10th CIRP Conference on
Photonic Technologies [LANE 2018]

Industrial Paper

Application benefits of welding copper with a 1 kW, 515 nm continuous wave laser

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Abstract

We demonstrate laser welding of copper joints with green continuous laser welding of 1 kW laser power. Compared to IR a big advantage of green is the feasibility of heat conduction welding, generating perfectly smooth seams on thin copper plates without distortion at high speed. For deep penetration welding there is a correlation of welding depth and beam diameter to achieve sputter free weldings. The melt needs a stationary pool deposit which is generated by spatial beam forming. The limit of laser power for incoupling depends on the dimensions of heat conduction into work piece and fixture. A classification for different joints is recommended. High speed videos show welding performance and melt pool behavior.

Keywords: green laser, copper, DPSS, 515 nm, welding,

1. Introduction

Currently, driven by the emerging electromobility market, a massively growing demand for laser welding of copper (Cu) is observed. However, it is well known that laser welding of Cu with solid-state high-power lasers emitting at ~1 µm can be a daunting task: the poor absorption of the IR wavelength in Cu gives rise to several unwanted effects e.g., formation of sputters and dependency on surface conditions (oxidation) (Engler et al. (2011)). High-power, green-wavelength disk lasers are a promising solution to this problem. The absorption of the green wavelength in solid Cu is ~5 times higher than for IR. In this context it is comprehensible that researchers and engineers in the field currently pay even more attention to improving the weld quality rather than increasing the welding speed.

The pulsed green laser *TruDisk Pulse 421* has already been tested and described (Pricking et al. (2016)). In this paper we present application results of Cu welding using a new high-power CW laser system from TRUMPF with 1 kW output power at 515 nm. Welding curves (welding speed as a function of welding depth) for green and IR wavelength are compared. Bead on plate and overlap welds have been performed on ETP-Cu plates in a range of 0.25 mm to 5 mm thickness (full penetration and partial penetration welds). We discuss the influence of the spatial power distribution on the shape of the welding cross section both for green and IR. Related to this we also study the formation of sputters when welding at different focal positions. Furthermore, we investigate the dependency of the achievable penetration depth on the geometry of the workpiece.

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Nomenclature

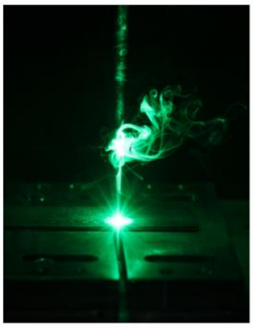
BD	beam diameter ($1/e^2$ width) on workpiece
d_{0f}	focus diameter (d_{0f} = BD for FL = 0)
FL	focal position
z_R	Rayleigh length
P_{av}	average power
v	velocity/feed rate
LLK	laser light cable
CW	continuous wave
$s_{\eta,\varepsilon}(z)$	edge steepness

2. Properties of the beam source

Recently, motivated by the growing demand in high-quality laser welding applications of Cu, TRUMPF developed a high-power CW laser system emitting in the green (515 nm): *TruDisk 1020*. It is based on a frequency-doubled Yb:YAG thin-disk laser platform. As opposed to other laser concepts (i.e. fiber lasers) the modular setup of our disk laser allows for intracavity frequency doubling. This renders our concept simple and robust since no external cavity for resonant enhancement of the second harmonic generation is needed.
The *TruDisk 1020* is a CW laser delivering a maximum output power of 1 kW at 515 nm. To the best of our knowledge this is the most powerful industrial solid-state green-wavelength laser demonstrated so far. Thanks to the CW operation, with the *TruDisk 1020* the length of the weld seam is not limited. This feature further broadens the spectrum of Cu welding applications that can be addressed and makes the CW system a perfect complement to the aforementioned pulsed laser. To show the influence of wavelength, we compare the *TruDisk 1020* to the *TruDisk 1000* which has the same properties except with a wavelength of 1030 nm. Figure 1 shows an overview on important parameters of the *TruDisk 1000* and *TruDisk 1020*.

