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RESEARCH PAPER

Aluminum welding by combining a diode laser with a pulsed Nd:YAG laser

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Abstract Laser welding of aluminum alloys (AA 5754 and AA 6016) by superimposing a pulsed Nd:YAG laser with a continuous wave (cw) diode laser has been investigated in order to improve the weldability and the process efficiency. The low absorption of laser radiation at a wavelength of 1064 nm and the high thermal conductivity make it difficult to laser weld aluminum alloys efficiently. Therefore, a pulsed Nd:YAG laser and a low power diode laser emitting a wavelength of 980 nm were spatially superimposed. This configuration allows to enhance the absorption for the Nd:YAG welding laser due to the preheating of the diode laser. Thus, the process efficiency as well as the weld quality is enhanced. The experiments revealed that a small output power of the diode laser (<150 W) allows increasing the welding speed up to 80 % and the weld depth up to 38 %. Furthermore, the superposition leads to a significant improve of the weld seam quality, in particular to avoid hot cracking.

Keywords Yag lasers · Diode lasers · Aluminium · Hot cracking

1 Introduction

Aluminum has a density of approximately one third compared to steel and is used in applications where a high strength/weight ratio is required [1]. This includes automotive application, where a reduced weight results in a bigger load capacity and reduced fuel consumption [2]. In addition, aluminum has a high thermal and electrical conductivity as well as a good corrosion resistance. Thus, it can be employed for a high variety of applications such as electronic interconnections [3], heat exchangers, and packaging material [4].

Aluminum components can be joined by several different methods, including welding, brazing, soldering, adhesive bonding, and mechanical methods such as riveting and bolting [1]. Regarding welding processes, laser welding is an opportunity to join aluminum products, as it can provide high productivity, weld quality, welding speed, weld aspect ratio, manufacturing flexibility, and easy automation [5, 6].

The high thermal conductivity and coefficient of expansion of aluminum lead to high strains and residual stresses especially when welding thin sheets (<1 mm) [1]. Therefore, pulsed laser sources are often used, since the heat input is discontinuous and relatively low. This effect leads to a small heat affected zone, low residual stresses, and distortions. Possible applications are seal welding of aluminum housings for electrical applications and titanium welding for medical components [7]. A disadvantage of pulsed Nd:YAG laser is the low welding speed compared to other laser processes.

This is caused by the required frequency, the degree of overlaps of the single spot welds and the required pulse energy [8]. The pulse energy is the energy contained within a pulse and a product of peak power and pulse width. The lower the pulse energy, the higher frequencies can achieve at the same degree of pulse overlap and correspondingly higher welding speeds.

However, laser-based welding processes of aluminum and its alloys are connected to certain challenges. As shown in Fig. 1, aluminum has a very low absorption coefficient to laser light (high reflectivity) [9] and a high thermal conductivity [10]. These properties cause difficulties in the optical coupling of the laser beam, as most of the incident laser light (1064 nm)

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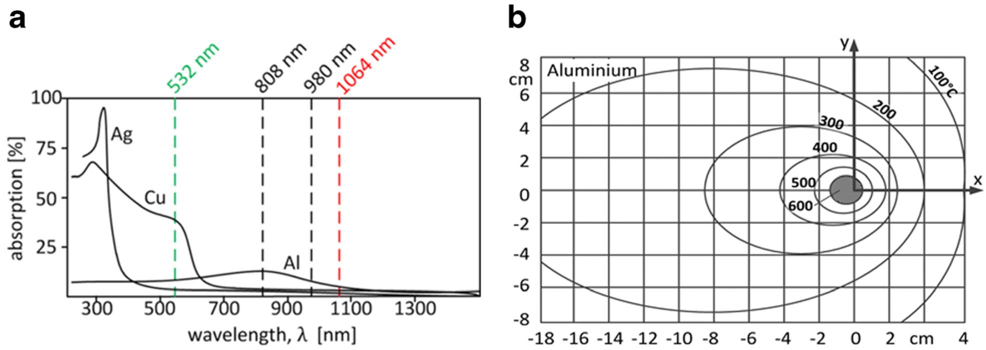


Fig. 1 **a** Coefficient of absorption of different metals [18], **b** thermal conductivity of aluminium [19]

is reflected on the surface and the small fraction of absorbed energy is very quickly conducted into the surrounding material. Therefore, high welding energies or high intensities and slow welding speeds are required to obtain the sufficient penetration depth and bead width.

Another, rather metallurgical, challenge in aluminum welding is the occurrence of hot cracks during solidification. The susceptibility to solidification cracking defines the weldability of an aluminum alloy and depends upon the alloy system, the welding conditions and the weld geometry [1, 11]. In some alloys, this effect is so severe that welding without cracking cannot be obtained [1]. Unfortunately, this concerns many high-strength Al alloys (5xxx and 6xxx alloys). For this reason, an important way to increase the weldability of crack-sensitive Al alloys is the use of a filler material with a different composition and shorter solidification interval. In this way, the weld metal chemical composition and freezing range is shifted away from the crack-sensitive range. Mainly used filler materials are 4xxx alloys (Al-Si), whose elevated Si contents change the composition and viscosity of the liquid phase thus reducing the cracking susceptibility [12, 13]. However, filler metal alloys are not always available in the desired shapes and manufacturing steps additionally required are time consuming and costly.

