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Influence of laser power on the melt pool shape of handheld laser beam welding of 1.5 mm thick micro alloyed steel

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Abstract. Manual welding of structures requires highly skilled welders due to the large heat-affected zone of arc-based processes, that can negatively impact microstructure and cause distortion. Handheld laser beam welding is a promising alternative with high welding velocity and a concentrated heat input. However, its current use in industry is limited to parts with aesthetic requirements, often made of high-alloyed steel. To extend the use of handheld laser beam welding to low-cost steels with good mechanical properties, this study investigates the influence of laser power on the melt pool shape for micro-alloyed steel with a thickness of 1.5 mm. Tested joint geometries are T-joints welded with filler wire as well as butt joints and overlap joints without filler wire, which are typically found in assemblies under mechanical load. Weld quality is assessed by weld porosity analysis. The results show that the handheld laser beam welding with filler wire produces T-joints with a very good external appearance, but with porosity between level C and D in the cross sections according to DIN EN ISO 13919-1. By increasing the laser power, a deep penetration of the T-joint zone can be achieved without increasing the actual throat thickness. For handheld laser beam welding of butt joints a full penetration weld of the highest quality class can be reached. Overlap joints can be welded with full or partial penetration depending on the laser power selected, with quality classes between B and C in terms of porosity.

1. Introduction

Handheld laser welding (HHLW) uses a small focus spot size combined with beam oscillation to achieve weld width and can be used with or without filler wire [1]. Compared to arc-based processes, laser welding is known to have a small heat affected zone, leading to less distortion and residual stress [2]. This is due to the deep and narrow melt pool. When this keyhole collapses, gas and metal vapour is trapped in the bottom zone of the keyhole [3]. Adapting process parameters like shielding gas or welding velocity can reduce this keyhole induced porosity [4–6].

Especially for thin walled structures, small batch sizes and parts with aesthetic requirements, the low distortion due to the laser of HHLW is an interesting alternative to manual arc welding [7].

As HHLW is characterised by higher welding velocity and less straightening, industry reports an increase in throughput of 30 % when replacing arc-based welding by HHLW [8]. Also, training is simpler as the process is easier to handle, allowing new employees to produce quality welds in less time [8]. This is supported by a study analysing the influence of operator skill level on the weld quality and mechanical properties of the weld. Skilled workers and students were asked to weld butt joint welds of AISI 301LN sheets without filler wire with HHLW. Results show that operator training and experience has no significant effect on the mechanical properties of the weld. Using a mechanical roller device for constant welding velocity improved the optical appearance of the weld but led to a reduction of mechanical properties. [9]

HHLW is also used for spot welding AISI 304 steel with different thicknesses, showing a change in weld quality depending on the angle between weld surface and laser beam [10].

Commercial HHLW systems are also capable of cleaning surfaces by using a high beam scanning frequency, in example for pickling and passivation of the welded steel surface. Regarding gas influence for HHLW of 2 mm stainless steel, welds with low porosity can be achieved using nitrogen as shielding gas instead of argon. [1]

The studies regarding HHLW emphasise different aspects of the welding process, showing that various parameters have an effect on the weld quality [1, 8–10]. The impact of operators is assessed, but the influence of the welding parameters on the weld geometry is unknown. Current research focuses on high-alloyed steel, while HHLW of low-cost steels has not been intensively researched yet. Thus, the objective of this study is to characterise the influence of the laser power on the melt pool shape for the micro-alloyed steel HX340LAD. This offers possible application of HHLW in the automotive and the railway sector, especially for repair welding. Investigated joint geometries are butt joints and overlap joints without filler wire and T-joints with filler wire, all typically found in welded components under mechanical load. The influence of laser power on the melt pool geometry is characterised on cross sections. Porosity of the welds is assessed according to DIN EN ISO 13919-1.