Table 1: Technical parameters of *TruDisk 1000* and *TruDisk 1020*

Parameter	TruDisk 1000	TruDisk 1020
Pulse peak power	1 kW	1 kW
Average power	1000 W	1000 W
Wavelength	1030 nm	515 nm
Pulse duration	cw	cw
LLK diameter	≥ 50 µm	≥ 50 µm
No. of outputs	max. 2	max. 2
BPP	2 mm·mrad	2 mm·mrad
WPE	33 %	25 %



For beam delivery the *TruDisk 1020* is equipped with two output ports for pluggable laser light cables (LLKs) to enable maximum flexibility in machine concepts. An excellent beam quality of 2 mm×mrad is available at both output ports allowing to connect multimode LLKs with a minimum core diameter of 50 µm. We use LLKs that are optimized for low absorption in the green. The value of 1 kW is to be understood as the power that is available at the work piece, i.e. after LLK and processing optics.

2.1. Beam diameter and power distribution

To characterize the laser beam of the *TruDisk 1020* a beam caustic measurement was performed behind the processing optics using a beam profiling device (Primes Focus Monitor). The result is shown in Figure 1. As can be seen, the intensity distribution at different z positions shows the typical behavior known from a multimode fiber. In focus (FL=0) the power distribution is a top hat. Out of focus (1 to $2z_R$) the shape becomes more and more bell shaped. Two things change with defocusing: the beam diameter (BD) and the edge steepness (DIN ISO 13694). The following studies show the influence of both, edge steepness and beam diameter, on the quality of the welding.

In focus the edge steepness is nearly zero. We achieve a higher edge steepness with more defocusing and we change the beam diameter by different combinations of LLK diameter and optical ratio (focusing lens to collimation lens).

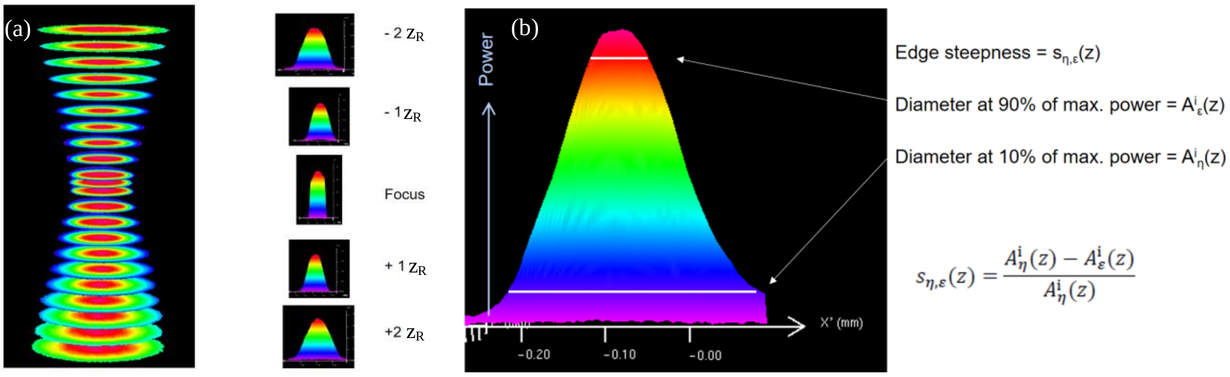


Fig. 1: (a) Beam caustic measurement of *TruDisk 1020*. The power density axis in each layer is adapted to maximum. (b) Edge steepness

3. Welding results

3.1. Comparison between green and IR

To compare green and IR we performed welding tests with Cu using the green-wavelength *TruDisk 1020* and an IR-wavelength *TruDisk 1000*. The welding was performed with the surface of the workpiece at FL=0. The employed power was 1 kW at both wavelengths. Because of absorption of the 515-nm wavelength in copper vapor

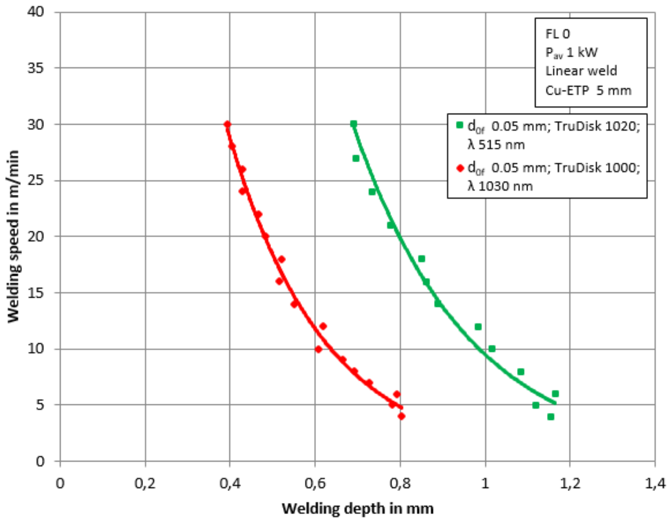


Fig. 2: Bead on plate welds of Cu for green (515 nm) and IR (1030 nm) wavelength using a power of 1 kW. Welding was performed in focus.

