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Hybrid laser-arc welding of thick-walled pipe segments with optimization of the end crater

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Abstract

The study deals with the application of the high-power hybrid-laser arc welding process on up to 15 mm thick pipe segments with the intention to avoid end crater imperfections during closing of the circumferential welds, where the pipes were turned during welding in 1G- and 2G-positions. Different techniques such as laser power ramp-down, abrupt switch-off of the laser power and change of the magnification of the laser spot diameter and defocusing of the laser beam relative to the workpiece were tested to remove the laser energy from the process. It could be shown that a high defocusing of the optic system above 40 mm with a resulting beam diameter > 2.9 mm in a short overlap length of approx. 20 mm leads to the formation of a cup-shaped weld seam, which is preferred for avoidance of cracks and pores in the end crater. A laser optics with motor-driven lens system was used for the welding experiments to defocus the laser beam without changing the position of the arc.

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1. Introduction

High-power laser beam welding (LBW) or hybrid laser-arc welding (HLAW) processes have become one of the most important welding processes for joining of thick-walled steel constructions in the last years. Due to the high power density of the laser beam, high welding penetration depths can be achieved by using these welding processes. The effectiveness of these processes lies in the reduction of the layer number especially for welding of thick-walled steels and resulting decrease of the welding time. These economic advantages have already been recognized by the industry, where these processes achieved the breakthrough e.g. in the shipbuilding industry in the 2000s [1]. Numerous studies showed the applicability of HLAW for single-pass welding of flat steel sheets up to thicknesses of 28 mm [2-4]. Due to process-specific features, the applicability of the HLAW of thick wall

constructions is still limited for many applications e.g. for circumferential welds. One of the limitation factors is the formation of a faulty overlap area during closing of the circumferential weld in most cases. Practical examples show that an abrupt switch-off of the laser beam power at the end of the seam induces a formation of a hole over the entire seam thickness, while a laser power ramp-down causes solidification cracks in the overlap area, see Figure 1 (a) and Figure 1 (b) respectively. By applying a laser power ramp-down, the energy of the laser beam reduces and as a result, the penetration mode change from full penetration to partial penetration. Several studies show that partial penetrated welds are more prone to solidification cracks [5,6]. The cold (cooled down) material with high yield strength below the molten material in partial penetrated weld acts like a local restraint and prevents weld shrinkage. This is one of the reasons for

solidification cracks in the root part of the partial penetrated welds.

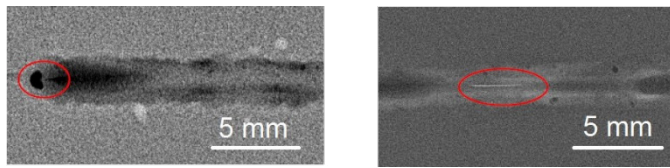


Fig. 1. X-ray images at the end of a laser beam welded plate; (a) end crater hole at a switch-off of the laser power; (b) solidification crack in the case of a laser power ramp-down

Bakir et al. show that the solidification cracks in the root during hybrid laser-arc welding in partial penetration can be reduced with a decrease of the welding speed [7].

A further literature review shows that there are some developed methods for avoidance of end crater imperfections for circumferential seams. By applying a laser power ramp-down from 4 kW to 0 kW in combination with a defocusing of 4 mm above the workpiece surface, 5 mm thick circular welds made of 16MnCr5 and 41Cr4 steels were performed with a minimization of the end crater [8]. By removing or defocusing the laser beam from the surface while keeping the laser power constant, the end crater could be eliminated [9]. In this way, the heat is not abruptly removed from the process and a more uniform solidification zone of melt is formed. With an additional lateral movement of the laser beam a more uniform heat distribution can be realized. Another method to avoid the end crater is described in [10] where the laser beam is moved counter to the welding direction at the end of the weld seam to obtain a heat accumulation before switching off the laser beam power. It prolongs the cooling time.