In order to overcome the process and metallurgical challenges in pulsed laser welding of thin aluminum sheets, the pulsed Nd:YAG laser will be superimposed with a low power diode laser in this investigation. The diode laser operates at a lower wavelength of approximately 980 nm in order to meet an improved absorption coefficient at this wavelength (about twice as high as 1064 nm). Due to the preheating effect of the diode laser, the temperature on the aluminum surface rises. On the one hand, this causes an increase of the absorption rate of the Nd: YAG laser, as shown in Fig. 2. On the other hand, the welding laser requires less energy in order to melt the aluminum [11]. The increased absorption is associated with improved process efficiency, increasing weld width and depth, and increasing welding speed. Another advantage is the improved coupling characteristic of the Nd:YAG laser. Due to the lower peak power, the spatter formation will be prevented and hence leads to an improved weld quality [11].

An additional important advantage of the diode laser is the direct influence on the solidification conditions. Due to the modification of the thermal cycle, especially the cooling rate by the advantageous solidification conditions is promoted and therefore, hot cracks can be reduced or avoided. All these factors mentioned above lead to a stabilization of the welding process [14–16].

2 Experimental

In this study, the wrought base metals used were Alloy AA 5754 (AlMg3) and Alloy AA 6016 (AlMg0,4Si1,2), known for applications in the automotive industry and for hermetic housings in the electronic industry (see Table 1).

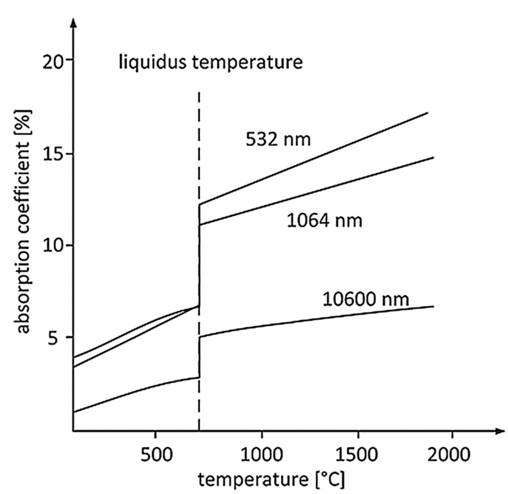


Fig. 2 Coefficient of absorption of aluminium as a function of temperature [11]

Table 1 Chemical composition of the used base metals

Alloys	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Balance
AA 5754	0.40	0.40	0.10	0.50	2.6–3.4	0.3	–	0.20	0.15	Al
AA 6016	1.1	0.2	0.10	0.20	0.40	0.10	–	0.10	0.20	Al

The sheet thickness was 0.5 and 1 mm for both alloys. Before welding, the surface of each specimen was cleaned with isopropanol in an ultrasonic bath followed by air drying. After the samples were placed in the clamping device and laser welded. All performed laser seam welds were performed using a LASAG SLS 200 CL pulsed Nd:YAG laser. The investigations were carried out with a conventional rectangular pulse of the pulsed laser, as shown in Fig. 3. The dual beam experiments were carried out with an additional Laser Line LDM 1000 continuous wave diode laser emitting at a wavelength of 980 nm. The beam of the diode laser beam was delivered via fiber optics into a laser head. Table 2 shows the employed diode laser spot sizes used in this study.

As shielding gas, Argon 99,996 %, was conducted at a flow rate of 12 l/min through a 12-mm diameter copper nozzle positioned approximately 8 mm above the specimen. The dual beam arrangement and experimental setup are shown in Fig. 4a, an exemplary arrangement of both laser spots in Fig. 4b. The superposition of both lasers was carried out off axis. Due to the layout and the mounting conditions of both laser heads on a linear rack, the laser spots could be adjusted independent from each other, so that different thermal regimes could be investigated. The sample geometry for the bead on plate welds and the butt joint configuration is shown in Fig. 5. Furthermore, temperature profiles were recorded with a thermocouple (type k, Ø=0.13 mm), laterally at a distance of 3 mm of the weld center line.

By employing various optic elements, the collimated beam could be shaped differently, so that different temperature fields could be set for the process. In this study, a circular spot, circular ring spot, and a line spot were examined. The geometrical dimensions and power densities at 100 W of each spot are listened in Table 2.

