

Lasers in Manufacturing Conference 2013

## Effects of diode laser superposition on pulsed laser welding of aluminum

J. P. Bergmann<sup>a</sup>, M. Bielenin<sup>\*,a</sup>, M. Stambke<sup>a</sup>, T. Feustel<sup>a</sup>, P. v. Witzendorff<sup>b</sup>,  
J. Hermsdorf<sup>b</sup>

<sup>a</sup>Department of Production Technology, Ilmenau University of Technology, Neuhaus 1, D-98693 Ilmenau, Germany

<sup>b</sup>Laser Zentrum Hannover e.V., Hollerithallee 8, D-30419 Hannover, Germany

### Abstract

Pulsed laser welding of thin aluminum sheets is common for housing, where welding defects are detrimental especially in terms of hermetic packaging as well as electromagnetic compatibility. This paper shows investigations on laser welding of aluminum by superposition of a pulsed Nd:YAG laser with a diode laser in order to improve the weldability of aluminum. This configuration allows to enhance the absorption of the Nd:YAG welding laser due to preheating by the diode laser. Furthermore the effects of temporal pulse shaping have been studied experimentally. Deeper penetrations as well as an increased weld quality in terms of cracking were observed in welds manufactured with diode laser superposition. Besides this the modification of the thermal cycle by the combination of the two laser beams promotes advantageous solidification conditions and therefore hot cracks were efficiently reduced or avoided. Additionally solidification conditions can be actively influenced. The results show a decreasing number of defects and additionally an increase of the welding quality.

© 2013 The Authors. Published by Elsevier B.V. Open access under [CC BY-NC-ND license](https://creativecommons.org/licenses/by-nc-nd/4.0/).  
Selection and/or peer-review under responsibility of the German Scientific Laser Society (WLT e.V.)

*Keywords:* laser welding; aluminium alloy; diodelaser superposition; Nd:YAG laser; cracking

### 1. Introduction

Laser welding achieved in the last years to be one of the most applied metal joining methods, as it can provide high productivity, high weld quality, high welding speed, high weld aspect ratio, low heat input, low distortion, manufacturing flexibility and ease of automation. Because of the high welding speed, reduced heat

\* Corresponding author. Tel.: +49-3677-69-3809; fax: +49-3677-69-1660.  
E-mail address: [martin.bielenin@tu-ilmenau.de](mailto:martin.bielenin@tu-ilmenau.de).

affected zones can be achieved, which leads to low distortion compared to TIG or GMA. Pulsed laser welding is compared to cw-laser welding a further way in order to reduce heat input and is used for example for seal welding of aluminum housings for electrical applications or for titanium welding in medical application. Due to the high reflectivity of aluminum at wavelengths above 1000 nm high laser power when coupling is needed for laser welding, as a big part is lost by reflection. This causes an increase of energy and investment costs. For thin metals sheets pulsed laser sources have been established industrially, since the heat input is lower than continuous wave lasers. The low absorption of a Nd:YAG laser radiation causes difficulties to weld aluminium efficiently. A large part of the laser radiation is reflected at the surface. Figure 1 shows the absorption of aluminum as a function of the wavelength. Aluminum absorbs only 5% of the incident laser radiation from an Nd:YAG laser with a wavelength of 1064 nm. Therefore, a laser source with high peak power is necessary in order to obtain sufficient penetration depth and weld width. A disadvantage of pulsed lasers is the low welding speed. The welding speed when welding with a pulsed laser is limited by the required frequency and overlap of the welded “points”. The low travel speeds during pulsed laser welding and the formation of pores and cracks leads to defective components.

The temporal pulse shaping is a technique to reduce or eliminate defects in welds. It allows to modify the laser beam power during the pulse in a defined time. Thus, the laser power can be adjusted to the material. A conventional rectangular pulse shape leads to a high cooling rate in the material. Through a defined change in the pulse shape the temperature gradient in the melt pool can be controlled directly, so that the solidification process can adapted to the material behavior.

To overcome these disadvantages, the pulsed Nd:YAG laser can be superimposed with a continuous wave diode laser. The diode laser with the wavelength of 808 to 980 nm supports the welding process of the pulsed Nd:YAG laser. The absorption coefficient of aluminum shows a peak around 800 – 815 nm. In this area, the absorption of laser radiation is up to 3 times higher than that of Nd:YAG. During the diode laser supported welding process, the temperature on the surface of aluminum rises. Thus the absorption for the Nd:YAG laser increases. The phenomenon and mechanism of this welding process with the combination of both lasers are investigated and reported in this paper.