plume, all tests with green have been performed using a nozzle with airflow. For reproducible results it is necessary to keep the nozzle setup constant. As can be seen from Figure 2 the welding depth when using 515 nm is approximately 50% higher compared to 1030 nm. This means, other things being equal, that with the green wavelength a significantly increased feed rate can be applied while obtaining the same welding depth as with IR. Note that the delta in welding depth between green and IR is not necessarily this high. It can deviate from this value for other beam diameters and multiple reflections in the vapor channel. There was no emphasis on high quality welds in this test.

In Figure 3 cross sections of weld seams in Cu are shown. Welding was conducted at three different focal positions and with 1 kW laser power at 515 nm and 1030 nm, respectively. In case of the 515-nm laser the width of the weld seam is smaller than with the IR laser and higher welding depths can be achieved.

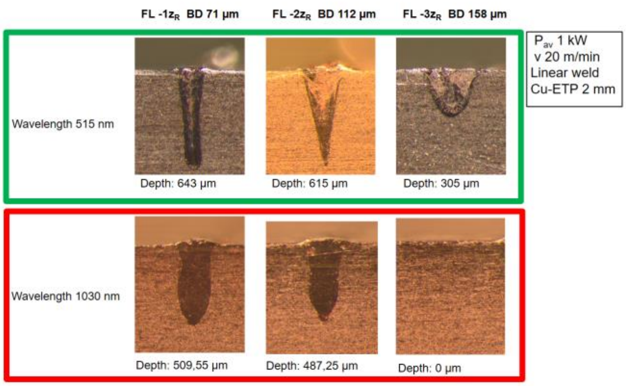


Fig. 3: Comparison of weld seam cross sections for Cu welding with the 515 nm and the 1030 nm TruDisk at different focus positions/beam diameters. The feed rate was 20 m/min in both cases. With IR lasers a reliable heat conduction welding is not possible as can be seen on the picture bottom right.

One fundamental difference between green and IR in Cu welding is the following: with the green laser we successfully performed heat conduction welding while with the IR laser this was impossible.

3.2. Melt deposit and keyhole shape

In another test we examined keyhole stability at 515 nm. Several different kinds of power distribution lead to a sputter-free, smooth weld. All of them have in common that there is a corona which produces melting temperature on the surrounding of the keyhole to form a melt deposit and/or produces vaporization temperature around the keyhole to open it up to a V-shape. For a gaussian shape both effects occur simultaneously.

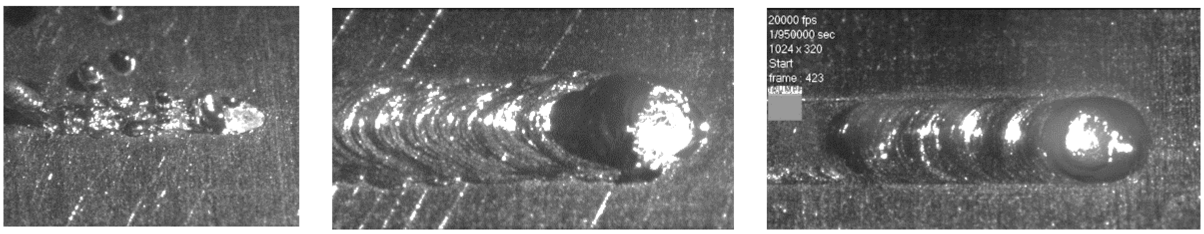


Fig. 4: Stabilizing the keyhole by changing the power distribution from top hat to Gaussian (via defocusing). (a) FL=0; d_{0f} =0.2 mm: sputters are clearly visible; (b) FL=2$z_{R;}$ BD=0.45 mm: sputters are significantly reduced, smoother melt pool; (c) FL=4z_R; BD=0.82 mm: no sputters, very smooth melt pool.

