Hybrid Laser-Arc Welding of Thick-Walled, Closed, Circumferential Pipe Welds

Different strategies were tested using this process to learn how to avoid crater imperfections

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Abstract

The application of hybrid laser-arc welding (HLAW) for joining closed circumferential welds is a challenge due to the high risk of forming a defective overlap area with a shrinkage void or solidification cracks in the material thickness. A series of HLAW experiments were performed to understand the development of a faulty overlap area when closing the circumferential weld. Welding trials on flat specimens and pipe segments were supported by numerical analyses in which the thermomechanical behavior of the welds in the overlap area was investigated. Different process control strategies were tested, including variations in defocusing levels and the overlap length. The newly developed HLAW head, including laser optics with a motor-driven collimation system, made it possible to defocus the laser beam during welding without disturbing the stability of the welding process. High-level defocusing of the laser beam of more than 40 mm relative to the specimen surface with a resulting beam diameter of > 2.9 mm, and in combination with a short overlap length of 15 mm, was promising with respect to the formation of a desired cup-shaped weld profile that is resistant to solidification cracks.

Keywords

- Hybrid Laser-Arc Welding
- Circumferential Welds
- Pipe Welding
- Crater
- High-Power Welding
- Thick-Walled Steel

Introduction

The hybrid laser-arc welding (HLAW) process is a coupling of laser beam welding (LBW) and gas metal arc welding (GMAW) in one interaction zone. It offers many advantages, such as high welding speed and high penetration depth, both of which result in a decreased number of layers, lower heat input, and fewer heat-induced distortions compared to conventional arc-based welding processes. The efficiency of this hybrid welding process has already been recognized in industrial practice. For example, it achieved a breakthrough in the shipbuilding industry and crane construction in the early 2000s. According to the current state of development, the applicability of HLAW technologies for single-pass welds in butt joints with wall thicknesses of up to 28 mm and a laser output power of up to 20 kW has been demonstrated (Refs. 1–4). From a technological point of view, the efficiency of HLAW processes can mainly be shown for linear welds, where the problematic start and end areas of the weld can be executed outside the welded component or the imperfections in these areas are not decisive for the weld quality. Nevertheless, HLAW is limited for other applications, such as circumferential welds, due to process-specific features and technological considerations. Circumferential welds can be found, for example, in the construction of wind turbines; devices for oil, gas, and chemical services; and various shafts and axes, or they are required to join pipe edges during pipe laying. It should be mentioned that extensive studies have already been carried out for HLAW of circumferential welds in the field of pipeline construction. An orbital HLAW process with laser power up to 20 kW on 10- to 16-mm-thick pipe rings of American Petroleum Institute 5L steel grade X65 was investigated (Refs. 5, 6). Another representative example concerns the circumferential welding of hollow hydraulic cylinders with a wall thickness up to 14.5 mm (Ref. 7). Thus, the general applicability of the HLAW process for performing circumferential welds for pipe installation as well as in hydraulic manufacturing has been demonstrated. However, optimization of the start and stop areas of the circumferential welds remained outside the scope of the investigations or was only addressed to a limited extent. This unsolved problem is one of the reasons the

Fig. 1 — X-ray images at the end of a laser beam weld. A — Crater formed from switching off of the laser beam power; B — solidification crack from ramping up the laser beam power; C — the outer appearance of the weld with an end point in the base material; D — the associated x-ray image of Fig. 1C without defects.

HLAW process for thick-walled, circumferential welds cannot yet be used in the industrial applications mentioned.