The process variants mentioned above were tested with laser powers up to 4 kW and are therefore suitable for thinner sheets such as those used in the automotive industry. Gook et al. demonstrate the effectiveness of the defocusing technique for high-power laser beam welding of circumferential welds with a wall thickness of 10 mm [11]. It could be shown that with a high defocusing of the laser beam over 40 mm from the workpiece surface in a short overlap length the end crater could be eliminated. An increase of the magnification of the laser beam from 2.5 to 6 did not lead to satisfactory results due to the still too high power density.

This study deals with the transfer of the defocusing technique to the hybrid laser-arc welding of pipe segments with a higher wall thickness in the range from 12 mm to 15 mm.

2. Experimental setup

2.1. Welding equipment

The high-power disk laser TruDisk 16002 with a maximum output power of 16 kW, an emission wavelength of 1030 nm and a beam parameter product of 8 mm mrad was used as laser beam source. The laser radiation was transmitted with an optical fiber with a core diameter of 200 μm . A laser processing head with a motor-driven lens system and a focal

length of 300 mm was used for the experiments. The special feature of the optical head is that the focal position in z-direction could be varied in a range of -40 mm to 60 mm in relation to the reference focal position. Furthermore, the magnification M could be adjusted in the range of 2.5 to 6, so that the laser beam diameter in the focal position could be changed between 500 μm and 1200 μm . The magnification M and the focal position could be varied almost independent of each other. A microprocessor-controlled welding machine Qineo Pulse 600 with a maximum welding current of 600 A was applied as a power source for the arc.

The welding head combining the laser optics and the GMA torch was mounted on a 6-axis industrial robot arm, where the laser beam axis was positioned 90° relative to the weld specimen surface and the GMA torch was tilted 30° relative to the laser beam axis. All welding experiments were performed with an arc leading orientation and a distance of 4 mm between the two heat sources. The stick-out was kept at 16 mm. The welding trials were performed in 1G- and 2G-position dependent on the material thickness and due to the conditions of existing plant technology. The pipe bends and the 15 mm thick pipe rings were welded in 2G-position. During the welding trials the pipes were rotated with a turntable while the laser head and the GMA torch was stationary. The experimental setup is shown in Figure 2.

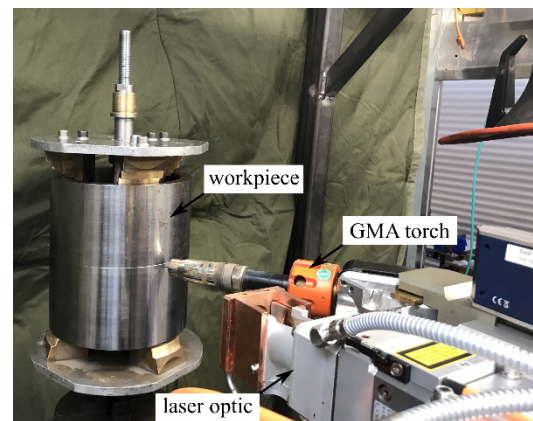


Fig. 2. Experimental setup for hybrid laser-arc welding (HLAW) of circumferential welds in 2G-position

The practical significance of the optical head with motor-driven lens system and the MZ-collimator for the objectives of these experiments is that the power density of the laser beam could be changed with a defocusing or increasing of the magnification when closing the circumferential weld without any change of the position of the arc relative to the weld specimen surface. So, a stable process of the arc welding process could be realized.

Before starting the welding experiments, beam profile measurements were taken with an Ophir Spiricon Beam Watch non-contact laser measurement device. With a defocusing of the laser beam 100 mm in z-direction relative to the operating point on the component, the laser beam diameter can be changed from 560 μm to 6900 μm . During the defocusing of the laser beam the beam profile was not changed. This means that a nearly Gaussian-like power density distribution of the laser energy was achieved through the entire defocusing range. With an increase of the

magnification from 2.5 to 6 the beam can be parallelized and the angle of divergence can be varied.