The easiest way of producing a melt deposit is defocusing and thereby changing the power distribution from top hat to gaussian shape (see section 2.1). With a ring of melt around the top of the keyhole, the direction of melt flow is changed and melt coming up from the bottom of the keyhole is incorporated by the ring instead of flung out. The effect is illustrated by photos taken with a high-speed camera as seen in Figure 4 and the drawing in Figure 5 (a) and (b). The size of the melt deposit should be adapted to the amount of melt in the pool by choosing beam diameter and edge steepness. In this test a LLK with 200 µm diameter and an optical ratio of 1:1 was selected.

The second reason for better quality is the shape of the keyhole. If the walls of the keyhole are V-shaped instead

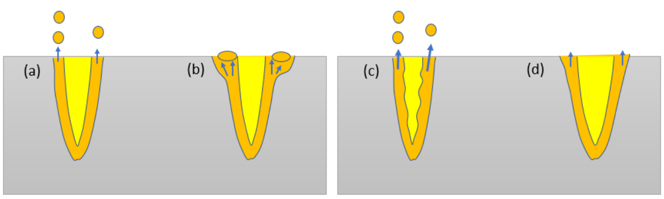


Fig. 5: Cross section without melt deposit (a) and with melt deposit (b). Cross section with I-shaped (c) and V-shaped keyhole (d). With gaussian power distribution both effects occur simultaneously.

of I-shaped, the keyhole is much more stable and boiling is reduced. Again, this is achieved by selecting beam diameter and edge steepness. We detected shape and stability of the keyhole by looking into the weld via high-speed videos. A reason for less turbulences and less sputters might be the angle dependent absorption or the way, the vapor pressure acts on the melt surface. This behavior is outlined in Figure 5 (c) and (d).

Both effects reduce the production of moving humps (P. Berger et al. (2010)). Moving humps lead to high dynamics inside the keyhole and to expulsions (to the top if it is a partial penetration welding and to the bottom if it is a full penetration welding).

3.3. Influence of heat conduction

With the 1-kW green-wavelength laser high-quality Cu welding results with sheet thicknesses from 0.2-0.5 mm are conveniently obtained. With thicker plates (≥ 1 mm) the high thermal conductivity of Cu (~5 times higher than steel) can be a challenge in laser welding applications. We point out that this does not depend on the wavelength but is a general effect. For 5-mm-thick Cu sheets or in cases where the fixture takes away a lot of heat, the coupling is not satisfying. Therefore, a big potential lies in joints that have less heat conduction. In Figure 6 all parameters except sheet thickness and speed are constant. At larger material thicknesses the penetration depth is significantly decreasing. It is interesting to note that with a higher speed the ratio of depth reduction is higher (20 % at 1 m/min and 50 % at 3 m/min.)

The results presented in this section confirm that in laser welding of Cu the geometry of the workpiece plays a crucial role regarding the achievable weld depth. This is different from laser welding of steel where the influence of workpiece geometry on weld depth is neglectable for practical cases. For pulsed green welding (with *TruDisk Pulse 421*) heat conduction and heat accumulation is seen, but has far less influence compared to CW.

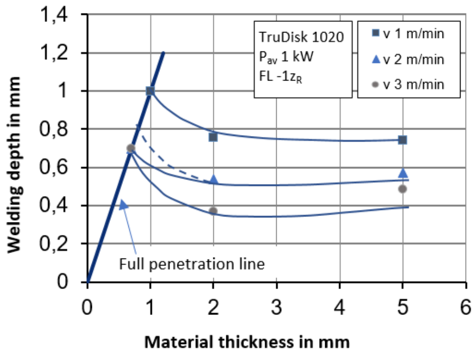


Fig. 6: Influence of heat conduction in Cu welding. At a sheet thickness of 0.7 mm a full penetration weld can be achieved. While feed rate, laser power and focus position are kept constant, the achievable weld depth decreases with increasing material thickness. This is due to the high thermal conductivity of Cu.

3.4. Examples

Figure 7 shows two examples of Cu foil welding done with *TruDisk 1020* as linear weldings. In comparison to section 3.1 the tests here were performed with a bigger focus diameter of 0.1 mm (LLK 50 µm; optical ratio 2:1) and additionally with defocusing for even bigger beam diameter on the workpiece and better edge steepness. In these tests we could achieve an excellent welding quality at high feed rates. No pores or ejections were observed.

