Laser welding with green and infrared lasers

Influence of the laser wavelength on process characteristics in laser welding of copper

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Laser welding of copper materials using established infrared laser sources is challenging due to the high reflectivity of the material. Recently, high-power lasers with an adequate beam quality emitting in a shorter wavelength spectrum have been developed, which are possibly more suited for copper welding. An infrared and a green laser source are compared with one another regarding key process characteristics in laser welding – penetration depth, defect formation, temperature development.

One of the key challenges in electric mobility is to improve the overall performance of the systems. This target can be achieved by using materials with a high thermal and electrical conductivity and by increasing the power density. The former can be achieved by selecting appropriate materials such as pure copper. The latter is often addressed by miniaturizing the overall installation space through e.g. highly precise joining technologies such as laser welding. In the past, laser welding of copper has proven due to the high reflectivity of copper for the typically used infrared laser sources. Especially in laser deep penetration welding, which is often needed e.g. in busbar welding [1], the thermophysical material properties promote an instable process. In the beginning, a low amount of the laser power is coupled into the material.

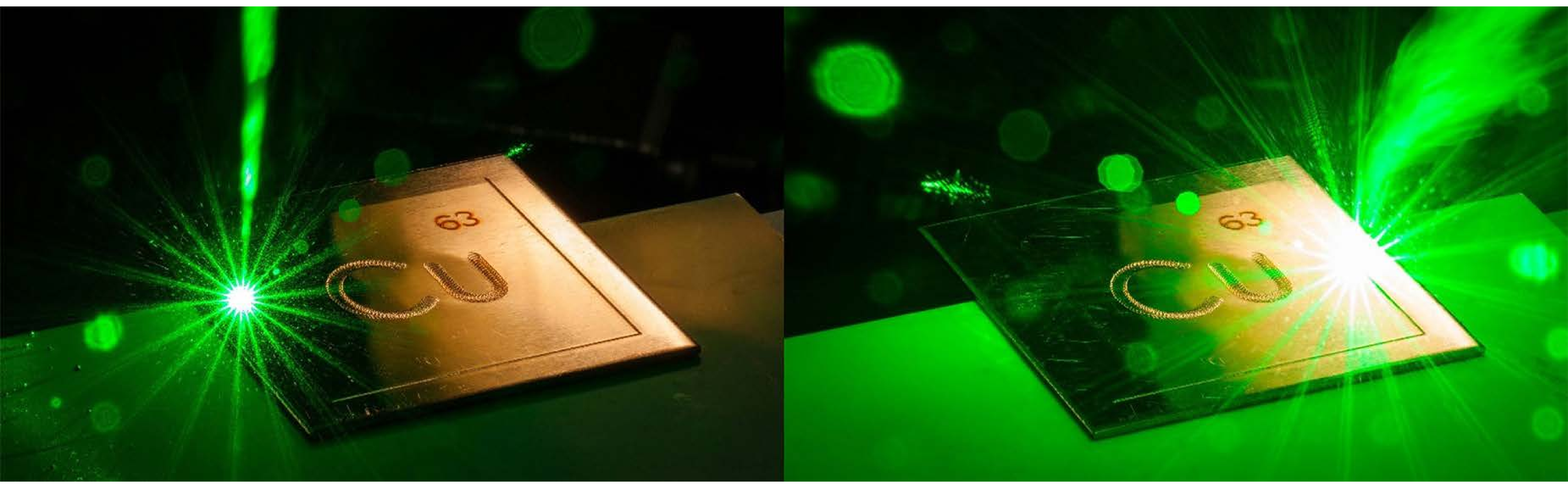

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Fig. 1 Welding of copper with green laser light

Upon melting, an increase in coupling efficiency is observed due to a higher absorption coefficient. Once evaporation temperature is reached and a keyhole is formed, the coupling efficiency drastically increases due to multiple reflection. These three different states with their respective jumps in the percentage values of the coupled energy can result in an instable process [2].