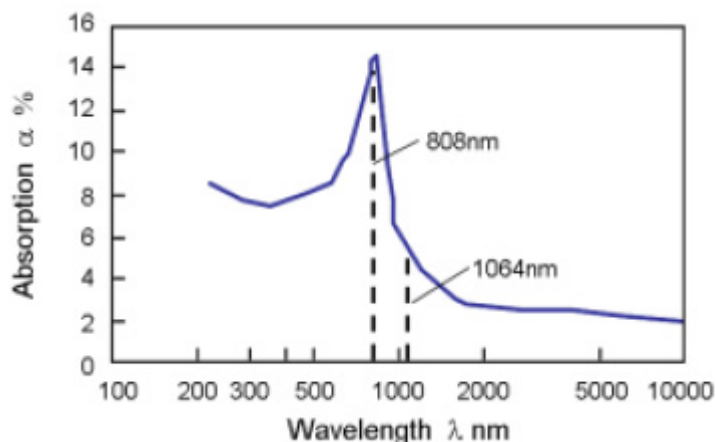


Fig. 1. Absorption rate of aluminum [8]

Weldability of thin aluminum sheets is strongly dependent on process conditions as well as on hot crack and pore formation. Pulsed laser welding with Nd:YAG lasers is an established welding process, with a further

high potential. When welding aluminum, pores and cracks are detrimental for the performance of these products. Pores are often caused by process gas and/or contamination on the sheet surface. Pores can be minimized through suitable shielding gas. Hot crack sensitivity of aluminum alloys is well described for automotive alloys for example in [1] and [2]. Aluminum alloys are sensitive to hot cracks, which can be attributed to relatively high thermal expansion of aluminum, its large change in volume upon solidification and its wide solidification temperature range. Two types of hot cracks, either solidification cracks within the weld fusion zone or liquation cracks in the heat affect zone, may occur when welding of aluminum alloys. Many wrought aluminum alloys, especially the 6xxx series aluminum alloys, are known to be susceptible to hot cracking during fusion welding due to their relatively high thermal expansion coefficient, large solidification shrinkage and wide solidification temperature range. The susceptibility of aluminum to solidification cracking is influenced by the composition of the weld metal, the welding process and the used process parameters. A high solidification rate will promote the formation of long thin dendritic morphology with poor fluid flow between the dendrites. Hot cracking susceptibility is influenced by the solidification microstructure, the distribution of the liquid phase in the final stage of solidification and the grain structure. Hot cracks are generally formed under three conditions [3]:

- low melting phase at the grain boundaries (dependent on chemical composition),
- formation of tensile stresses in the welded zone during cooling and solidification (dependence on thermo-mechanical conditions),
- solidification path.

In the case of thin aluminum sheets, pulsed welding is carried out with pulse lengths up to 20 ms. The non-continuous heat input leads to a low general heat input, reducing distortion. Furthermore, pulse shaping can be used to influence solidification conditions. In [4] Zhang et al. describe hot cracking when pulsed laser welding with shaping of the pulse (i.e. temporal changing of the laser power). According to these investigations, cracking occurs with high cooling rates, while hot crack sensitivity is remarkably reduced by using intermediate cooling rates. For this reason intermediate ramp-down gradients should be designed to reduce crack sensitivity. Dual beam laser welding has been used for aluminum alloys but not in order to prevent hot cracking. Punkari et al. [9] studied the effects of Mg content on the weldability of aluminum alloy sheet using Nd:YAG lasers. It is concluded that the weld penetration increases with Mg content. More recently, Chen and Molian [10] have welded thin AA 5052 aluminum sheets in lap-joint configuration using a pulsed Nd:YAG and a continuous wave diode laser with an zero inter-beam spacing. Chen observed an improved light absorption and enhanced weld quality compared to single beam welding. Furthermore in [11] Drezet describes a twin laser process of two independent laser beams. Crack free welds were generated by the superposition of a pulsed YAG laser and a CO<sub>2</sub> laser. Combination of solid state laser with diode laser is reported in [5] for high power applications (3 kW). A recent investigation on the combination of a pulsed laser and diode laser is reported in [7] and has the preliminary aim of increasing processing speed. The diode laser with 808 nm wave allows higher absorption rate in aluminum, enabling higher process speeds [6]. In [7] a 65 W diode laser was used and superimposed with a 2.4 kW Nd:YAG laser. The laser beams were delivered from one glass fiber with a 300 μm diameter and achieved an increase in penetration depth of 30 %. The width of the weld seam was also increased by 20 %. The authors of reference [8] used the superposition of a diode laser with a pulsed YAG laser delivered in one fiber to reduce heat cracking of Al3003 alloys. The hot cracking was reduced by performing post heating with the diode laser after the Nd:YAG laser pulse has welded the aluminum.

## 2. Experimental

Table 1 shows the specifications of the pulsed Nd:YAG laser and the three continuous diode lasers used in this study. The diode laser was defocused with spot diameter of approximately up to 3 mm, compared to the 400  $\mu\text{m}$  YAG laser spot. The pulsed Nd:YAG laser has a maximum average power of 200 W and can be pulsed up to 500 MHz. The base metal used for this study was AA-AW6016 – T4 aluminum with a nominal chemical composition as shown in Table 2. Before welding the surface of each specimen was cleaned with acetone in an ultrasonic bath followed by a methanol rinse and air drying. The specimens were then clamped on the welding jig. Figure 2 shows the experimental setup. The superposition of the diode laser and Nd:YAG laser was carried out off axis. Due to the lay out and the mounting condition of the laser heads on a linear rack, laser spots can be free adjusted to each other, so that different thermal regimes can be investigated.