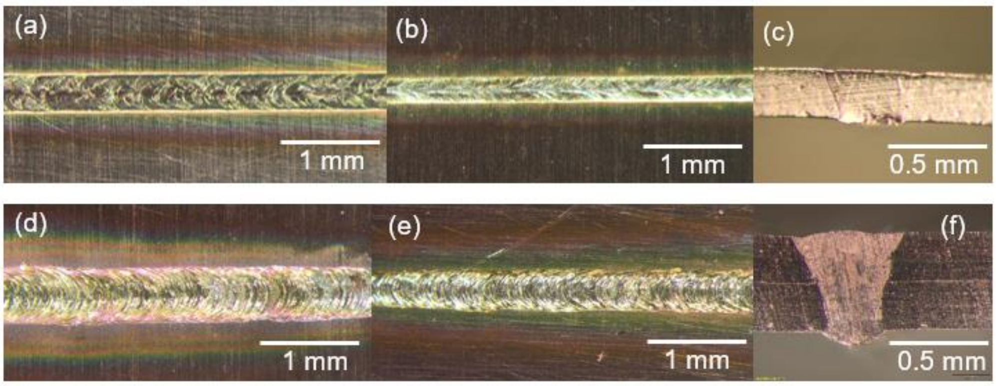


Fig. 7. (a)-(c) Bead on plate and heat conduction welding of Cu foil (material thickness=0.25 mm, v=10 m/min, BD=0.51 mm): (a) top side, (b) bottom side, (c) cross section; (d)-(f) overlap and deep penetration welding (material thickness=2×0.25 mm, v=8 m/min, BD=0.316 mm): (d) top side, (e) bottom side , (f) cross section

The results show that the *TruDisk 1020* is particularly suited for this kind of application. This is what distinguishes the CW green-wavelength source from IR lasers: in such thin Cu foil welding applications a very good quality at high processing speeds can be reached. IR-Lasers with linear welds or in combination with beam wobbling or BrightLine Weld *(Speker et al. (2017))* are not able to perform this quality and speed.

4. Comparison to welding processes with IR lasers

For penetrations deeper than ~1 mm a high-power IR laser will be a good solution, however welding in the IR will not show sputter free result. For good quality the feed rate should be between 15 and 30 m/min. To generate a larger welding depth IR multi-kW laser power should be applied. For improved seam quality one could use TRUMPF's patented *BrightLine Weld* technology (Speker et al. (2017)) which allows for flexible tailoring of the power distribution using a 2-in-1 fiber. A single-mode fiber laser (e.g. a *TruFiber* from TRUMPF) in combination with a galvo scanner for beam wobbling could be an alternative, especially when rather broad cross sections are desired or when feed rate is limited by machine or contour.

Note that these statements are valid under the assumption that the power of the green laser source is limited to 1 kW. While this is the current status quo we anticipate having a multi-kW 515-nm laser system in the near future. With such a system we could extend our application tests using higher power levels in the green. It is expected that even more significant benefit of green-wavelength laser welding of Cu will be observed in such tests.

5. Conclusion

The *TruDisk 1020* is a new and unique CW laser system delivering 1 kW of output power at 515 nm. We have demonstrated that it is particularly suited for Cu welding applications. By using the *TruDisk 1020* Cu welding becomes possible in a regime inaccessible to IR lasers so far: heat conduction welding is enabled. In addition, the green laser source enables a different kind of keyhole for deep penetration welding. This keyhole is much more stable and therefore reduces sputters and melt ejections. Even if the mechanisms of melt ejections for green and IR wavelength are the same, the advantage of the green lies in the way it couples into the copper. We have shown that melt ejections can be avoided by changing the form of the vapor channel from I-shaped to V-shaped and by forming a melt deposit. This is done by welding 2-3z_R out of focus resulting in a change of spatial power distribution. Furthermore, we showed that with Cu the achievable penetration depth at fixed process parameters is much more sensitive to the geometry of the work piece as compared, e.g., with steel. This behavior is a consequence of the good thermal conductivity of Cu and can be observed both with IR and green lasers.

Our application results prove that the *TruDisk 1020* is already well-suited for penetration depths <1 mm in Cu. High-power green-wavelength disk lasers offer great potential: in the future we anticipate extracting multi-kW power levels out of such systems. This will enable deeper penetration welds in Cu making green-wavelength lasers an invaluable tool for the mass production of parts in the fast-growing electromobility market.

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DIN EN ISO 13694