Various challenges in high-performance LBW or HLA of closed circumferential welds are particularly evident when welding in the thick-walled area. One of the challenges is the formation of a faulty overlap area, including excess weld metal in the weld root, pores, cracks, and shrinkage voids, also known as craters, which act as a geometric notch and can lead to a reduction of the fatigue strength. The mentioned problems are caused due to the changes of the welding parameters when closing the circumferential welds and finishing the welding process. Here, not only the end but also the start area of the weld requires a certain quality in order to achieve a flawless overlap of the welded joint. This challenge can easily be solved for linear welds by using run-on and run-off weld tabs. This method is not applicable for circumferential welds because the weld starts and finishes on the workpiece body. The most critical case is when the laser beam power is abruptly switched off at the end of the process. This sudden process termination leads to the formation of a crater, which can extend over the entire material thickness — Fig. 1A. Such weld imperfection can be avoided with a linear reduction of the laser beam power at the weld end. However, the risk of formation of solidification cracks increases, especially at the moment when the transition from complete joint penetration to incomplete joint penetration occurs — Fig. 1B. Alternatively, after closing the circumferential weld, the welding process can be terminated in the base material at a neutral or noncritical zone of the component — Fig. 1C. The associated x-ray image is shown in Fig. 1D, where no imperfections within the weld are visible. It should be noted, however, that the crater remained in the body of the component as it was only relocated into the base material.

Further review of the literature shows that different strategies can be applied to meet the challenges mentioned above. Avoidance of a crater was achieved with the removal or defocusing of the laser beam from the surface of the welds, whereas the laser power was kept constant (Ref. 8). There was an increasing expansion of the laser-processing surface due to the defocusing. A uniform solidification zone of the melt was formed, and the heat was not removed from the welding process abruptly. A further possibility for the avoidance of craters was realized by moving the laser beam counter to the welding direction at the end of welding to obtain heat accumulation before switching off the laser beam power (Ref. 9). This led to an increase of the cooling time and promoted the melt to flow into the crystallizing area. The crater was also prevented by using a bifocal technique with a second diode laser with a power of 3 kW and a leading orientation. This avoided removing the heat abruptly from the process at the end of the weld. The Nd:YAG laser was switched off shortly before the end of the weld was reached, while the diode laser was kept stationary until the crater was filled by wire material (Ref. 10). The process variants described above have been tested for laser powers up to approximately 3 kW and are, therefore, particularly suitable for LBW of steel sheets in the automotive industry. The transferability of these results to high-power LBW or HLA of thick-walled components is only feasible conditionally due to different process-specific challenges, such as formation of solidification cracking and weld root defects (e.g., weld root excess weld metal or formation of pores).

The existing investigations of these problems allow one to take a closer look at the mechanisms of the development of the mentioned weld irregularities. Solidification crack formation is influenced by the interaction of mechanical, thermal, and

Fig. 2 – Experimental setup for hybrid laser-arc welding of 10-mm-thick pipe segments.

metallurgical factors during welding (Ref. 11). There are various hypotheses regarding the formation of solidification cracks that are based on a critical strain at a temperature slightly above the solidus (Ref. 12) or in a brittle temperature range (BTR), which is the temperature range between the solidus and liquidus (Refs. 13, 14). The cracks are formed if the strain during solidification exceeds the deformation capacity. Zacharia showed a functional relationship between the resulting stresses in the weld and the formation of hot cracking (Ref. 15). The weld shape geometry also plays an important role in the formation of hot cracking. For high-power LBW, cracks are expected in the centerline due to the high depth-to-width ratio (Ref. 16). A bulging region, which solidifies last, is formed in the centerline due to the Marangoni vortex on the free surfaces. A refill of molten metal in the direction of the solidification front does not take place (Ref. 17). The phenomenon of the appearance of cracks and pores is more pronounced in the incomplete joint penetration mode. This is exactly the case when closing the circumferential weld. To close the weld defect free, the process energy has to be removed smoothly from the welding zone. A transition from complete joint penetration welding to incomplete joint penetration welding takes place, so this aspect has to be considered. Gebhardt et al. (Ref. 18) showed that the transversal, vertical, and longitudinal strains increased for incomplete joint penetration compared to complete joint penetration during solidification, especially in the weld root part. Schaefer et al. demonstrated that with changes of the focal position of the

Fig. 3 – Schematic representation of the overlap area and the problem zones.

laser beam and a brilliant beam parameter product of $2 \text{ mm} \times \text{mrad}$, cracks could be prevented even for incomplete joint penetration LBW of 5-mm-thick plates (Ref. 19). The influence of welding parameters on the formation of solidification cracks for incomplete joint penetration LBW of thick-walled structures was investigated by Bakir et al. (Ref. 20). It was shown that the focal position of the laser beam had a significant influence on crack formation. However, one of the most important factors for reducing the number of cracks in the incomplete joint penetration mode was found to be the reduction of the welding speed down to 0.5 m min^{-1} because this led to an increase in the cooling time and a reduction in the solidification rate.