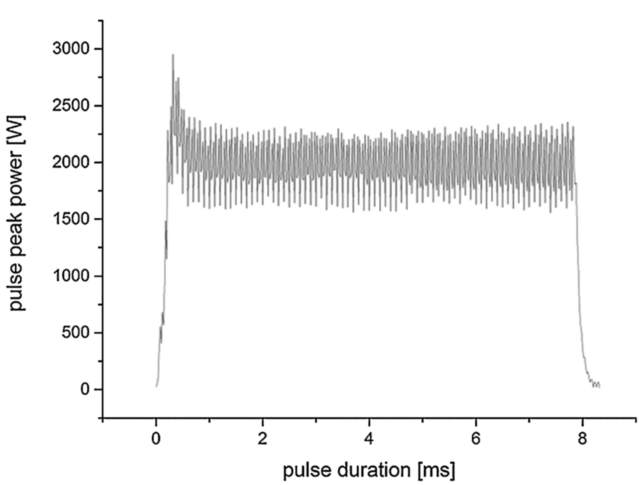


Fig. 3 Measured laser pulse shape

3 Results

At first, the influence of different spot diameters of the diode laser was examined. The diameter was varied with the use of various optic elements (focal lengths and collimations). Figure 6 shows for the alloy 6016 the relationship between different spot diameters, in this case (2, 3, and 5 mm) and the resulting weld depth and weld width that was measured in the cross section. As can be seen in Fig. 6, the highest increase of the weld depth and width can be achieved by diameter of 2 mm. The data point on the left side of this graph represents the result without the superposition. Even a small diode laser power addition of 100 W led to clear increase in weld penetration depth and width. The observed increase of the weld depth depends strongly on the present power density. The highest penetration depth was observed when a diode laser with a diameter of 2 mm (power density 31.85 W/mm^2) was used whereby the penetration depth was increased from 190 to 500 μm at 300 W. Welds made with a 3 mm spot (14.14 W/mm^2) showed an increase up to 487 μm and with a 5 mm spot (3.74 W/mm^2) up to 416 μm. Based on the results mentioned above, the further investigations were carried out with a spot size of 2 mm.

Figure 7 shows the measured penetration depth and weld bead width for the welding experiments with different arrangements of the laser spots and varying diode laser power up to 100 W. In this investigation, the diode laser was positioned either leading, centrally, and trailing to the Nd:YAG laser spot. It is evident that the overlap of both laser beams in the same axis leads to a significantly higher weld penetration depth as well as a weld width. Furthermore, it was observed that a leading and central arrangement of the diode laser spot produces a higher weld width and depth compared to the trailing arrangement. The investigations reveal that even very low diode laser powers lead to an increase of the penetration depth from less than 260 μm without diode laser support up to more than 360 μm with a diode laser power of 100 W and a leading configuration, as shown in Fig. 7. Thus, the penetration depth was increased by about 38 % and the weld width up to 43 %.

In order to show the influence of the diode laser, two parameter ranges were investigated, the single beam process

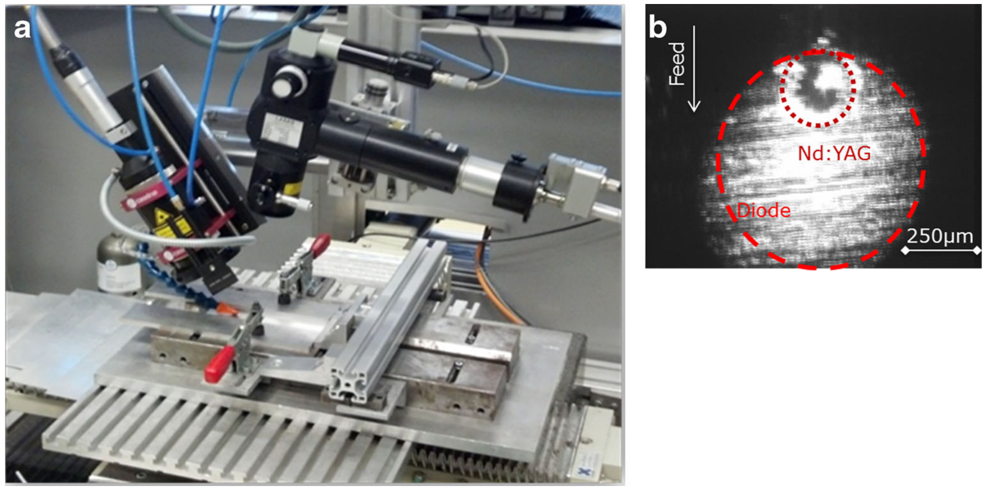


Fig. 4 **a** Experimental setup; **b** example of the geometric alignment of both laser spots

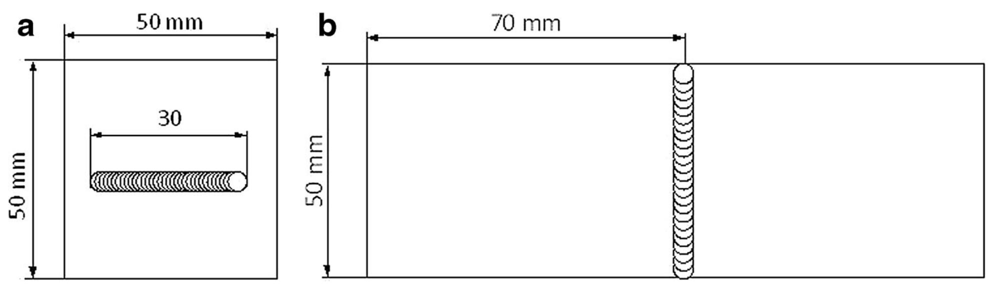


Fig. 5 Weld joint configuration **a** bead on plate **b** butt joint

(pulsed Nd:YAG) and the dual laser beam (diode laser and pulsed Nd:YAG) process. The results of both parameter ranges can be compared in Fig. 8. In an attempt to consider both parameter ranges as suitable as possible, they were defined for a constant frequency and welding speed in dependence of the peak power and pulse duration of the Nd:YAG laser. The welded samples were evaluated regarding the full penetration of a 0.5-mm-thick alloy AA 5754 plate. For the dual laser beam experiments, the geometric alignment of both laser spots was set concentric. The output power of the diode laser