2.2. Welding materials

The welding experiments were conducted first on 12 mm thick pipe segments of fine-grained structural steel S460NH. Then, the transferability of the results on 15 mm thick pipes with an outer diameter of 178 mm were tested. Finally, pipe bends made of pressure vessel steel P235GH with a wall thickness of 12.5 mm and an outer diameter of 166 mm were hybrid laser-arc welded. All samples were welded in square butt joint configuration. A solid wire G3Ni1 according to EN ISO 14341 with a wire diameter of 1.2 mm was used as filler wire. A gas mixture consisted of 82 % Ar and 18 % CO₂ with a gas flow rate of 20 l min⁻¹ was served as shielding gas. All welding tests were performed without root forming gas.

Table 1 shows the chemical composition of the materials used in this study. The values were taken from the specifications of the manufacturers.

Table 1. Chemical composition of materials used, shown in wt%.

Material / Element	C	Si	Mn	P	S	Al	Cr
S460NH	0.22	0.23	1.74	0.007	0.028	0.032	0.17
P235GH	0.16	0.35	1.2	0.025	0.01	0.02	0.3
G3Ni1	0.06	0.7	1.5	-	-	-	-
	Cu	Mo	Ni	Ti	Nb	V	Fe
S460NH	0.18	0.02	0.11	0.001	0.005	0.12	bal.
P235GH	0.3	0.08	0.3	0.03	0.02	0.02	bal.
G3Ni1	-	-	0.9	-	-	-	bal.

3. Results

Series of welding trials were performed to find the optimal welding parameters for the formation of a circumferential seam without formation of cracks, pores, inadmissible root excess weld metal and holes in the end crater. A faultless overlap area during hybrid laser-arc welding of closed circumferential seams of 12 mm thick pipe segments could be achieved with the defocusing technique by using motor-driven focusing and collimation lenses system. The required laser beam power for a stable welding process was 12.5 kW, while the wire feed speed was 10 m min⁻¹ at a welding speed of 2 m min⁻¹. The laser beam was defocused over 60 mm in z-direction which corresponds to a beam diameter of 4300 µm on the workpiece surface. A short overlap length of 15 mm was preferable. The welding trials were performed in 1G-position. Figure 3 shows a 12 mm thick pipe segment which was welded with the hybrid laser-arc welding process with an optimized overlap area. The outer appearance of the seam surface and the seam root are shown in Figure 3 (a) and Figure 3 (c) respectively. Figure 3 (b) shows the cross section in the overlap area. The circumferential weld metal and the seam profile of the overlap weld are clearly evident. A cup-shaped overlap weld was performed with a defocusing of the laser beam which has proven to be advantageous regarding

the avoidance of cracks in the mid-thickness of the seam. The corresponding X-ray image is shown in Figure 3 (d). Pores and cracks are not visible.



Fig. 3. Hybrid laser-arc welded 12 mm thick pipe segment: (a) outer appearance of the circumferential seam surface; (b) cross-section of the overlap area; (c) outer appearance of the weld root; (d) X-ray image of the pipe segment.

Due to the hydrostatic pressure in the capillary and the formation of dropouts while single-pass welding of 15 mm thick pipe segments in 1G-position, the welding trials on thicker pipes were performed in 2G-position. These dropouts could possibly be avoided by increasing the welding speed. But due to the available plant technology and the maximum laser beam power of 16 kW, the welding speed could not be increased to avoid the gravity dropouts. Figure 4 shows a circumferential weld on 15 mm thick pipe segment. The required laser beam power for a stable full penetration welding process was 15 kW. The welding speed and the wire feed speed was 2 m min⁻¹ and 9 m min⁻¹ respectively. A negative focal position of the laser beam of -5 mm was chosen for the circumferential weld. During closing of the weld, the laser beam was defocused over 96 mm in z-direction in a short overlap length of 15 mm. The beam diameter on the upper surface was increased up to 6900 µm at the end of the defocusing. The outer appearance of the weld is shown in Figure 4 (a) where the overlap area can be clearly seen. The X-ray image is shown in Figure 4 (b). The overlap area is marked where no cracks and pores could be detected. The root of the weld is also shown in Figure 4 (c). The root quality can be classified in the highest evaluation group B according to

the standard EN ISO 12932. The cross section of the single-pass hybrid laser arc welded pipe segment is shown in Figure 4 (d). The circumferential seam and the overlap seam with a cup-shaped weld profile are visible.