In-situ observations of the melt flow during LBW showed that the pore formation is strongly pronounced in the partial joint penetration laser beam welds. The reasons for this are instabilities, collapse of the keyhole, and the limited possibility for degassing (Refs. 21, 22). Local constrictions of the capillary can lead to a separation of the lower part of the capillary. If this area is caught by the solidification front, the constricted weld root of the capillary remains frozen as a pore in the weld (Ref. 23). As

Table 1 – Chemical Composition of the Materials Used for the Experiments, Shown in wt-%

Material/ Element	C	Si	Mn	P	S	Al	Mo	Cu	Ni	Fe
S355J2	0.2	0.55	1.6	0.03	0.03	—	—	0.55	—	Bal.
X100Q	0.18	0.42	1.41	0.007	0.005	0.037	0.03	0.02	0.03	Bal.
G3Ni1	0.06	0.7	1.5	—	—	—	—	—	0.9	Bal.

Fig. 4 — Schematic representation of the circumferential weld with overlap area.

reported by Jokisch et al., the use of a laser scanner technique transversal to the welding direction can effectively stabilize the keyhole and promote the degassing of the pores at the end of the circumferential laser weld (Ref. 24). Improvement of pore avoidance in the overlap area was achieved for the 2.7-mm-thick, selective-laser-melting-manufactured tubes of Inconel 625 and Inconel 718. The transferability of these results to thick-walled joints has to be confirmed by further investigations.

Another challenge in single-pass welding of thick-walled components, especially in the 1G position, is the formation of drop-outs at the weld root, the so-called root humping effect. Key factors for root humping are the hydrostatic pressure, which is dependent on the plate thickness; the counteracting surface tension; and the width of the weld root. The mechanism of formation of the weld root defects is investigated in several studies (Refs. 25–27). Weld root defects can be prevented by adjusting the welding speed and process power, such as laser beam or arc power. Other specific solutions to achieve a well-formed weld root are the use of a powdered substrate as a molten pool support (Ref. 28) or the use of the excessive laser power to partially remelt and smooth the opposite inside of the circumferential weld (Ref. 29). The mentioned methods can only be used for special applications where the geometry of the component allows it.

As the state of the art shows, the problem of a faulty overlap area in laser- and laser-hybrid-welded joints was recognized in industrial welding production. Some solutions to avoid this problem could already be offered for the laser beam welding process of thin sheets with a thickness of less than 4 mm. First approaches to avoid crater imperfections in pure laser beam welding of 10-mm-thick pipes have been shown by the authors' own investigations (Ref. 30). Here, a high defocusing of the laser beam of more than 40 mm in the Z direction within a short overlap length of less than 20 mm proved to be an effective method to avoid imperfections such as drop formation and solidification cracks in the material thickness. Due to the fact that the defocused laser beam left a crater shrinkage void on the upper side of the weld, an additional smoothing weld with lower laser power had to be applied. The latest study by Lai et al. (Ref. 31) shows that in addition to the process termination regimes, such as laser power ramping or laser defocusing, the proportion of deoxidizing elements, such as manganese and silicon contained in the base material, also

Fig. 5 — Weld root development at different overlap lengths of 10-mm-thick plates made with HLAW, a constant defocusing of the laser beam of more than 40 mm in the Z direction, a constant P_l of 12 kW, a v_w of 2 m min^{-1} , and a v_{wire} of 11 m min^{-1} (I 225 A, U 29 V).

have an influence on the weld pool dynamics and thus on defect formation. An approximately 80-mm-long, defect-free overlap area could be shown for both process termination regimes for the steel with a higher proportion of deoxidizing elements.