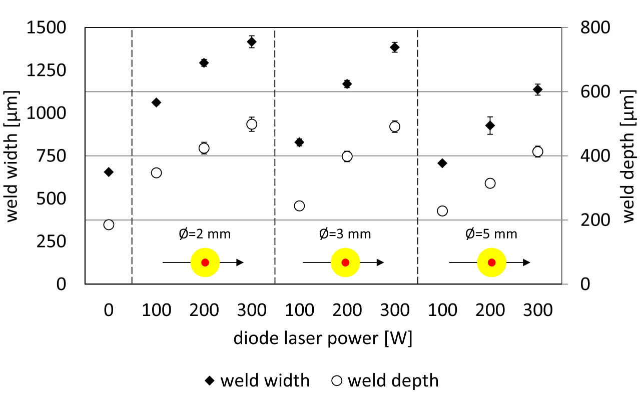


Fig. 6 Influence of different spot diameter on penetration depth and weld width of AA 6016, 1 mm, bead on plate, pulse length 15 ms, pulse peak power 2.3 kW, rep. rate 6 Hz, welding speed 1 mm/s

was 100 W and focused to a circular spot with diameter of 2 mm (Nd:YAG, Ø=400 µm). The determined parameter range for the pulsed laser process is illustrated in the red marked region and for the dual laser beam process in the green area in Fig. 8. It can be concluded that the addition of the diode laser with an output power of 100 W enlarges the parameter range by a factor of 6 in order to penetrate a 0.5-mm-thick sheet. The parameter range is limited on the one hand due to excessive melt ejection, which occurs at high-peak powers and deteriorates the seam quality, as shown in Fig. 8 a. On the other hand, the parameter range is limited by the available average power of the pulsed laser beam source as well as by insufficient penetration. Within the total number of single-beam welds, some hot cracking, void, and spatter formation were noted and the surfaces were found to be rather rough, as shown also in Fig. 8 a. This result is in agreement with Dorn (1999) findings which showed that to high power density leads to spatter formation. Furthermore, by the continual opening and closing of the vapor capillary, a poor outgassing of the melt is present. In contrast to that, the dual-beam welds exhibited smooth surfaces with no evidence of the commonly observed weld defects in aluminum such as solidification cracking (hot cracking), porosity, and spatter (Fig. 8). In summary, the weld quality and the

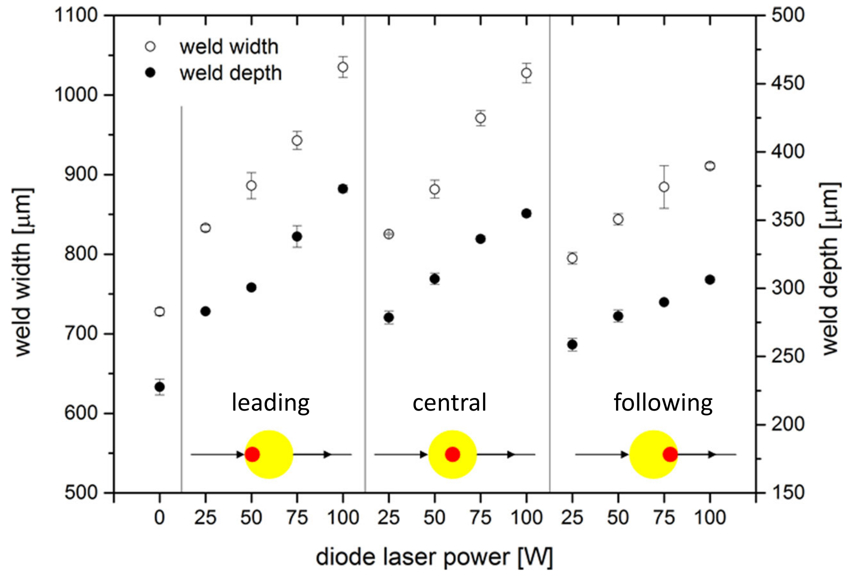


Fig. 7 Influence of spatial arrangement on penetration depth and weld width of AA 6016, 1 mm, bead on plate, pulse length 15 ms, pulse peak power 2.3 kW, rep. rate 6 Hz, welding speed 1 mm/s, diode laser Ø 2 mm

process itself could be stabilized and improved by means of the superposition with only 100 W output power of the diode laser.

The present study was also designed to determine the effect of the superposition on the achievable welding speed, as shown in Fig. 9. This part of the investigation was repeated under almost the same conditions as the experiments above. In this case, the 0.5-mm-thick plates were also evaluated regarding full penetration. However, the pulse duration and the degree of overlap of the individual laser pulses were kept constant, and the repetition rate (frequency) was adapted to the welding speed in order to maintain the overlap degree of the sequential pulses.