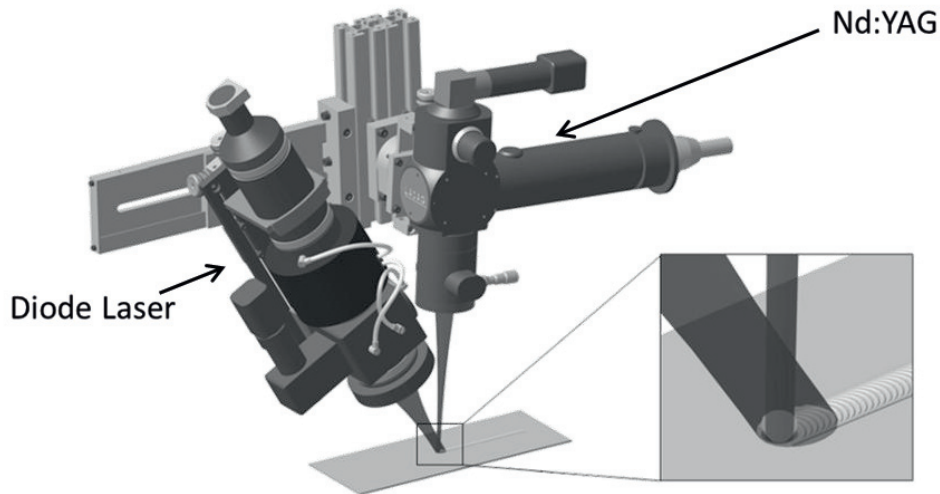


Fig. 2. Schematic diagram of experimental setup

Table. 1. Specifications of pulsed Nd:YAG laser and continuous diode laser

	Nd:YAG	diode laser
Average Power	200 W	Up to 300 W in the study
Max Peak Power	8000 W	/
Pulse Repetition rate	0,1 – 500 Hz	Continuous Wave
Pulse Energy Max	110 J	
Pulse width	0,2 – 200 ms	Continuous Wave
Spot size	400 $\mu\text{m}$	Up to 3000 $\mu\text{m}$
Wavelength	1064 nm	808 nm, 808/940 and 980 nm

As shielding gas, argon was applied to the welding zone with a gas flow rate of 8 l/min. The weld geometry is reported in the figures during presenting results. After welding specimens were evaluated optically regarding macro defects on the surface, further specimens were polished and etched, in order to perform metallographic characterization.

### 3. Results

#### *Effects of superposition continuous diode laser and pulsed Nd:YAG (square wave pulse)*

Figure 3 shows the results of welding a 0.5 mm sheet in the bead-on-plate condition and the position of the lasers to each other. The visual inspection of the back-side of the plate showed no homogeneous penetration using 2.2 kW output power. The 2.5 kW maximum pulse output allowed deep penetration with spattering. Superposition of only 75 W (wavelength 808 nm) with the 2.2 kW allowed a homogeneous weld seam formation and no spattering. Spattering due to high output power could be completely avoided. Furthermore the investigations reveal that even very low diode laser powers leads to an increase of the molten cross section from less than 0.15 mm<sup>2</sup> without diode laser support up to more than 0.25 mm<sup>2</sup> with diode laser power over 50 W, as shown in Figure 4.