Despite some progress in the LBW of circumferential welds, it can be stated that effective strategies for the HLAW of thick-walled constructions to achieve a proper overlap area when closing circumferential welds are still lacking. Taking into account positive results achieved with defocusing in LBW, the present study dealt with the transfer of the defocusing technique to the HLAW of pipe segments with a wall thickness of up to 10 mm. The experiments were supported by numerical analyses, where the thermomechanical behaviour of the welds were investigated.

Experimental Setup

Welding Equipment

All welding tests were carried out with the HLAW process. The laser source used was a high-power TruDisk 16002 Yb:YAG disk laser with a maximum output power of 16 kW at a wavelength of 1030 nm and a beam parameter product of 8 mm $\times$ mrad. The laser radiation was transmitted by an optical fiber with a core diameter of 200 μm . Qinco® Pulso 600, a microprocessor-controlled welding machine with a maximum welding current of 600 A, was applied as a power source for the arc. To position the welding head relative to the welding sample, it was mounted on a six-axis industrial robot. The HLAW head represented a system consisting of laser optics and a GMAW torch, which were mechanically fixed together. The GMAW torch was inclined by 25 deg relative to the laser axis,

Fig. 6 — X-ray image and cross section of the hybrid laser-arc welded flat specimen S355J2 with a thickness of 10 mm using $P_l = 12 \text{ kW}$, $v_w = 2.0 \text{ m min}^{-1}$, $v_{\text{wire}} = 11 \text{ m min}^{-1}$ ($I 225 \text{ A}$, $U 29 \text{ V}$), and constant defocusing of the laser beam of 40 mm in the Z direction. A — 5-mm-long overlap; B — 40-mm-long overlap.

while the laser axis was perpendicular to the weld specimen. The laser optics included a motor-driven focusing and collimating lens system with a focal distance of 300 mm. This system allowed a variation of the focus position in the range of 0 to 40 mm along the laser beam axis (Z direction). With this option, it was possible to defocus the laser beam so the focal spot diameter on the operation level, here workpiece surface, could be increased from 500 to 2900 μm . The magnification M could be increased from factor 2.5 to 6, which also led to an increase in the focal spot diameter to 1200 μm . From a practical point of view, the most important goal for the use of the optics with a motorized focusing and collimating lens system was the possibility of defocusing the laser beam or increasing the magnification without changing the position of the GMAW torch relative to the sample surface. In this case, the HLAW process could be performed without any disturbance. The round pipe segments were turned by an external rotating axis, while the position of the robot arm with the welding head remained unchanged. All welding tests were performed in the 1G position. The experimental setup is shown in Fig. 2.

Welding Materials

Both 10-mm-thick flat samples of mild steel S355J2 according to EN 10025-2: 2004, *Hot rolled products of structural steels — Part 2: Technical delivery conditions for non-alloy structural steels*, and pipe segments were used for the welding tests. The pipe segments were made of American Petroleum Institute (API)

5L X100Q steel and had a wall thickness of 10 mm, a length of 200 mm, and an outer diameter of 127 mm (5 in.). The filler material was G3Ni1 according to EN ISO 14341, *Welding consumables — Wire electrodes and weld deposits for gas shielded metal arc welding of non alloy and fine grain steels — Classification*, with a diameter of 1 mm. The chemical composition of the test materials is shown in Table 1. It should be mentioned that the strength characteristics of the test materials were not matched, as no investigations of the mechanical-technological properties of the produced welds were planned. During the tests, only phenomena of defect formation in the welds were studied. The welding trials were performed in square butt-joint configuration where the pipe edges were milled and sandblasted before welding.

A gas mixture consisting of 18% CO_2 in Ar with a flow rate of 16 l min^{-1} was used as protective gas. No weld root backing was inserted.