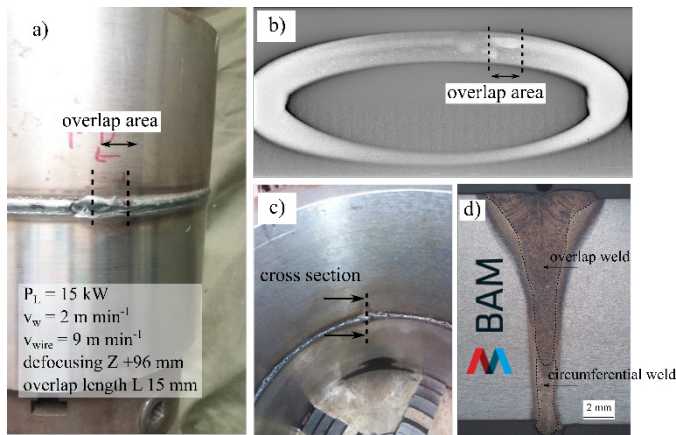


Fig. 4. Hybrid laser-arc welded 15 mm thick pipe segment: (a) outer appearance of the circumferential seam surface; (b) X-ray image of the pipe segment; (c) outer appearance of the weld root; (d) cross-section of the overlap area.

With the same approach, pipe bends with a wall thickness of 12.5 mm made of P235GH were welded using the defocusing technique during closing of the circumferential welds. The required laser power for a stable process was 12 kW and kept constant during the circumferential weld. The wire feed speed was 10 m min⁻¹ at a welding speed of 2 m min⁻¹. The working position of the laser focus during the welding was -3 mm. The focus position of the laser beam was shifted by 60 mm in the z-direction when the circumferential seam was closed. The beam diameter was 4300 µm after defocusing the laser beam. A short overlap length of 15 mm was chosen and it showed best results regarding the minimization of the end crater. The outer appearance of the pipe bend is shown in Figure 5. The overlap area is shown on the workpiece surface and on the root. Visual inspections show no inadmissible root defects or notches on the root of the seam as on the surface. The end crater was filled for a time of 0.7 s with a wire feed speed of 4.5 m min⁻¹ when the laser beam power was switched-off.

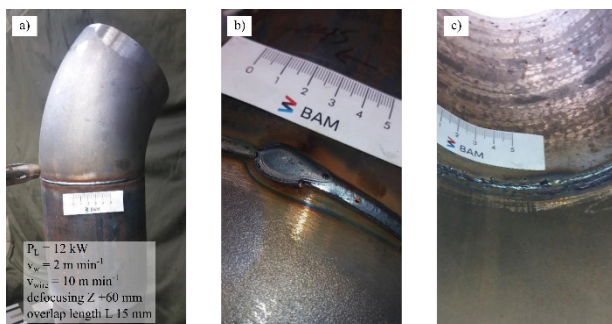


Fig. 5. Hybrid laser-arc welded 12.5 mm thick pipe bend made of P235GH.

Conclusion

The defocusing technique were tested for high-power hybrid laser-arc welding of 12 mm to 15 mm thick pipe segments. The end crater imperfections such as root defects,

notches, cracks and pores in the mid-thickness during the transition from full penetration to partial penetration could be eliminated. The defocusing of the laser beam was performed with help of an optical head of laser with integrated motor-driven collimation system without change of the position of the GMA torch. Pipes with a wall thickness of 15 mm were welded in 2G-position due to the formation of gravity drop-outs. Finally, the HLAW of circumferential welds was demonstrated on pipe bends successfully. With the new findings, the industrial applicability of the HLAW can be increased for welding of circumferential welds.

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