In recent years, high-power laser sources emitting in shorter wavelength ranges were developed and characterized for laser material processing [3]. The main potential of these sources lies in the higher absorption coefficient of copper for visible light already at room temperature [4]. Consequently, the process dynamics are decreased since the jumps in coupling efficiency are significantly reduced. Goal of the presented investigations is a qualitative and quantitative comparison on the laser welding of pure copper when using IR and green laser sources at the same boundary conditions.

Experimental procedure

An infrared (TruDisk 6001, 6 kW, 1,030 nm) and a green laser (TruDisk 3022, 3 kW, 515 nm) were used for generating lap joints of two copper sheets. Both systems were manufactured by Trumpf, Germany. The lasers were guided using a laser fiber with a diameter of 100 µm. The laser was scanned across the workpiece's surface using a scanning optics of type PFO33. One optics was tailored for the IR laser while the other one was designed for the green laser. After illumination, a laser beam diameter of around 170 µm was achieved at the surface of the specimen. The laser beam diameters were the same for both wavelengths.

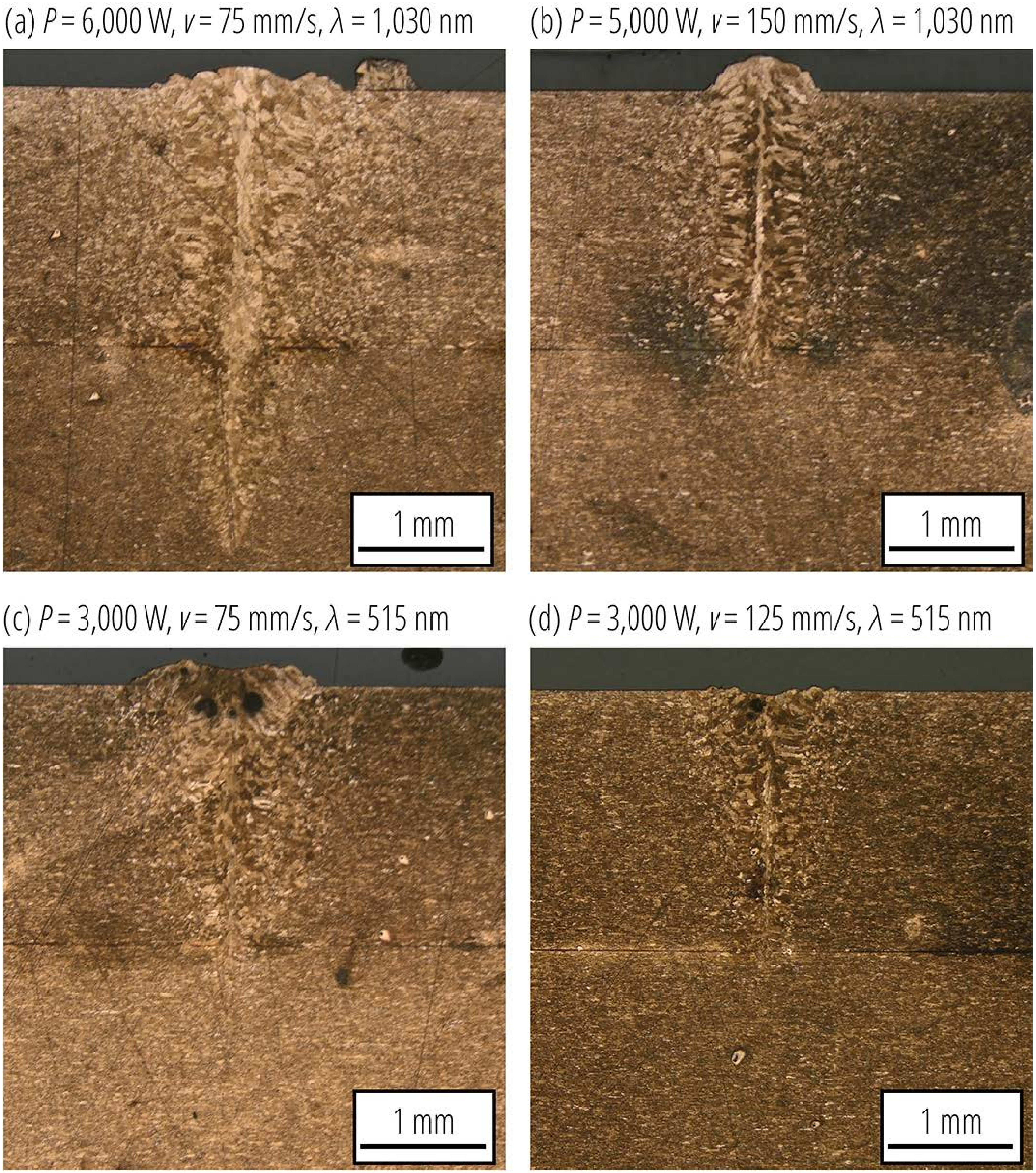

Fig. 2 Cross-sections of weld seams generated with the IR (a, b) and the green (c, d) laser source

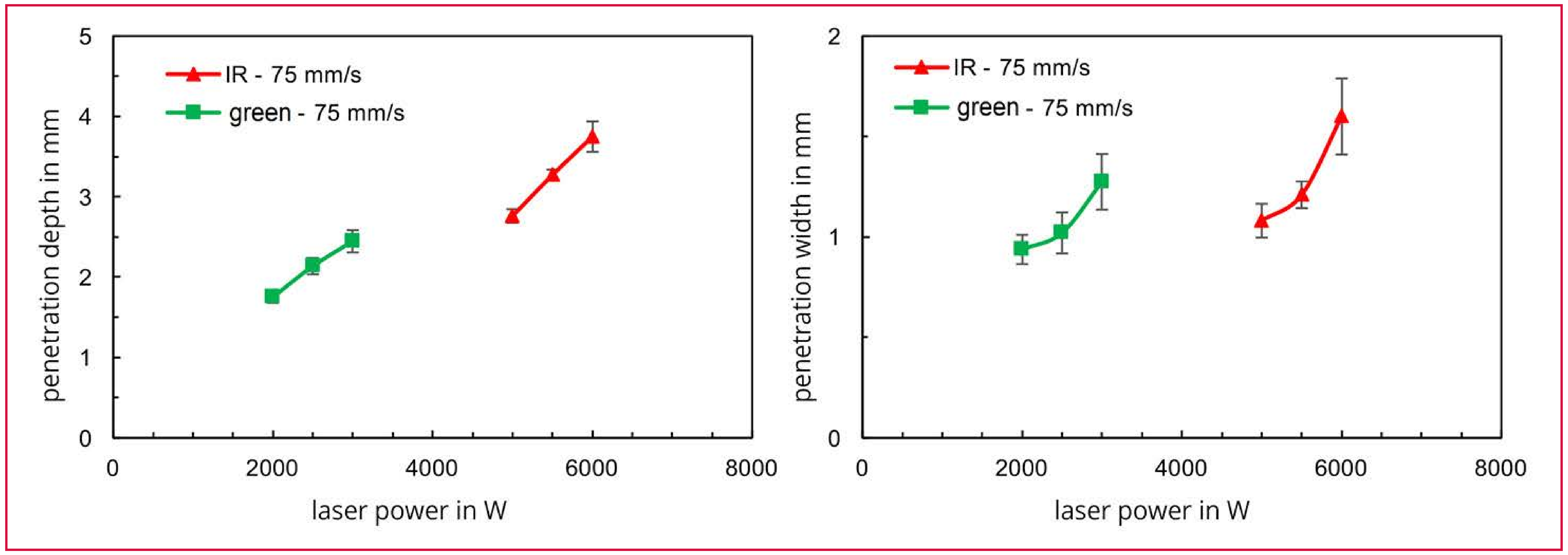

Fig. 3 Comparison of weld seam depth (l) and width (r) for the IR and green laser

