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Laser Welding of Copper Using Superposed Green and Near-Infrared Laser Radiation

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Abstract

Joining of copper materials is gaining in importance due to the increasing electrification in the automotive sector. Conventional joining technologies suffer from low dynamic strength or high specific weight of the welded structure. Laser beam welding seems to be a suitable alternative without the aforementioned drawbacks. Copper shows a high reflectivity for laser light at near-infrared wavelengths, which is emitted by state-of-the-art beam sources. Therefore, near-infrared laser beam welding does not seem to be a promising alternative. In contrast, copper shows a high absorptivity for laser radiation at green wavelengths. Since green beam sources can only provide a power up to several hundred Watts, the weld depth is limited. To overcome this limitation, a continuous wave beam source at a green wavelength with an output of thousand Watts is coupled to a near-infrared disk laser. In this paper, an investigation for such an attempt is presented using different laser powers as well as the relative alignment of both laser beams. The findings provide knowledge for an alternative joining method of copper materials that is based on laser beam welding.

Keywords: green laser radiation; near-infrared laser radiation; laser hybrid welding; copper; macro joining;

1. Introduction

Technological trends such as electromobility, Internet of Things, and the overall digitalization in general lead to an increased usage of electronic devices. Due to its superior electrical conductivity, copper often becomes the material of choice. A key challenge in manufacturing is the joint between different components which have to fulfill requirements with respect to electrical and mechanical properties.

Laser beam welding (LBW) holds several advantages compared to already common joining technologies, e.g. resistance welding or soldering. LBW, which is a contactless process by nature, enables short processing times, allows a defined energy input on both joining partners, and does not require any filler material. In addition, a smaller processing area is needed. Solid-state lasers are commonly used for welding of steel and aluminum alloys in industrial applications. Laser beam welding of copper with solid-state lasers at a near-infrared (NIR) wavelength is a difficult task because of the low absorptivity of copper in that wavelength range.

This leads to unstable melt pool dynamics, formation of spatter, and increased occurrence of weld seam defects. In contrast, the absorptivity of copper increases significantly for laser beam sources at a green wavelength, which has a stabilizing effect on the welding process. However, one of the current drawbacks is the limitation of the laser power. To overcome this disadvantage, a promising approach is the superposition of green and NIR laser radiation.

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2. State of the art

2.1. Welding of copper materials with near-infrared lasers

Several scientific publications have demonstrated the weldability of copper with NIR laser systems and identified factors of influence and process behaviors. HEIDER ET AL. (2011) [1] showed that the laser power influences the welding process significantly. Applying a sinusoidal modulation to the laser power, the amount of melt ejections could be reduced. This increased the keyhole stability and reduced fluctuations in the penetration depth. Using multi-mode fiber lasers, LIEBL ET AL. 2014 [2] investigated the influence of the welding velocity and shielding gas on the process. An increased velocity resulted in a better weld seam quality. The use of helium leads to a higher seam width and shifted the threshold to a lower welding speed at the expanse of the penetration depth. LIEBL ET AL. 2014 [2] referred this behavior to a change in the surface tension and the heat dissipation during the process.

CHEN ET AL. 2015 [3] used a different approach to increase the welding efficiency by applying a copper-based nano-composite material on top of the workpiece. Acting as an absorber, it led to a decrease in reflectivity and an increase in the efficiency of the welding process. A drawback of this method is the reduction of the tensile strength by 12 %.

2.2. Welding of copper with laser beam sources at 515 nm wavelength

A more recent innovation in laser beam welding is the development of continuous wave laser systems in the visible wavelength range based on frequency-doubled solid-state lasers.

ENGLER ET AL. 2011 [4] compared the influence of NIR and green laser radiation on the weldability of copper materials. While an oxidized surface can lead to an increased absorptivity of NIR wavelengths, no changes can be observed for green laser radiation. The increased energy absorption also affects the weld depth and the width of the weld seam while NIR welds were much wider at the expense of the weld depth. PRICKING ET AL. 2016 [5] used an experimental setup with a laser power of 1 kW and investigated the weldability of copper materials with high-powered green laser radiation. Through heat conduction welding and the absence of a vapor channel, reproducible and controlled spot welds with a calm melt pool can be achieved. Due to the increased absorptivity for green laser radiation, the surface quality influences the welding process less significantly than NIR laser radiation.