For each welding speed, the necessary pulse peak power was determined for properly penetrating the sample. The welding speed for the pulsed process could be improved from 1 mm/s up to 100 mm/min until the average power limit of the laser was achieved, as shown in Fig. 9. Therefore, in a next step, the pulsed process was superimposed with a diode laser, first with 100 W output power and then 150 W. A strong correlation between the preheating effect of the diode laser

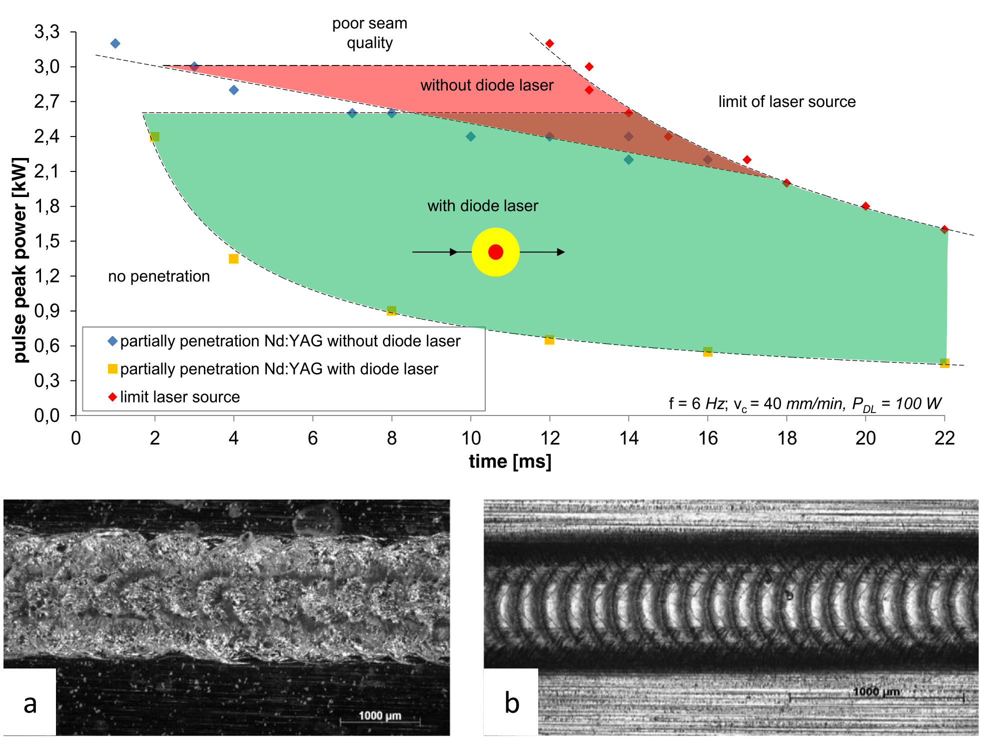


Fig. 8 Influence of penetration AA 5754, 0.5 mm, bead on plate, rep. rate 6 Hz, welding speed 0667 mm/s, diode laser Ø 2 mm, YAG Ø=400 µm