Experimental Procedure

The task of achieving a defect-free weld end when closing the circumferential HLAW weld required an effective process control strategy due to the complex nature of this problem area. For this aim, the overlap area of the laser-hybrid-welded tube segment was divided into three individual areas, or so-called problem zones, whereby these zones were spatially separated from each other both in the welding direction and in the material thickness. Figure 3 shows the mentioned problem zones and a schematic

Fig. 7 – Total crack length over overlap length. Hybrid laser-arc welds on 10-mm-thick S355J2 plates, $P_l = 12$ kW, $v_w = 2.0$ m min⁻¹, and $v_{wire} = 11$ m min⁻¹ (I 225 A, U 29 V).

representation of the overlap area and the weld profile during the closing of the circumferential HLAW weld.

Changing the parameters to reduce the energy at the end, such as defocusing, occurred after the start point was reached following one full rotation of the pipes (point A). Only then did the defocusing take place till the end point (point B). According to this concept, there are two weld areas between points A and B. The first is the complete joint penetration circumferential weld, and the second is an overlap weld with incomplete joint penetration. The zones and the potential weld imperfections are as follows:

- Zone I: defects in the weld root, such as weld root excess weld metal and weld root notches/shrinkage voids;
- Zone II: defects in material thickness, such as pores and center cracks; and
- Zone III: defects on the upper side of the weld, such as craters and shrinkage voids.

The complex strategy of process control when closing the weld could be divided into individual stages. For each problem field or zone, a certain procedure or a suitable set of parameters was applied step by step. The consecutive parameter sets were matched to the corresponding zones in the overlap area in such a way that the welding parameters at the end of Zone I were taken over as input parameters for Zone II. The same principle also applied to the transition from Zone II to Zone III

Numerical Model

The weld in the overlap area (see Fig. 3) in Zone II was present as a partial joint penetration weld, which is more susceptible to the formation of centerline cracks than a weld with complete joint penetration. The formation of solidification cracks in the overlap area should be suppressed by controlling the solidification conditions. The development of an effective heat management strategy for a crack-free weld overlap was supported by virtual experiments. Complementary to the welding tests, the heat distribution in the solidification zone when closing the circumferential weld was simulated. A three-dimensional model was employed to perform

the thermomechanical simulation. The numerical simulation was carried out for a pipe segment of 90 deg with a wall thickness of 10 mm. The schematic representation of the circumferential weld with overlap area is shown in Fig. 4.

The model was designed with a symmetrical boundary condition in the weld centerline to reduce the calculation effort. The numerical calculation started in the middle of the segment and remained until the starting point was reached again. Only then was the crater strategy applied. In the times when the heat source was outside the model, time steps were considered as the cooling time steps.

The quasi-steady-state temperature field during laser-arc welding is governed by the following equation:

$$\rho \frac{\partial(c_p T)}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + Q_{arc} + Q_{laser} \quad (1)$$

where ρ is the density; c_p is the specific heat; T is temperature; t is time; k is thermal conductivity; x, y, z are Cartesian coordinates; Q_{arc} is the Goldak heat source given in Ref. 32; and Q_{laser} is the conical volumetric heat source with Gaussian heat flow distribution given in Ref. 33.

Validation was carried out by adjusting the cross sections and temperature measurement using thermocouples according to ISO/TS 18166, *Numerical welding simulation — Execution and documentation*. The numerical simulation was carried out for welding with a welding speed of 2 m min⁻¹, laser power of 12.5 kW, wire feed speed of 11 m min⁻¹, and arc power of 6.5 kW. The stress-strain curves were taken from the SYSWELD material database (ESI Group, Paris, France) (Ref. 34) and the data were provided for the material S355J2. It was assumed that the material follows an elasto-plastic law with isotropic hardening behavior.

The stress increment in the model can be calculated via the elastic stress-strain relations:

$$\{d\sigma\} = [D]\{d\epsilon^e\} \quad (2)$$

where D is the stiffness matrix and the total strain increment can be summarized in the form: w

$$d\epsilon^{total} = \{d\epsilon^e\} + \{d\epsilon^p\} \quad (3)$$

where $d\epsilon^e$ and $d\epsilon^p$ represent elastic and plastic increments, respectively.