HAUBOLD ET AL. 2018 [6] identified the threshold between heat conduction welding and deep penetration welding and derived the influence of the welding velocity. To stabilize the deep welding processes, the vapor flare had to be blown out of the beam path with the aid of an air stream parallel to the component surface in order to realize a uniform energy input. HAUBOLD ET AL. 2018 [6] also observed an increased weld seam width and a reduced penetration depth for a defocused laser spot.

2.3. Welding of copper with combined green and near-infrared radiation

Using green laser radiation, laser beam welding of copper becomes more efficient due to its increased absorptivity. However, because current state-of-the-art laser beam sources are significantly restricted in their output power, only limited weld depths can be obtained. To overcome this drawback, a superposition of green and NIR laser radiation has been studied. HESS ET AL. (2010A) [7], HESS ET AL (2010B) [8] and HESS ET AL. (2011) [9] investigated the effect of a low power green laser (<100 W) which was used to preheat and pre-melt the material. The green laser radiation increased the weld depth and enabled deep-penetration welding for the NIR radiation. Hereby, the deep penetration welding threshold could be reduced.

HEIDER ET AL. (2011) [10] took the focal positioning of both spots into consideration. The investigation showed that by pre-processing the weld trajectory with the green laser radiation, a more stable welding process could be achieved. Through application of power modulation on the NIR beam, the melt ejections were reduced significantly. However, the laser beam source for green radiation for this observation was limited to an output power of 200 W.

3. Objectives and approach

High requirements in electromobility, e.g. high currents or high dynamic loads, demand a reliable joining technology for the copper materials. Therefore, laser beam welding using green laser radiation seems to be a promising approach. Since the weld depth is restricted by the output power of available continuous wave or pulsed wave frequency-doubled laser beam sources, previous investigations demonstrated the potential of a superposition with NIR laser radiation.

In this study, a high power continuous laser beam source with 1 kW at a green wavelength was supplemented by a state-of-the-art disk laser at NIR wavelength to weld pure copper. The study focuses on the deep penetration threshold and the weld depth as key criteria. It will be clarified how the alignment of the focus spots and the use of high-powered green laser radiation influence the welding process in combination with NIR radiation.

4. Experimental setup

4.1. Welding of copper materials with near-infrared lasers

To realize a superposed green and NIR laser radiation, two different laser beam sources were used, see Figure 1. The NIR laser radiation was provided by the commercially available disk laser TruDisk 4001 of TRUMPF Laser GmbH. For the beam guidance, a fixed optics of the type BIMO was applied. The frequency doubled disk laser TruDisk 1020 and the programmable focusing optics PFO 20-2 of TRUMPF Laser GmbH were utilized to deploy the green laser radiation. The characteristic values of both systems are listed in Table 1 and 2.

The focal points of the beam sources at a green and an NIR wavelength were arranged concentrically or tangentially, see Figure 2. Bead-on-plate weld seams on oxygen-free copper (Cu-OF, CW008A) were used for the investigations to analyze the deep penetration threshold and the weld depth. The copper specimens had a size of 100 mm by 50 mm by 5 mm.