2. Materials and Methods

2.1 Handheld laser beam welding

The HHLW device used for experiments was a commercially available BLT 1500 PenWelder Scan from BLUE LASERTOOLS, equipped with a 1.5 kW laser of 1080 nm wavelength. All welds were conducted with argon as shielding gas at 14 l/min. Sheets of HX340LAD with 150 mm length, 50 mm width and 1.5 mm thickness were used. All weld seams were tack welded on the backside and the area to be welded was cleaned using the HHLW with a laser power of 175 W, a scan width of 6 mm and a scan speed of 5000 mm/s. The laser focus point was set to the sheet surface.

Butt joints and overlap joints were welded without filler wire and welding velocity measured through videos. The butt joints were welded with increasing laser power starting from 250 W up to 700 W in 50 W steps. The width of the scan was set to 1 mm with a scan speed of 150 mm/s.

To investigate the influence of welding parameters on overlap joints, two series of increasing laser power from 500 W to 1300 W in 200 W steps were welded. One series was welded with 0.5 mm scan width and one with 1 mm width. The scan speed was set to 150 mm/s.

T-joint investigation was conducted by increasing the laser power from 500 W to 800 W in 100 W steps. The scan width was set to 2 mm with a speed of 260 mm/s. As the T-joints were welded with filler wire, the feed rate was set to 80 cm/min, being equal to the welding velocity in HHLW. T-joints were welded with filler wire SG 3, also known as G4Si1 or 1.5130, with a diameter of 1.2 mm. The chemical composition of the base material and filler wire are stated in Table 1.

Table 1. Chemical composition of the welded materials in wt.%

Grade	Fe	C	Si	Mn	P	S	Al	Nb	Ti
HX340LAD/1.0933	Bal.	0.12	0.5	1.4	0.03	0.025	0.015	0.10	0.15
SG 3/1.5130	Bal.	0.07	0.95	1.7					

2.2 Material characterization route

After welding, the specimens were optically inspected as well as prepared for the metallographic analysis. Three cross sections per specimen were cut via abrasive sectioning, one in the middle of the weld line and one on each side with a distance of 15 mm. Cross sections were grinded and etched with 2 % Nital. Porosity according to DIN EN ISO 13919-1 was measured through vectorisation of the unetched cross sections in the commercially available software CorelDRAW and compared to the melt pool surface measured on the etched sections in the same software.

3. Results and discussion

3.1 Butt joint welding

Figure 1a shows a detailed view of the butt joint produced with the maximal tested laser power of 700 W. One of the corresponding cross sections is depicted in Figure 1b, showing the full penetration weld of the sheet with a narrow molten zone, typical for keyhole welding [3]. The weld bead width of this specimen has a mean value of 1.14 mm, being very close to the scan width of 1 mm. The welding velocity determined by video measurement is 152 cm/min. Due to the full penetration of the sheets, porosity is low and the largest pore is 0.07 mm in diameter.

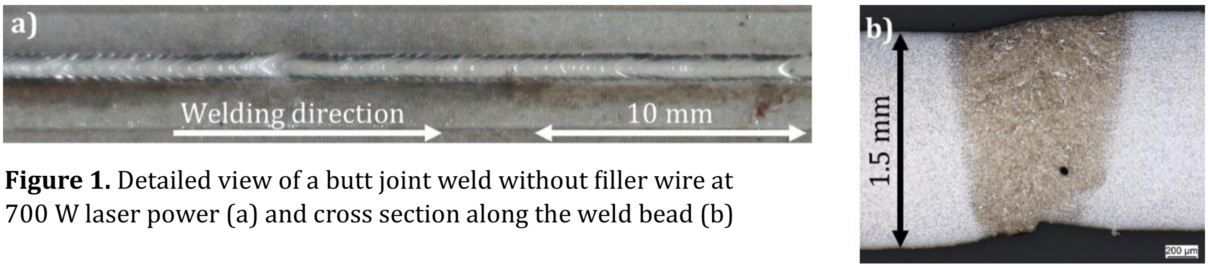


Figure 1. Detailed view of a butt joint weld without filler wire at 700 W laser power (a) and cross section along the weld bead (b)

The weld penetration over the laser power for all butt joints is depicted in Figure 2a, with the corresponding porosity measurements and weld quality classes in b. For each point, the mean value of the three cross sections is shown, with bars corresponding to the minimum and maximum value. The measured welding velocities vary between 101 cm/min and 152 cm/min with a mean value of 132 cm/min. A roller device as described in literature would have led to a more uniform welding velocity [9]. Regarding porosity measurements, only the butt joint weld at 250 W leads to high porosity exceeding weld quality classes. All other parameter settings result in maximum pore diameters of class B with varying porosity values according to Figure 2b.