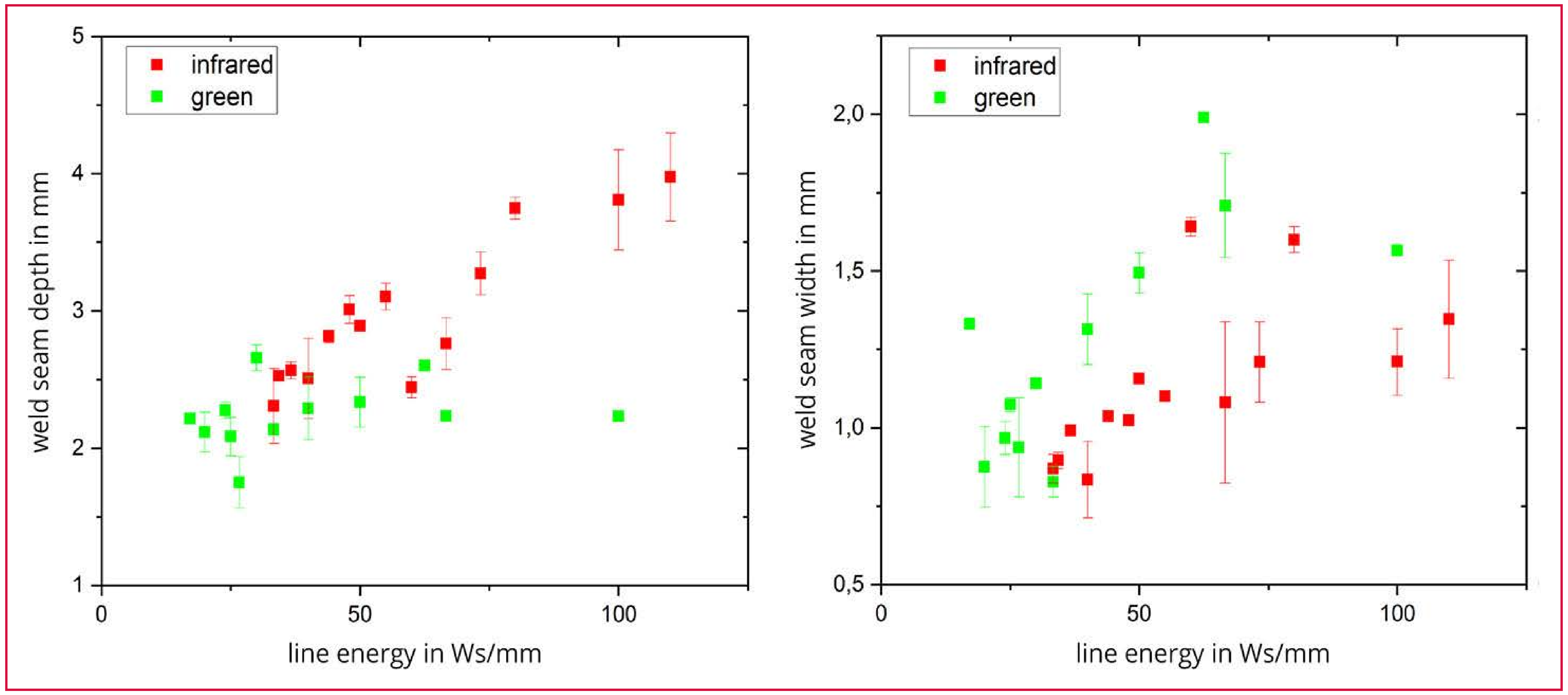

Fig. 4 Comparison of weld seam depth (a) and weld seam width (b) depending on the line energy

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Apart from that, all other process boundary conditions were maintained constant. Thus, the experiments are comparable with one another and the influence of the operating wavelength can be correlated with the obtained process results. Two copper substrates (Cu-OF) with a thickness of 2 mm (top) and 3 mm (bottom) were joined in a lap joint configuration. The substrates possess an edge length of 50 mm in both x- and y-direction. No shielding gas was applied during welding. With regard to the process parameters, scanning speed was modified between 25 and 175 mm/s. A collimator with a focal length of 155 mm was used. The experiments were performed in the focal plane (f = 265 mm) of the scanner's focusing lens. Laser power was varied in the range of 2,000 – 3,000 W for the green laser system and between 5,000 – 6,000 W for the IR laser system. The investigated processing parameters are summarized in Table 1.