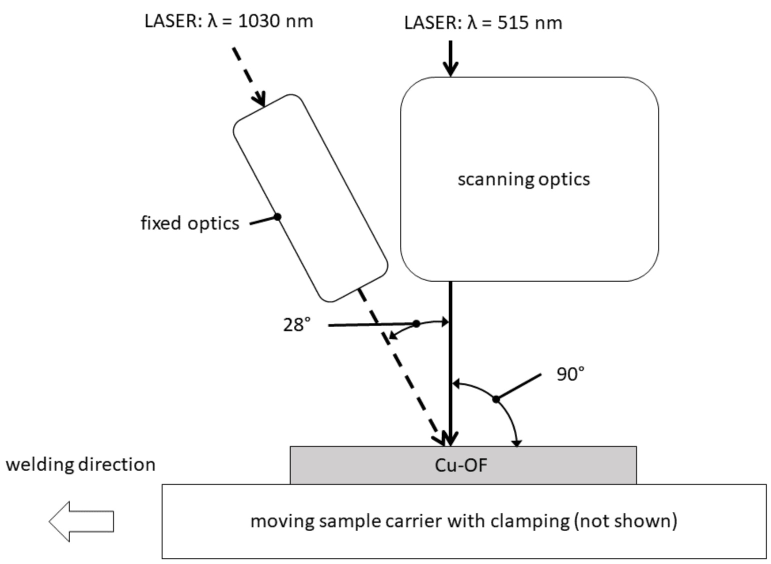

Fig. 1. Experimental setup for the investigations described in the following

Table 1. Properties of the laser system (NIR)

Parameter of TRUMPF TruDisk 4001	**Value**	**Unit**
Maximum laser power	4000	W
Wavelength	1030	nm
Fiber diameter	100	µm
Parameter of HIGHYAG BIMO	**Value**	**Unit**
Magnification of the collimation lens	1.2	-
Magnification of the focal lens	2.3	-
Focus diameter	276	µm

Table 2. Properties of the laser system (green)

Parameter of TRUMPF TruDisk 1020	**Value**	**Unit**
Maximum laser power	1000	W
Wavelength	515	nm
Fiber diameter	50	µm
Parameter of PFO 20-2 (F-Theta)	**Value**	**Unit**
Aspect ratio	2.93	-
Focus diameter	146.5	µm

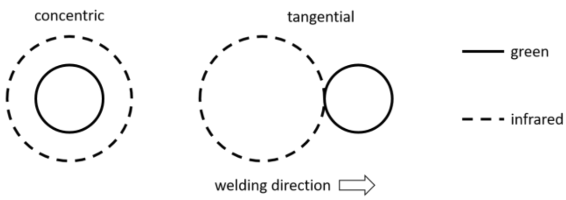

Fig. 2. Arrangement of the focal points

5. Results and discussion

5.1. Analysis of the deep penetration threshold

The deep penetration threshold in laser beam welding indicates how much power is needed to form a vapor capillary during the welding process. By using NIR laser radiation, the process is restricted to the deep penetration welding mode. This is due to the low absorptivity of radiation in the NIR range. Overall compared to other materials, copper shows a high deep penetration threshold. Therefore, this value has been further investigated for a combined process depending on the welding speed to assess the potential of the concentric superposition, which is displayed in Figure 3. The deep welding threshold could not be reached with a welding speed higher than 15 m/min due to the NIR laser power being limited to 4 kW on the experimental setup that was used for this study.