Full penetration of the sheets can be achieved at a laser power of 650 W with a measured welding velocity of 137.5 cm/min. However, the corresponding porosity in Figure 2b showcases that the process is more stable at 700 W laser power and 152 cm/min, leading to less porosity in a more productive process window. This is in line with literature stating a higher welding velocity can stabilize the keyhole of the process [4].

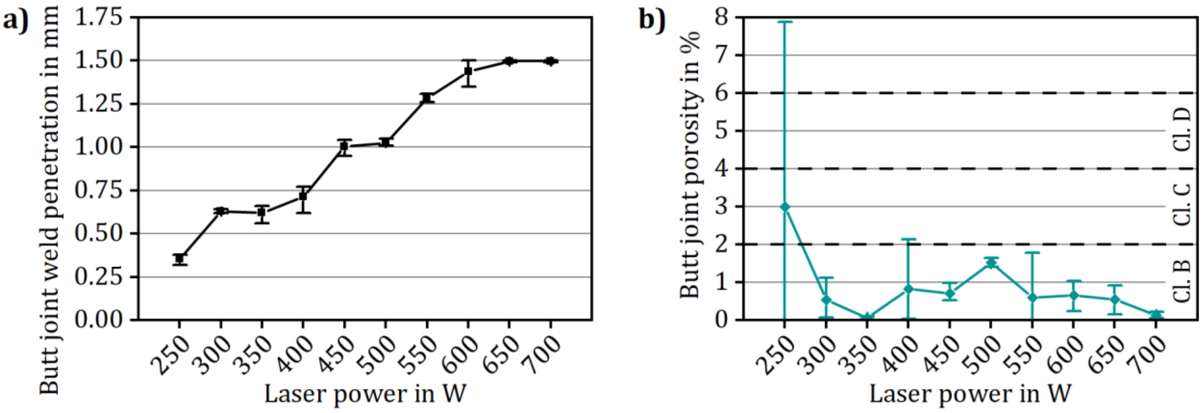
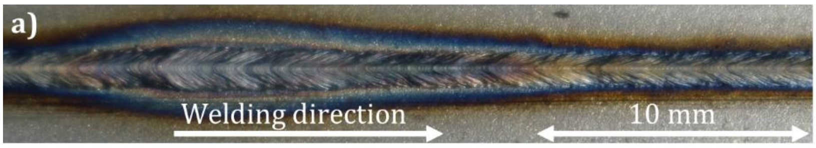


Figure 2. Butt joint weld penetration at different laser power (a) and corresponding porosity (b)

3.2 Overlap joint welding

A detailed view of the overlap joint weld without filler wire in HHLW at 1100 W laser power and a 1 mm scan width is shown in Figure 3a, with one of the three cross sections in b. The high laser power leads to annealing colors on the surface of the top sheet throughout the weld line, which could be removed by laser cleaning after welding [1]. Also, regions of different welding velocity can be distinguished. However, the cross section reveals a penetration of the upper sheet with an average weld seam width at the interface of 1.04 mm. With an average value of 1.25 % and a maximum pore diameter of 0.29 mm in b, porosity is classified as B according to the standard. A change in the shielding gas should lead to reduction of the porosity [5].