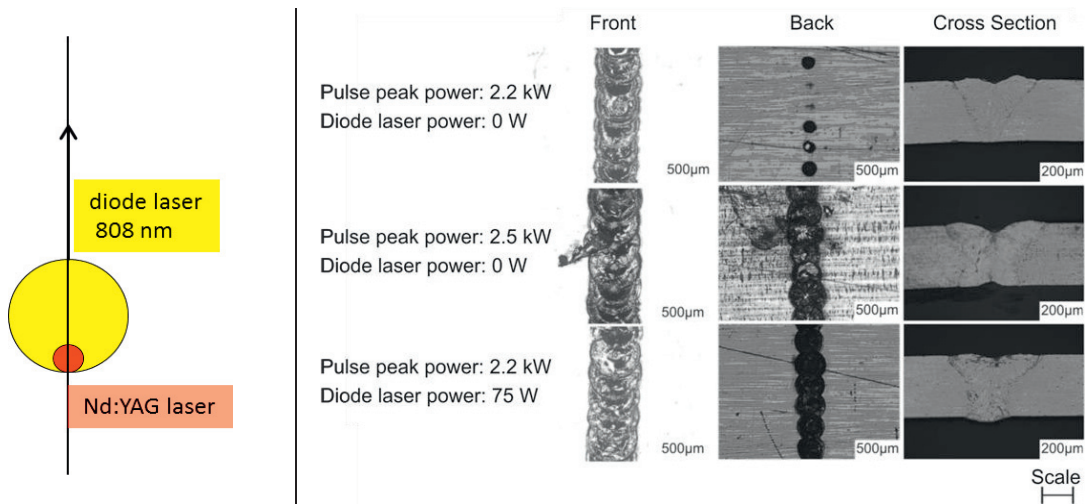


Fig. 3 : Bead-on-plate welding of 0.5 mm AA1xxx aluminum sheet with 60 mm/min speed (pulse length: 2 ms, repetition rate: 3 Hz, diode laser Ø2mm, YAG Ø = 400 µm)

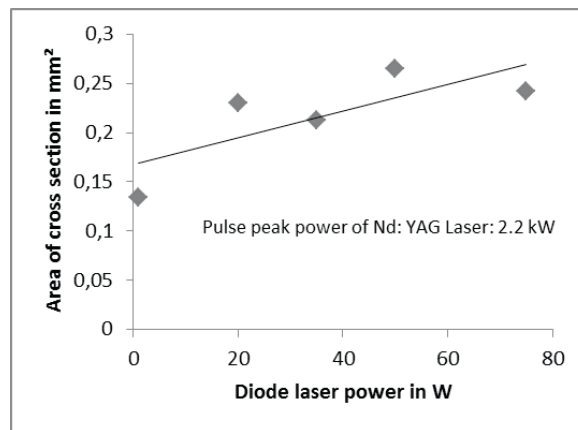


Fig. 4 : Cross section area depending on diode laser power (pulse length 2 ms, maximum laser output 2.2 kW, repetition rate 3 Hz, diode laser Ø 2mm, YAG Ø = 400 µm)

The superposition of both laser sources allows increasing the effectiveness of process conditions. For the characterization of the weld geometry aluminum sheets with a thickness of 1,15 mm were used (in this case diode laser with a wavelength of 980 nm). It is evident that the weld bead width and weld penetration depth are increased (Figure 5). While bead width increases from 700  $\mu\text{m}$  to over 1000  $\mu\text{m}$  with 100 W diode laser, the weld depth increases over 30 % up to approx. 370  $\mu\text{m}$ . The correlation is linear in this range.

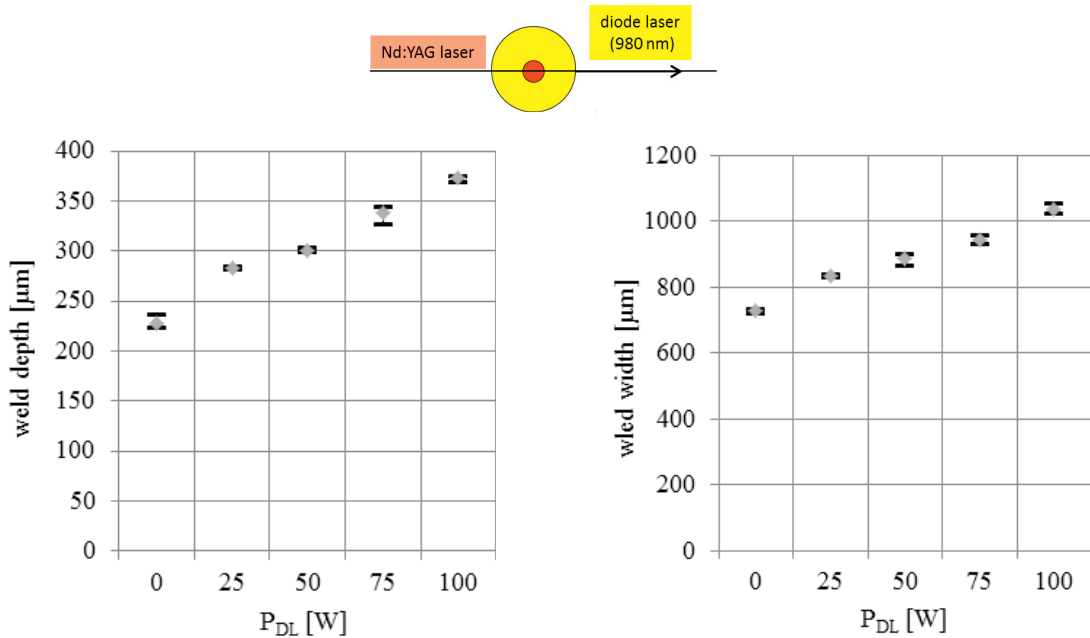


Fig. 5. Influence of superposition on weld width and weld depth of  $\text{AlMg0,4Si1,2}$ , 1,15 mm, bead on plate, rep. 6 Hz, pulse length 15 ms, max. output power 2,3 kW, speed 60 mm/min, diode laser  $\varnothing$  3 mm, YAG  $\varnothing$  = 400  $\mu\text{m}$

