w = 600 Hz.

The wobble diameter determines the weld spot size and depth. Fig. 9 shows stills from a high speed video for the first five weld spots of a linear pulsed weld seam. Each spot looks like the other and the quality and stability is independent of the material surface. Additional to that, the heat input is much smaller, so critical electrical components are easy to join with pulsed fiber lasers.

Summary

The experimental work showed, that high brightness lasers are suitable to overcome all known issues in copper welding. The high power density allows an immediate coupling and initiation of a keyhole which allows for stable and high absorption even at a wavelength of 1070 nm. With high dynamic beam deflection the weld process is stabilized and blow holes and spatter can be reduced or avoided, resulting in high quality weld seams. Process parameters settings for the beam deflection allows a controlled design of the weld geometry leading to very shallow welds in a stable deep penetration process. With long pulsed QCW fiber lasers it is even possible to create spot welds with high dynamic movement of the beam within a single pulse. In this way high quality welding seams can be created by adding pulse by pulse at a very low average power.

DOI: 10.1002/latj.201700014

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Authors

Michael Grupp studied mechanical engineering at the University of Stuttgart. From 1998 to 2004 he worked at the Bremer Institute for Applied Beam Technology (BIAS) in the fields of laser welding and surface treatment. Getting there in contact with the first high power fiber lasers he joined IPG Laser in 2005. Today he is application manager and responsible for the laser application and demonstration center in Burbach, Germany.

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