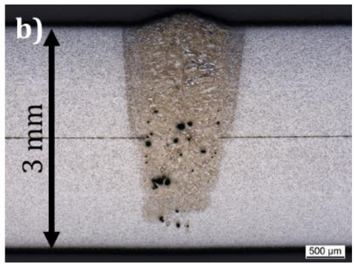


Figure 3. Detailed view of an overlap joint weld without filler wire at 1100 W laser power and 1 mm scan width and cross section along the weld bead (b)

The overlap weld seam width for both scan widths at different laser powers are depicted in Figure 4a, the corresponding porosity in b. For all overlap joints, the largest pore diameter is within quality class B. Results show that at 700 W laser power and a scan width of 0.5 mm, the upper sheet can be penetrated with a mean weld seam width of 0.56 mm. Increasing the laser power up to 1300 W at 0.5 mm scan width results in a mean weld seam width of 0.85 mm. Porosity is minimal at this parameter settings, as both sheets are fully penetrated. The larger scan width of 1 mm needs a higher laser power before resulting in a proper weld seam width at 900 W. Further increasing the laser power to 1100 W stabilizes the process and reduces the joint porosity down to quality class B. The highest laser power of 1300 W and 1 mm scan width fully penetrates both sheets in the last cross section, but shows also a drop in the seam width probably due to irregular welding velocity. As the seam width is governing the joint strength, a larger scan width should be preferred.

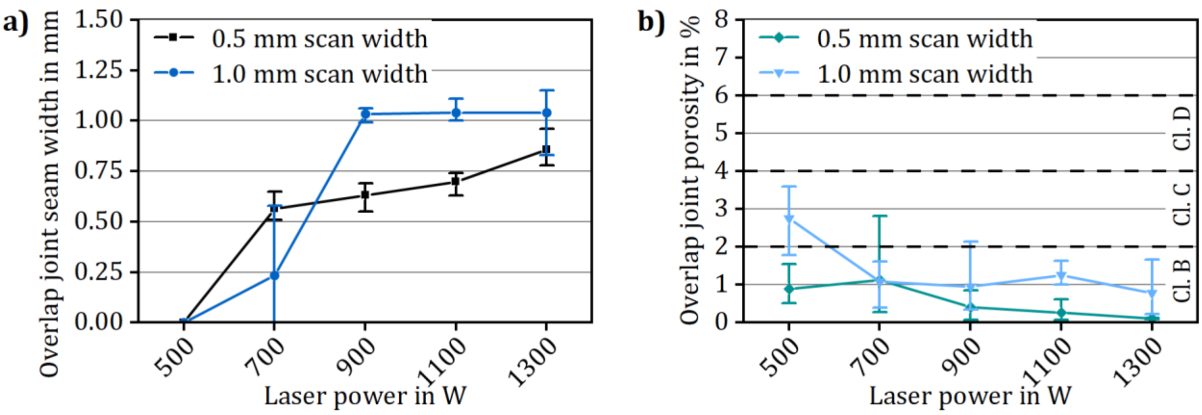
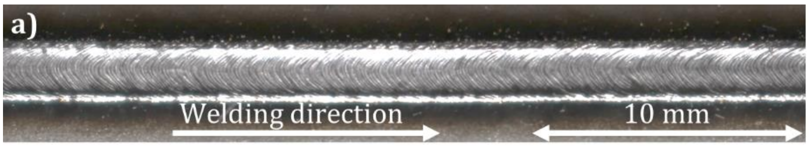


Figure 4. Overlap joint seam width at 0.5 mm and 1 mm scan width at different laser power (a) and corresponding porosity (b)

3.3 T-joint welding

A detailed view of T-joint HHLW with filler wire at 600 W laser power is depicted in Figure 5a with the corresponding cross section in b. The use of filler wire in HHLW leads to a very good outer appearance of the weld line, as the welding velocity stays constant through the wire pushing back. This is in line with findings regarding HHLW without filler wire using an additional mechanical roller to enhance weld quality through a uniform welding velocity [9]. The melt pool shape of the T-joint with filler wire corresponds to the shape of other HHLW studies, with a more rectangular appearance due to the laser scanning [7, 8]. However, the cross section shows porosity in the bottom zone of the melt pool, comparable to porosity in keyhole welding [3]. The mean value of the porosity is 2.61 % with the biggest pore diameter of 0.18 mm in Figure 5b, resulting in quality class C.