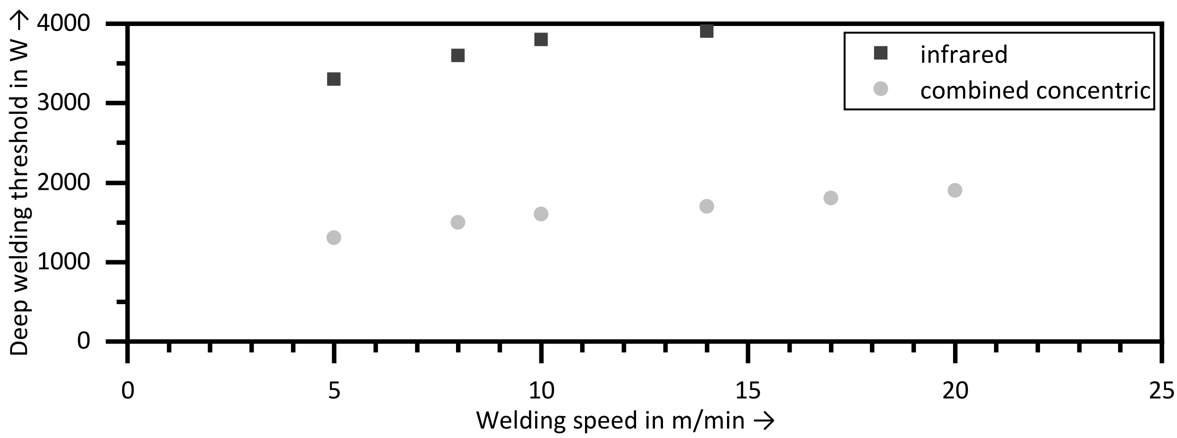

Fig. 3. Comparison of the deep welding threshold for NIR laser radiation and concentrically superposed green and NIR laser radiation

It can be observed, that the deep welding threshold is reduced by 2200 W by a combination with a 500 W green laser at a welding speed of 10 m/min. As a result, the power of the infrared laser system can be reduced by 2700 W. An increase in welding speed has a negative influence on the threshold. It can be assumed that the lower exposure time of the laser beam on the material leads to an increase in necessary power to achieve the same level of penetration depth.

In contrast to the concentric superposition, a significantly lower reduction of the threshold has been determined for a tangential arrangement of the laser spots, see Figure 4. Although the laser has a positive influence, the effect is much less significant and only leads to a reduction of the threshold by 300 W at 500 W green radiation and 10 m/min welding speed.

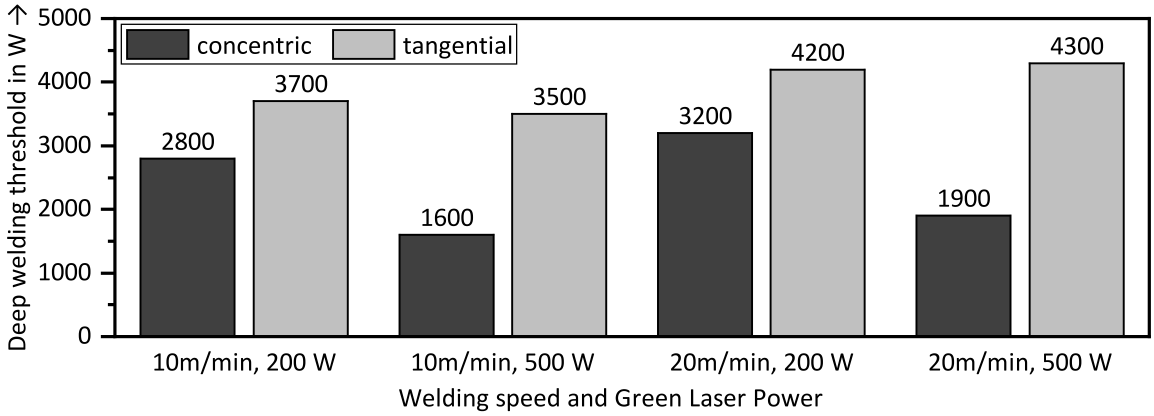

Fig. 4. Comparison of the deep penetration threshold for a concentric and a tangential arrangement of the focal points

5.2. Analysis of the weld depth

The weld depth was analyzed for different ratios of green and NIR laser power for a concentric arrangement of both laser spots, see Figure 5. The welding speed was kept constant at 10 m/min.