The influence on the weld geometry of the superposition of the diode laser with Nd:YAG laser is easy to detect even in the micrographs of the beads (Figure 6). Furthermore the influence on crack formation is shown in Figure 6 for the above mentioned welds. Figure 6 (a) shows the bead-on-plate welded seam with only pulsed laser welding, while Figure 6 (b) shows the effect of superposition with a 50 W diode laser and Figure 6 (c) shows the effect of superposition with a 100 W diode laser. The major benefit of superposed laser welding is the lower cooling rate in the welding seam and the base metal, which obviously leads to reduced crack susceptibility especially in the transition from base material to molten pool. Figure 6 demonstrates that cracks could be decreased by increasing the power of the continuous diode laser. The superposition of the diode laser could not yet prevent hot cracking completely. Compared to the metallographic results without diode laser, the crack length could be reduced and the site was shifted.

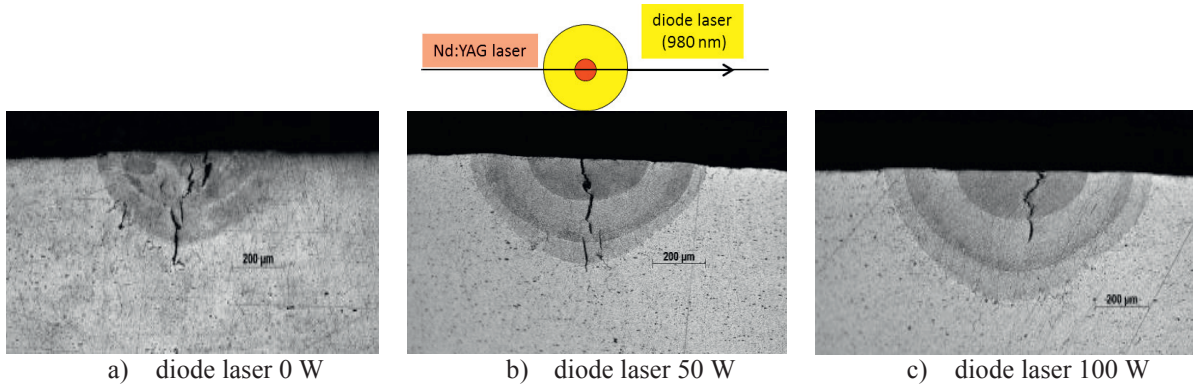


Fig. 6. Influence of superposition on cracking susceptibility of AlMg<sub>0,4</sub>Si<sub>1,2</sub>, 1,15 mm, bead on plate, rep. 6 Hz, pulse length 15 ms, max. output power 2,3 kW, speed 60 mm/min, diode laser Ø 3 mm, YAG Ø = 400 µm, (a) without diode laser (b) with diode laser 50 W (c) with diode laser 100 W

A significant reduction of solidification cracks can be achieved with diode laser energy of over 100 watts. The influence of higher laser power (diode laser wave length 980 nm) is reported in Figure 7, where the difference in center line cracking between 100 W and 300 W is reported. In the last case no cracking occurs.

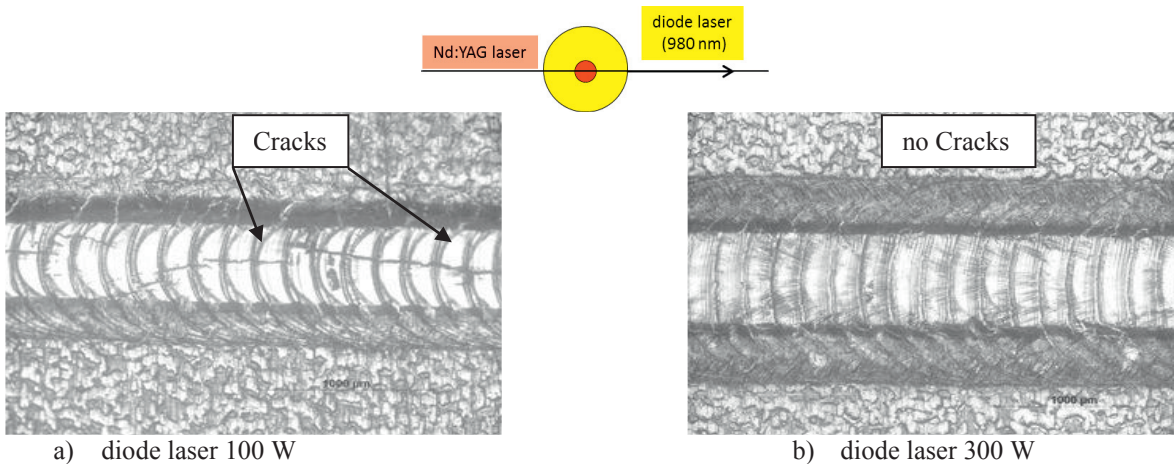


Fig. 7. Influence of superposition on cracking susceptibility of AlMg<sub>0,4</sub>Si<sub>1,2</sub>, 1,15 mm, bead on plate, rep. 6 Hz, pulse length 15 ms, max. output power 2,3 kW, speed 60 mm/min, diode laser Ø 3 mm, YAG Ø = 400 µm, (a) with diode laser 100 W (b) with diode laser 300 W