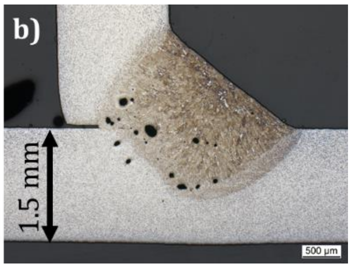


Figure 5. Detailed view of a T-joint weld with filler wire at 600 W laser power (a) and cross section along the weld bead (b)

The effective and actual throat thickness of the T-joints according to DIN EN ISO 17659 at different laser powers are depicted in Figure 6a, the corresponding porosity in b. With 500 W, the effective throat thickness is slightly bigger than the actual thickness. Increasing the laser power leads to a higher effective thickness, while the actual thickness stays nearly unaffected. Thus, higher actual throat thicknesses can only be achieved by filling in more material. The porosity in Figure 6b decreases when the laser power is increased, as the porosity is relative to the melt pool size. At higher laser power the mean value of the surface of pores increases less than the area of the molten material. Thus, the porosity diminishes and results in weld quality class C for the welding with 600 W. The T-joints at laser power of 500 W and 700 W have a largest pore diameter of class B. At 800 W, the process becomes unstable, with a large spread of the porosity and pore diameters exceeding the limits of the standard. As porosity is linked to process parameters like welding velocity or shielding gas, further investigation are needed [5, 6].

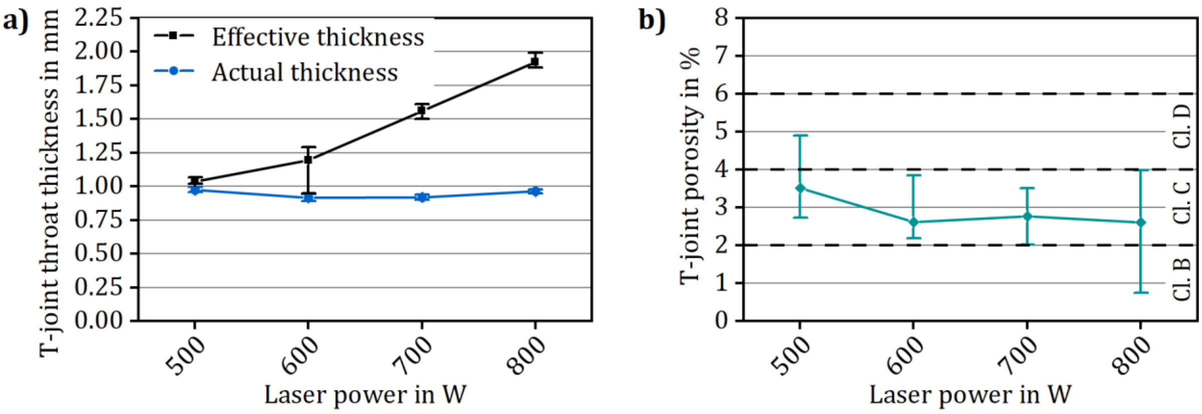


Figure 6. T-joint effective and actual throat thickness at different laser power (a) and corresponding porosity (b)

4. Conclusion

In this study, the effect of the laser power on melt pool geometry and porosity for three joint geometries of 1.5 mm thick micro alloyed steel in HHLW was investigated. The findings can be summarised as follows:

- A full penetration butt joint weld can be achieved without filler wire at 700 W laser power with a 1 mm scan width at 152 cm/min welding velocity, resulting in weld quality class B of DIN EN ISO 13919-1.
- Overlap joints without filler wire at 1 mm scan width lead to a larger weld seam width than at 0.5 mm scan width. For both scan widths, the porosity equals quality class B when at least 1100 W laser power is used.
- T-joints with high effective throat thickness can be achieved in HHLW with filler wire when increasing the laser power, while the actual throat thickness stays nearly unaffected. Quality class C can only be attained at 600 W.

The investigation shows that the laser power has a major influence on the weld quality for all joint types in HHLW. Further studies could include an investigation of the welding velocity on the welding quality through robot-guided automation, in order to eliminate variance in welding velocity when welding without filler wire.

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