The generated weld tracks were analyzed in three steps. First, the surface of the tracks was determined using a laser microscope (Keyence VX-6000). The obtained images were used to assess the homogeneity of the weld seams.

In the second step, cross-sections and longitudinal-sections were generated. The specimens were cut into two halves, embedded in an epoxy resin, grinded and polished down to 1 µm. An optical light microscope was used for taking images of these specimens to assess parameters such as defect formation, penetration depth and process stability.

Results and discussion

Achieving a good connection at the absence of defects is crucial in laser welding, especially when joining copper. Consequently, the cross-sections of the generated specimens were analyzed in the first step (see Fig. 2). Almost pore and defect-free specimens processed both using IR and green laser could be observed. Most importantly, no defects in the bonding region between the two metal substrates were obtained. Gap-free joints could be generated through laser welding. At maximum laser powers (6,000 W for IR and 3,000 W for green) and the same scanning speed (75 mm/s), a significantly larger penetration depth was observed for the IR laser.

Comparing IR (a, b) and green (c, d), further differences can be seen. The average elevation of the weld track above the surface appears higher for specimens processed with IR laser. A possible explanation for this are higher process dynamics in IR laser processing due to e.g. spatter formation. Furthermore, the average width of the weld track in the top region is larger for specimens processed using the Green laser. This is attributed to the excellent heat conduction of copper in combination with the better energy absorption for shorter wavelengths. Moving towards the bottom end of the weld seam, a finer structure caused by deep penetration welding can be observed. The weld seam can thus be described as conical. In contrast, the weld seam generated with the IR laser is rather cylindrical until the bottom end of the keyhole is reached.

In the second step, the weld seam depth and width are compared for the different laser sources for different process parameters (see Fig. 3). The main boundary condition was that a full penetration through the first specimen and a firmly bond with the lower sample was achieved. An efficient bonding was possible starting with a laser power of 2 kW (green laser) and around 5 kW (IR laser).

Both laser sources result in an increasing weld track width. However, the width of the weld seams of the green laser is similar to the ones of the IR laser already at low laser powers. It can be seen that the average weld depth is increasing with higher laser powers, as expected.

Comparing IR and Green, a full penetration through the upper sample can be observed already at laser powers of 2.5 kW for the Green disk laser at a scanning speed of 75 mm/s. Reducing the scanning speed helped to achieve a through-welding of the first substrate already at laser powers of 2 kW.