Further investigation on the cracking behavior of aluminum due to the superposition of a Nd:YAG laser with a diode laser are reported in Figure 8. In this case, the diode laser had a spot of 3 mm and wave length of 808/940 nm. The beam geometry was also a bead on plate. On the surface cracking can be detected during pulsed laser welding (Figure 8 a), while with 100 W diode laser superposition crack-free joints could be produced.

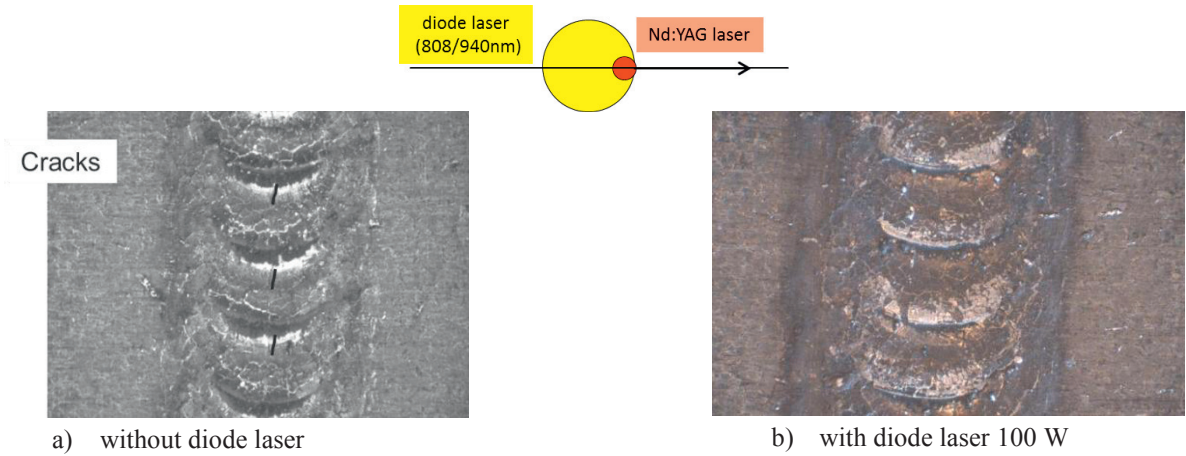


Fig. 8: Influence of superposition (base process AlMgSi1, 1.5 mm, bead on plate, rep. rate 18 Hz, pulse length 10 ms, max. output power 2 kW, speed 60 mm/min, diode laser  $\varnothing$  3 mm, YAG  $\varnothing$  = 400  $\mu$ m)

Figure 11 reports the longitudinal cross section of beads showed in Figure 9. The overlapping of single points to form a line weld can be recognized, as well as the crack free weld with a superposed diode laser.

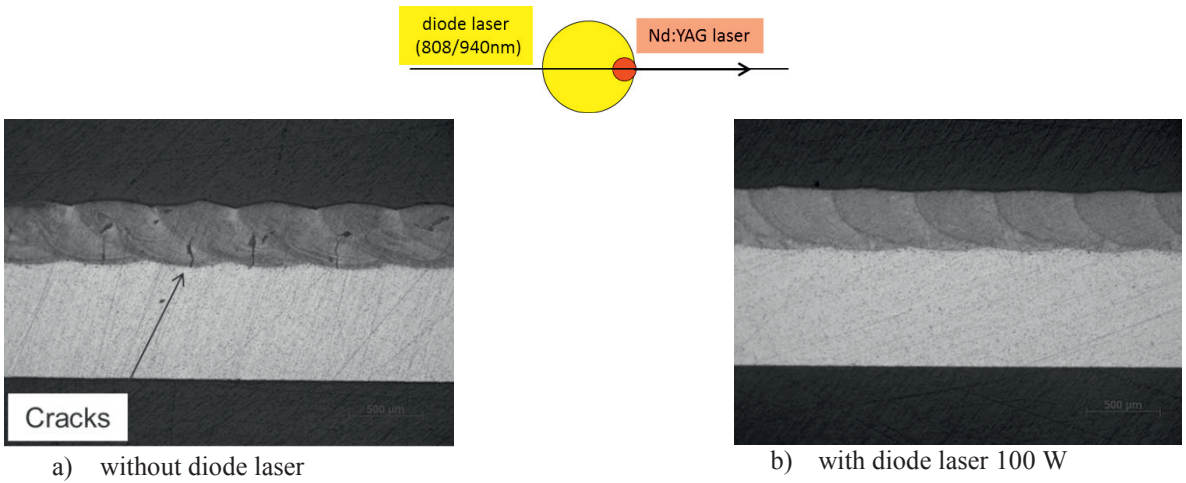


Fig. 9: Influence of superposition in longitudinal cross section (base process AlMgSi1, 1,5 mm, bead on plate, rep. rate 18 Hz, pulse length 10 ms, max. output power 2 kW, speed 60 mm/min, diode laser  $\varnothing$  3 mm, YAG  $\varnothing$  = 400  $\mu$ m)