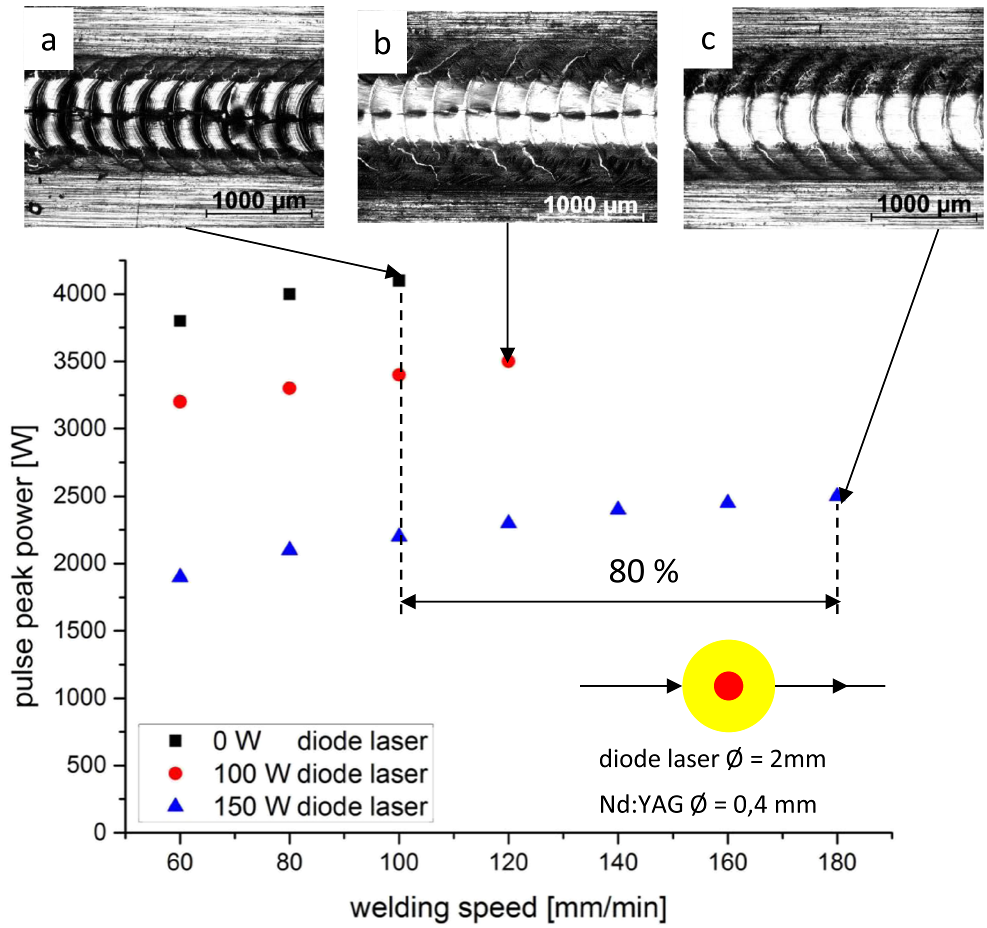


Fig. 9 Influence on welding speed of AA 5754, 0.5 mm, bead on plate, pulse length 5 ms, diode laser Ø 2 mm, YAG Ø=400 µm

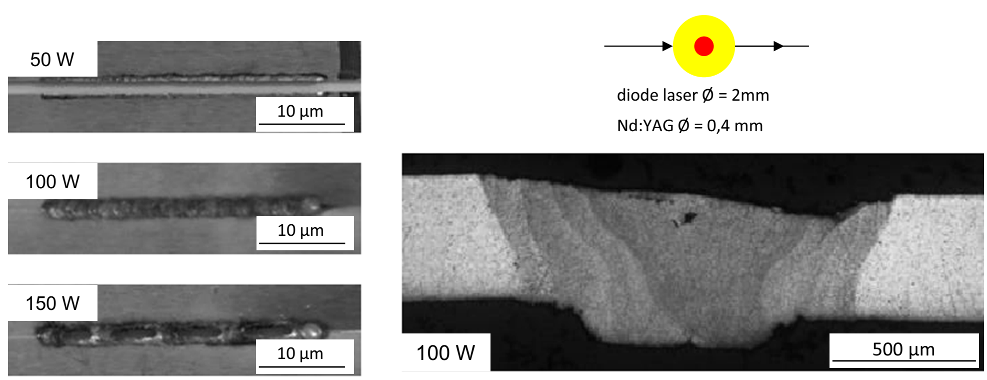


Fig. 10 Dual laser beam welding of butt joints on AA 5754, 0.5 mm, bead on plate, pulse length 15 ms, pulse peak power 2.3 kW, rep. rate 6 Hz, welding speed 1 mm/s, diode laser Ø 2 mm, YAG Ø=400 µm

Table 2 Specifications of different beam shapes of the diode laser

Spot geometry			
Spot size [mm]	d = 2 mm	l = 17mm / w 1 mm	id = 3,5 mm od 5 mm
Power density on 100 watts [W/mm²]	31,83	5,9	9,9

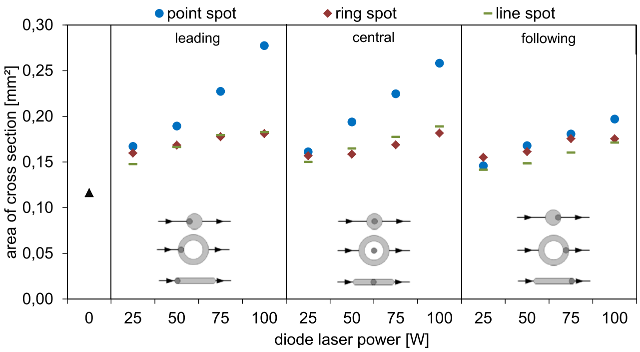


Fig. 11 Influence of beam shaping on weld size on AA 6016, 1.15 mm, bead on plate, pulse length 15 ms, pulse peak power 2.3 kW, rep. rate 6 Hz, welding speed 1 mm/s, diode laser Ø 2 mm, YAG Ø=400 µm

and the minimum pulse peak power of the Nd:YAG laser was noted. For example, at 1 mm/s and with a diode laser power of 100 and 150 W, the necessary pulse peak power could be reduced by 500 W and up to 2000 W, respectively. Hence, an addition of 100 W of the diode laser power allows an increase of the welding speed at 2 mm/s. If the diode laser is operated at 150 W, welding speeds up to 3 mm/s can be realized. While the welding speed is increased up to 80 %, the seam quality is also enhanced significantly, as shown in Figs. 8a and b.