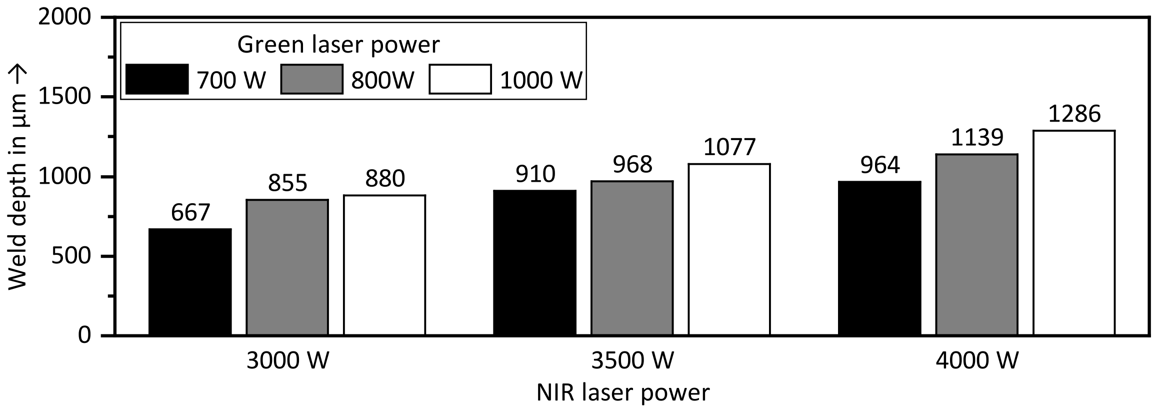

Fig. 5. Measured weld depths for a concentric arrangement of the focal points

In general, an expanded weld depth was achieved by an increased usage of the green, as well as NIR laser power. The maximum weld depth was determined to be 1286 µm with maximum output power for both lasers.

A second study was conducted to analyze how the arrangement of the focal points influences the weld depth, see Figure 6. It is obvious that the tangential arrangement of the laser spots shows a higher weld depth than the concentric superposition of laser radiation. The maximum weld depth was determined to be 1417 µm.

A concentric superposition of the two laser spots at the level of the sheet surface leads to a divergence of the laser beams with increasing welding depth, caused by the angular offset between the two beam axes.

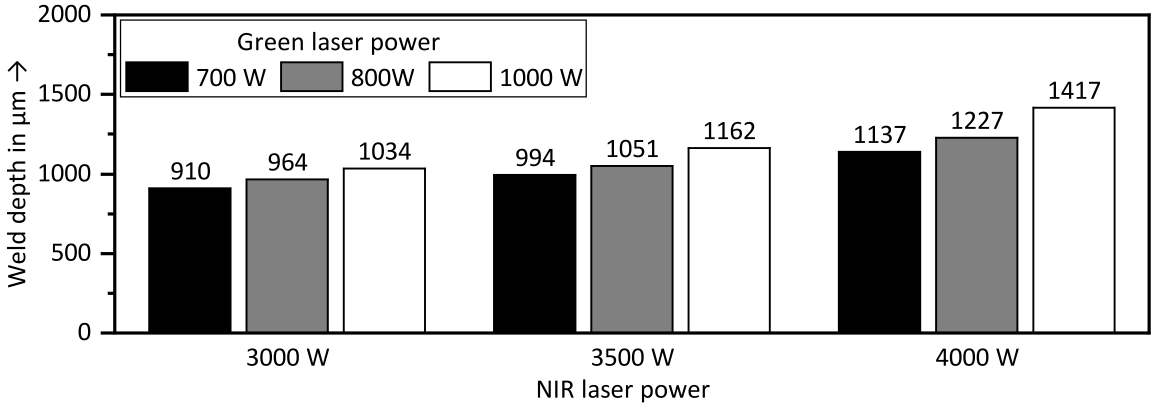

Fig. 6. Measured weld depths for a tangential arrangement of the focal points

The welding process with combined laser beams showed fewer melt ejections in form of spatter in comparison to the welding process with a single NIR beam source. It can be assumed that this is caused by the reduced deep welding threshold, which consequently requires a lower laser power to achieve comparable welds.

6. Conclusion

An investigative study for the superposition of a high power laser beam source at a green wavelength and a state-of-the-art disk laser at an NIR wavelength has been presented in this paper. By increasing the ratio of the green laser power, the deep penetration threshold can be reduced. At the same time an increase in weld depth can be achieved. For that matter, the tangential arrangement of focal points with the NIR laser spot behind the green laser spot results in a higher weld depth than when welding with a concentric superposition. The combined process showed a lower tendency for spatter and melt ejections in comparison to only using the NIR laser.

Further investigations will focus on the influence of the angle of incidence on the process alongside investigations on the formation of melt pool ejections for the combined welding process.

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