Porosity formation due to lower cooling rates could be detected as well, even with some overheating visible on the bead surface (Figure 10)



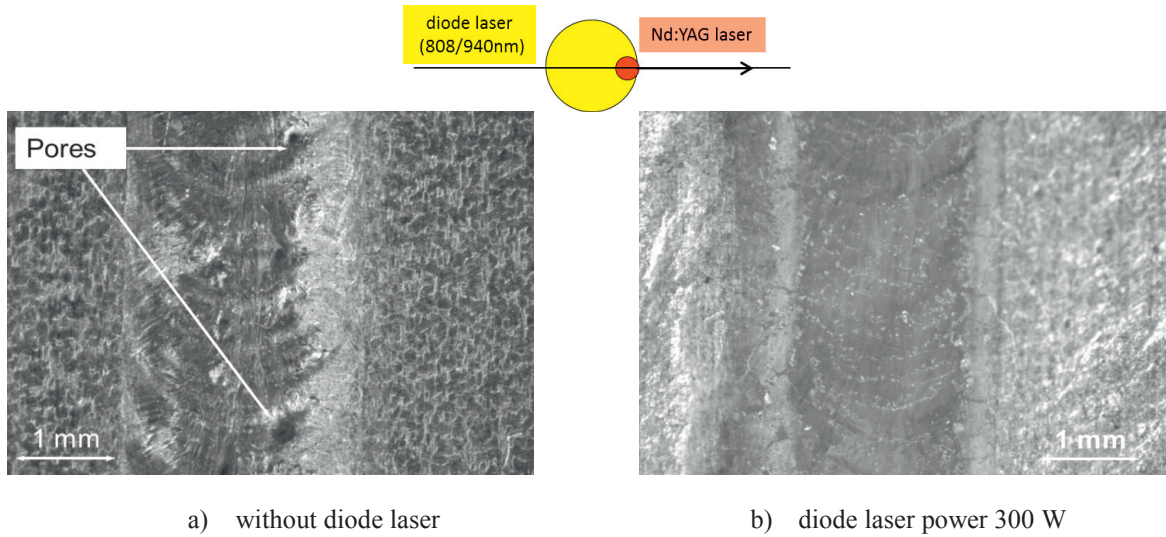


Fig. 10: Surface conditions of pulsed laser welded seam a) without superposition of diode laser and b) with superposition of 300W diode laser (base process AlMgSi1, 1,5 mm, repetition rate 5 Hz, pulse length 4 ms, max. output power 2kW, speed 18 mm/min, diode laser Ø 3 mm, YAG Ø = 400 µm)

*Effects of temporal pulse shaping*

The influence of a modified pulse shape (ramp down) is reported shown in figure 11 (a and b). The long ramped-down pulse leads compared to the rectangular pulse to no visible cracking, while the overlapping with a diode laser (Figure 11 c) leads to higher penetration. The pulse shape is beneficial because of its long lasting annealing effect, which influences solidification and distortion.

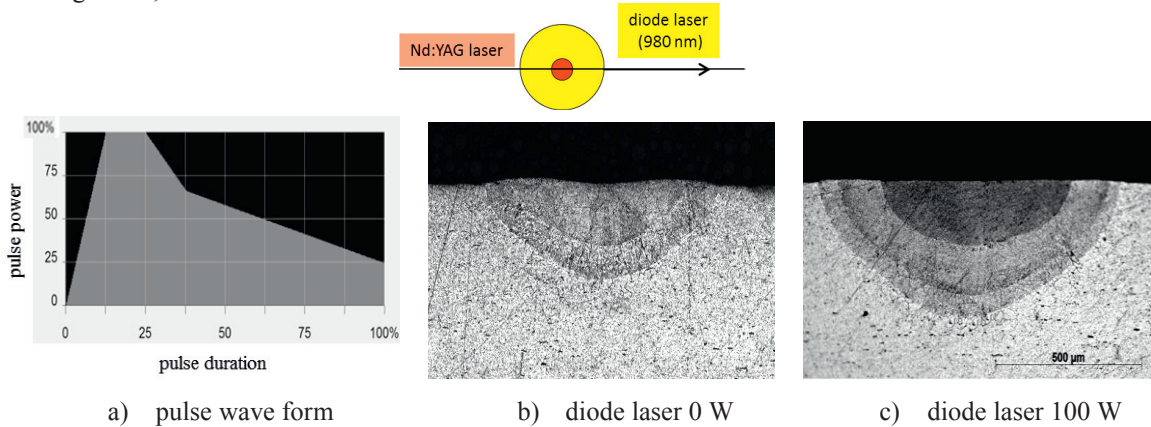


Fig. 11. Influence of superposition and pulse shaping on cracking susceptibility of AlMg0,4Si1,2, 1,15 mm, bead on plate, rep. 6 Hz, pulse length 15 ms, max. output power 2,3 kW, speed 60 mm/min, diode laser Ø 3 mm, YAG Ø = 400 µm, (a) Ramp-down pulse wave form (b) without diode laser (c) with diode laser 100 W