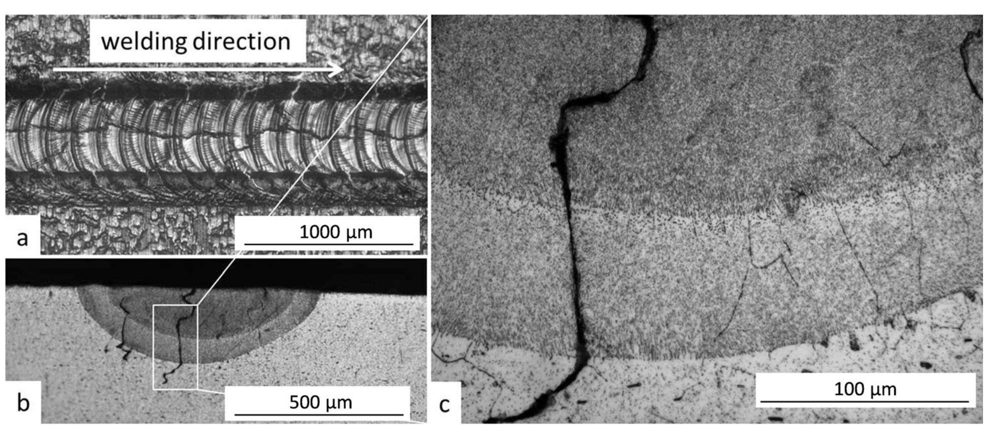
In the next step, the results mentioned above should be transferred to butt joints. Therefore, the plates were clamped and aligned with high accuracy. This is particularly important, since the spot diameter of the Nd:YAG laser has only 400 µm, and a gap or a displacement of the sheet edges to the spot can lead to an insufficient joint [17]. It was found that without diode laser no connection between two sheets could be obtained. It is clearly to see in Fig. 10 that a diode laser power of 50 W also leads to an insufficient connection. At high heat input of the diode laser, in this case at 150 W, a breakthrough of the liquid aluminum occurs, as shown by an overlay with 150 W. Welds with an adequate joint strength were achieved with a power of 100 W of the diode laser. The cross section in Fig. 10 reveals that also in butt joints the formation of hot cracks can be completely avoided.

Furthermore, the influence of different spot geometries of the diode laser as well as their spatial arrangement to the Nd:YAG laser spot was investigated. Within these investigations, the beam was shaped to a ring and line spot. The dimensions and power density at 100 W of all spots are listed in Table 2. Figure 11 shows the measured area of the weld seam for all three used spot geometries and different arrangements to the Nd:YAG spot. The results in Fig. 11 reveal that the largest weld size can be achieved when the Nd:YAG laser is superimposed with diode laser having a spot with a diameter of 2 mm in the leading arrangement. This is due to the higher power density of the point spot compared to the line and circular ring spot.

Figure 12 shows a bead on plate, processed by a pulsed laser without superposition with a diode laser. As shown in this figure, centerline cracking in the weld seam can be observed. The top view in Fig. 12 illustrates that solidification cracking was initiated during the first pulse and continuous subsequently with further pulses in the solidification direction. The examinations of the cross section exhibit that solidification cracking occurs in the weld metal and liquation cracking in the partially melted zone as shown in Figs. 12b and c. The semicircular bands in Fig. 12b are the fusion boundaries of the sequential overlapping spot welds that form the seam weld.

The influence of different beam shapes on the occurrence of hot cracking is illustrated in Fig. 13 for AA 6016. The plan views show that the superposition of a 100 W diode laser significantly influences the solidification conditions. Crack formation can be reduced by increasing the power of the continuous diode laser. As illustrated in Fig. 13, the performance of different beam shapes was analyzed. While the circular and the line shape lead qualitatively to an obvious crack reduction, no significant change could be achieved, when the circular ring shape was applied. It can be presumed that, in this case, the area of local heat input is not consistently close enough to the weld centerline to affect the temperature distribution sufficiently. The superposition of the diode laser could not yet prevent hot cracking completely.

Fig. 12 Influence on hot cracking susceptibility on AA 6016, 1.15 mm, bead on plate, pulse length 15 ms, pulse peak power 2.3 kW, rep. rate 6 Hz, welding speed 1 mm/s, diode laser Ø 2 mm, YAG Ø=400 µm



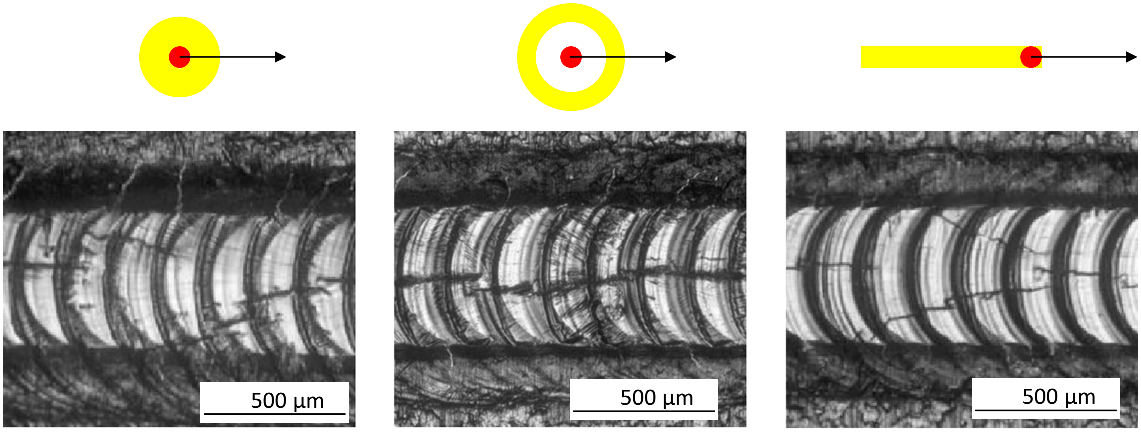
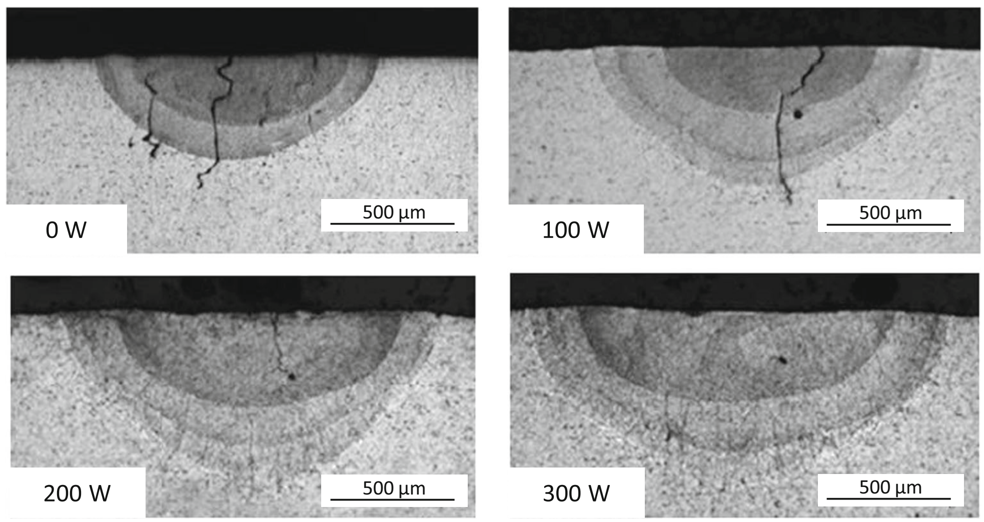