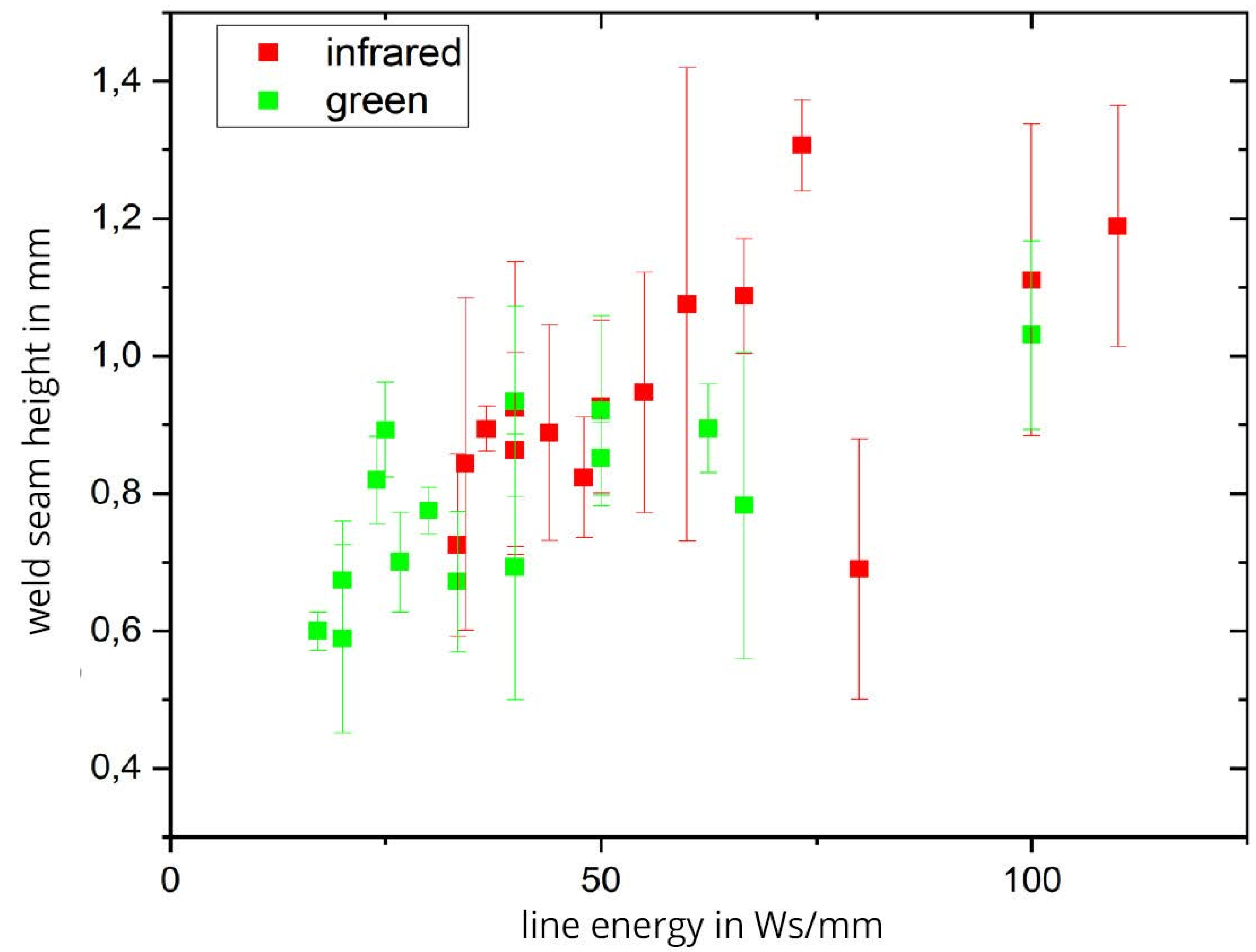
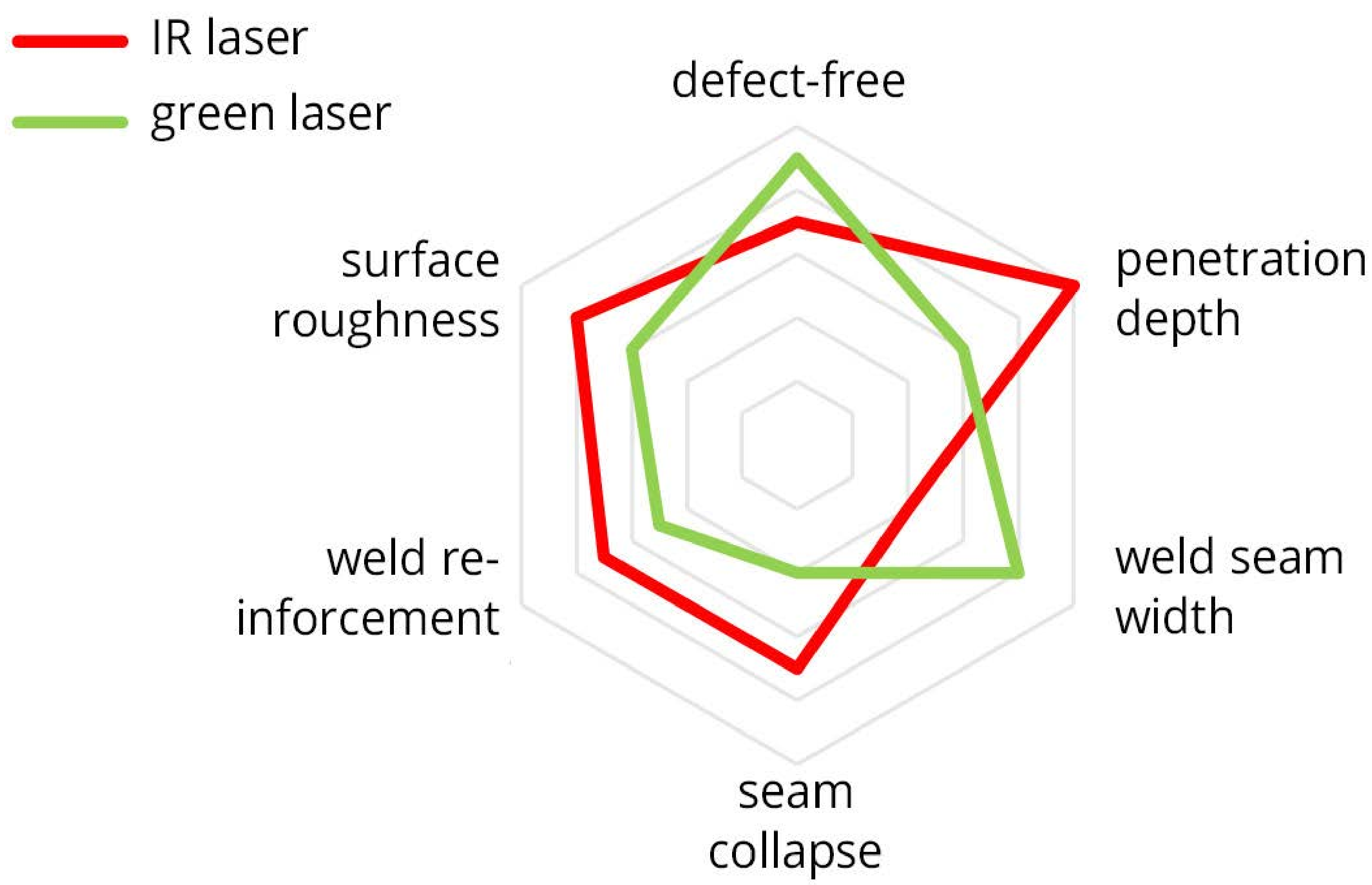