#### 4. Conclusions

This paper provides preliminary results of the superposition of a pulsed Nd:YAG laser with a low power diode laser in order to improve process conditions and reduce hot crack and pore formation. With 100 W it was possible to increase the weld depth of approximately 30 %. The superposition also allows active modification of the welding and solidification conditions. Based on the previous results, it is clear that the effect of longer solidification time has a benefit on the reduction and elimination of solidification cracking by decreasing the cooling rate. Hot cracking was systematically detected when using rapid cooling. Crack-free welds were achieved with diode laser power of 300 watts (980 nm wave length). Both, bead width and penetration depth increased largely as the output power of continuous diode laser was increased. Also, the positive influence of the overlapping on the pore formation during the welding could be observed. From the investigations it is clear that the hot cracking susceptibility and pore formation is dependent from different conditions, such as wavelength and spot diameter ratio between pulsed Nd:YAG laser and diode laser. At wavelengths of 808 nm and small spot diameters only low power of diode lasers are required to reach the reported effects. With wavelengths in the range of 980 nm and bigger spot diameters of the diode laser, higher power is required in order to make the effects visible

#### Acknowledgments

The investigations were carried out in the project “stabilized laser welding of aluminum” (01.10.2012-30.09.2014). The research project (AIF- IGF-17.487) was supported from the budget of the Federal Ministry of Economic Affairs through the Allianz Industrielle Forschung (AIF) and the German Welding Society (Forschungsvereinigung des DVS). We would like to thank all funding organisations.

#### 5. References

- [1] Waldmann H. Werkstofftechnische Aspekte des Laserstrahlschweißen von Aluminiumlegierungen für den Fahrzeugbau. PhD. Thesis; 2000; Bayreuth.
- [2] Hilbinger R M. Heißbrissbildung beim Schweißen von Aluminium in Blechrandlage. PhD. Thesis; 2001; Bayreuth.
- [3] Schuster J. Heißbrisse in Schweißverbindungen. Düsseldorf: DVS Verlag; 2004.
- [4] Zhang J., Weckman D C, Zhou Y. Effects of temporal pulse shaping on cracking susceptibility of 6061-T6 Aluminum Nd:YAG Laser welds. *Welding research* 2008; 87: 18– 30.
- [5] Trautmann A, Zäh M. Prozesssicheres Fügen von Aluminium-Tragwerkstrukturen mit einem hybriden, bifokalen Lasersystem. *Fortschritt Berichte, VDI, 2. Reihe: Fertigungstechnik*; 2007, p. 153-181.
- [6] Suttman O, Moalem A, Kling R, Ostendorf A. Drilling, Cutting, Marking and Microforming. In: Sugioka K, Meunier M, Piqué A editors. *Laser Precision Microfabrication*. Springer Verlag; 2010.
- [7] Haraguchi S, Okamoto Y, Uno Y, Sakagawa T, Makashiba S. Investigation on Welding Phenomenon for Aluminum Alloy by Superposition of Pulsed YAG Laser and Diode Laser. *Journal of Advanced Mechanical Design, Systems, and Manufacturing*: 2010. 4: 875-882.
- [8] Nakashiba S, Okamoto Y, Sakagawa T, Miura K, Okada A, Uno Y. Welding Characteristics of aluminum alloy by pulsed Nd:Yag Laser with Pre- and Post-Irradiation of superposed continuous diode laser. *Proceedings of International Congress on Applications of Lasers and Electro Optics 2011; Orlando, USA*; p. 23 - 27.
- [9] Punkari A., Weckman D.C. and Kerr H.W.: Effects of magnesium content on dual beam Nd:YAG laser welding of Al-Mg alloys, *Sci. and Tech. of Welding and Joining*, vol. 8 (4), 2003, p. 269-281.
- [10] Chen Weichiat, Molian Pal, Dual-beam laser welding of ultra-thin AA 5052-H19 aluminum. *The International Journal of Advanced Manufacturing Technology* November 2008, Volume 39, Issue 9-10, pp 889-897
- [11] J.-M. Drezet, M.S.F. Lima, J.-D. Wagniere, M. Rappaz, W. Kurz, Crack-free aluminium alloy welds using a twin laser process. *Safety and Reliability of Wlded Components in Energy and Processing Industry*