Fig. 13 Influence of beam shaping on hot cracking susceptibility on AA 6016, 1,15 mm, bead on plate, pulse length 15 ms, pulse peak power 2,3 kW, rep. rate 6 Hz, welding speed 1 mm/s, YAG Ø=400 µm

Fig. 14 Influence on hot cracking susceptibility of AA 6016, 1.15 mm, bead on plate, pulse length 15 ms, pulse peak power 2.3 kW, rep. rate 6 Hz, welding speed 1 mm/s, diode laser Ø 2 mm, YAG Ø=400 µm



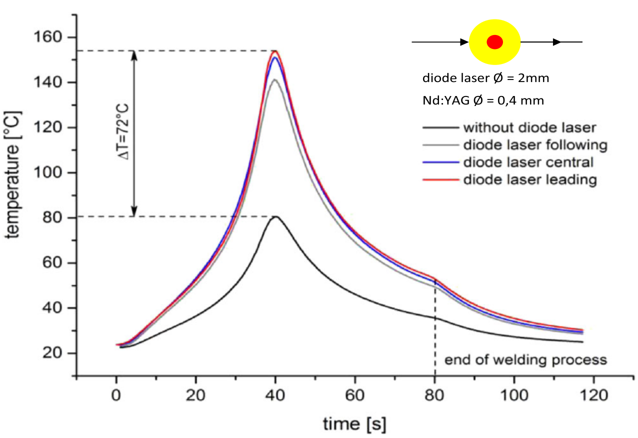


Fig. 15 Temperature profiles of AA 6016, 1.15 mm, bead on plate, pulse length 15 ms, pulse peak power 2.3 kW, rep. rate 6 Hz, welding speed 1 mm/s, diode laser Ø 2 mm, YAG Ø=400 µm

Compared to the metallographic results without diode laser, the crack length could be reduced.

Figure 14 shows the effect of superimposing the diode laser regarding the formation of seam irregularities, in particular hot cracks. By using a diode laser with a circular spot of 2 mm and a power of 100 W, which is positioned concentrically relative to the Nd:YAG laser, no significant improvement of the weld quality was observed. However, the solidification cracking was reduced to a single centerline crack that occurred intermittently along the seam weld.

The main improvements of the weld quality by coupling both laser sources, in particular, in terms of avoiding hot cracks, could be achieved by increasing the diode laser power. When the power of the diode laser is further increased up to 200 W, crack formation is significantly reduced. At 300 W, solidification cracking could not be observed anymore.

Figure 15 shows the measured temperature profiles with and without continuous diode laser using a circular spot geometry and 100 W output power. In the case of the superposition with a continuous diode laser, the temperature of the specimen surface after processing with the pulsed Nd:YAG laser was approximately 72 K higher than without diode laser. The different spatial arrangements of the diode laser to the pulsed laser only showed a small effect on the resulting temperature gradients.

4 Conclusion

Based on the results obtained in the experiment, it can be stated that laser welding using beam superposition is an emerging technique for implementation in industry applications due to the improved process efficiency as well as the quality and properties of the joints. In this work, it is presented that laser welding of aluminum alloy AA 6016 and AA 5754 sheets with pulsed Nd:YAG laser and CW diode laser leads to a better weld quality than welding with a single beam pulsed Nd:YAG laser. The relevance of the superposition is clearly supported by the current findings.

– Increasing welding speed by 80 % due to an overlay with 150 W and simultaneously improving weld seam quality
– Increasing weld penetration depth (38 %) and weld bead width (43 %) by the superposition with 100 W
– Enlargement of the parameter range by factor 6 for penetration of a 0.5-mm-thick aluminum sheet by an additional power of 100 W
– Significant reduction of hot cracking in 5xxx and 6xxx series alloys without the need of a filler material
– Crack free welding of 5xxx series alloys in butt joint configuration

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