Fig. 5 Influence of the welding speed on the weld seam height

Criterion	IR Laser	Green Laser	Step
Laser power in W	5,000 – 6,000	2,000 – 3,000	500
Scanning speed in mm/s	25 – 175	25 – 175	25
Beam diameter in µm	170	170	—
Wavelength in nm	1,030	515	—
Shielding gas	no gas	no gas	—

Table 1 Process parameters investigated within this work



Criteria	IR Laser	Green Laser
Defect-free	7	9
Penetration depth	10	6
Weld seam width	4	8
Seam collapse	7	4
Weld reinforcement	7	5
Surface roughness	8	6

Fig. 6 Radar chart on the potentials of green and IR laser sources in copper welding (l) and table of criteria (r)

The IR laser source requires higher laser powers in the range of 5 kW to assure a sufficient weld penetration depth. With regard to the width of the weld seam, the maximum penetration depth is higher for IR laser sources. This effect can be explained by two points: On the one hand, green laser light is absorbed better, thus resulting in a better coupling efficiency in process regimes like heat conduction welding.

On the other hand, this improved absorption is disadvantageous when aiming at deep penetration welding. Here, the lower absorption of the IR laser is beneficial for energy coupling into lower regions of the keyhole. Another crucial factor is the interaction with vapor plume above the workpiece surface. Shorter wavelengths are absorbed at a higher rate than longer wavelengths, leading to an additional shielding effect of the capillary [5]. Applying additional gases like argon or nitrogen could be helpful to avoid this shielding effect by blowing away the evaporated material. However, generating a homogeneous shielding gas flow in laser welding is challenging, especially when working with scanner optics and exploiting the entire scan field. Blowing the vapor plume away using pressurized air could also be a solution. However, pressurized ambient atmosphere could result in undesired oxidation of the surface.

Another key point is that reduced deviations in the weld penetration depth can be observed when welding with the green laser. Using shorter wavelengths helps to stabilize the process even at comparable penetration depths. This assumption is underlined when comparing the effective line energies for IR and green (see Fig. 4).

When comparing similar line energies for green and IR, the average weld depth is larger for the specimens processed with the IR laser source. The average weld width is characterized by the contrary effect. At a similar line energy, the tracks generated using the green laser are wider compared to the ones processed with the IR laser. A minimum line energy in the range of 20 Ws/mm is needed to achieve a sufficient penetration depth into the lower substrate for the Green laser. For IR, a higher line energy in the range of at least 30 Ws/mm is needed. Comparing the standard deviations in all cases, less fluctuations in penetration depth can be observed for the specimens processed with the Green laser. Consequently, using shorter wavelengths results in an improved process stability. Finally, the average weld reinforcement at the surface was analyzed and compared for IR and green (see Fig. 5).

The results indicate that the overall surface quality for the specimens processed with the green laser source. Joints generated using the IR laser in general possess a higher reinforcement of the surface. This excessive material can be attributed to the higher process dynamics due to (a) a poorer coupling for IR in the heat conduction mode and (b) higher process dynamics during the transition from heat conduction mode to deep penetration welding. In general, higher line energies are correlated with a poorer surface quality in laser welding of copper, independent of the applied laser source. Additional investigations on the surface roughness have also been performed, which can be shared upon request.

The findings indicate a smoother surface for the weld tracks generated using the green laser. Specimens processed with longer wavelength (IR) are characterized by an increased surface roughness. Potential explanations are the process dynamics and maybe melt flow velocities.

Assessment with regard to industrial applications

Industrially established laser welding processes face several challenges. Key characteristics that describe the overall quality of the weld seam include internal defects, penetration depth, weld seam width, seam collapse, weld reinforcement and surface roughness.

The most important factor is the quality of the inner weld seam. Internal defects such as pores or cracks reduce the strength of the joint, thus limiting its applicability. Defect-prone copper products are furthermore characterized by a reduced current carrying capacity. Further characteristics that are decisive for the performance of the weld are seam collapse and weld reinforcements. While weld reinforcements limit the build space and overall tolerances of the system, e.g. in busbar welding, seam collapses are weaknesses in the component since undesired stress states could result in a premature failure of the product. The maximum penetration depth and average cross-section in the joined region also needs to be considered when designing the welding process. It was shown that green laser sources produce a rather larger cross-section area compared to IR lasers. However, IR lasers, due to the lower absorption coefficient, are favorable to achieve deeper penetration depths – at least with the currently limited laser powers for green lasers available on the market. Finally, the surface roughness also plays an important role. These influencing factors as well as the respective potentials and limitations are summarized for the different laser sources in a spider chart (see Fig. 6).

The green laser system performs better with regard to the fabrication of defect-free weld seams and when aiming at the generation of wider weld seams to increase e.g. the joint's cross-section. IR laser sources in contrast result in a larger penetration depth. However, this increased keyhole depth comes at the cost of the quality of the weld seams top surface.

Summary

Two laser sources – green and IR – were compared for laser welding at identical laser spot sizes. It was found that weld tracks generated with the green laser source are characterized by wider welds and a smoother surface. The higher absorption at room temperature promoted a more efficient energy coupling. A maximum penetration depth of roughly 2.7 mm at a scanning speed of 100 mm/s was achieved, enabling a joint through 2 mm thick copper substrates.

Weld seams fabricated using the IR laser possess a larger penetration depth at smaller capillary diameters. Specimens welded with the IR laser source possess more surface irregularities – weld reinforcement, seam collapse – than their counterparts welded with the green laser. This is on the one hand attributed to the higher laser powers employed. On the other hand, the lower absorption of copper for longer wavelengths enables a promoted keyhole-welding mode, inducing undesired process dynamics such as spatters.

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We would like to thank Trumpf SE Ditzingen for providing the green laser source and the respective optics needed for performing the experiments.

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