The phase transformation was also taken into account in the model. The material properties of all elements reaching the end austenite temperature (AC3) changed during cooling to austenite. When austenite was cooled to the martensite finish temperature (MF), the material properties of the elements changed to martensite. Elements that did not reach the austenite start temperature (AC1) retained the properties of the base material. The birth and death feature was used for all elements that reached an aver-

Fig. 8 — Recording of the process parameters (A) and weld root quality (B) at the start area of a hybrid laser-arc welded API 5L X100Q pipe ring with a wall thickness of 10 mm.

Fig. 9 — Temperature measurement scheme (A) and temperature profile (B) during HLAW of a circumferential weld.

age temperature of 1440°C. All elements were “killed” when the melting temperature was achieved. The stiffness matrix for these elements was multiplied by a tightening factor, and all strains, as well as the plastic strains, were removed.

The numerical simulation was performed to understand the stress behavior in the overlap region and to predict the influence of the overlap length on the stresses or crack initiation.

Results

Welding Trials on Flat Samples

In the course of the welding tests, welds were first made on flat samples to examine the interaction between the welding parameters and the weld quality. The end of a circumferential weld could be emulated by a simple overlap of two linear welds.

In accordance with the schematic representation of the overlap area and problem zones (Fig. 3), the occurrence of weld root defects (Zone I) and methods for avoiding them were investigated in the first phase of the welding tests. Welding trials with different overlap lengths in a range between 5 to 40 mm were conducted on flat specimens with a constant defocusing of the laser beam of more than 40 mm in the Z direction, constant laser power (P_L) of 12 kW, welding speed (v_w) of 2 m min⁻¹, and wire feeding rate (v_{wire}) of 11 m min⁻¹. The arc current (I) and voltage (U) were 225 A and 29 V, respectively. The parameters for the linear joints originated from the authors’ own preliminary investigations. The images of the weld root side of the HLAW 10-mm-thick plates with various overlap area lengths are presented in Fig. 5.

After optimizing the weld root (Zone I), the formation of weld irregularities in the material bulk (Zone II) was analyzed. The typical location of cracks and pores in the welds on flat samples S355J2 for two representative overlap lengths of 5 and 40 mm is shown in Fig. 6.

Fig. 10 — Weld root formation of circumferential welds in the overlap area. A — Formation of drop-outs without parameter adjustment; B — avoidance of drop-out formation with optimized welding parameters.

The radiographic image analysis software ISee! was used to evaluate the geometrical sizes of internal defects such as cracks and pores according to ISO 17636-2, *Non-destructive testing of welds*. The measurement uncertainty was below $\pm 3\%$. A crack length of 4.7 ± 0.14 mm was detected after a constant defocusing of 40 mm in the Z direction in a short overlap length of 5 mm. Cracks with a total length of 20.5 ± 0.61 mm were characteristic for an overlap length of 40 mm.

The welding tests on flat samples were performed for parameter study only. No goal was set to completely eliminate the internal irregularities. Rather, the weld tests on flat specimens served to identify the trends. It was assumed that when transferring the results to the circumferential welds, the situation with the crack appearance would be different due to the circular geometry of the weld specimens. Nonetheless, a correlation between the overlap length and the crack length was found. It could be shown that the crack length increased with increasing overlap length — Fig. 7.

Welding Trials on Circular Samples

For the 10-mm-thick tube wall studied, it was effective to use a laser ramp time of 200 ms in combination with a low start wire feed rate of 3 m min^{-1} at the beginning of the process to avoid the formation of weld root drops. The arc was ignited with a delay of 300 ms; that is, only when the laser power had reached the nominal value (working power) of 12.5 kW. The arc working power was not reached until 1200 ms (corresponding to approximately

40 mm in length at the welding speed $v_w = 2 \text{ m min}^{-1}$) after the process start. Figure 8A illustrates the recommended parameter adjustment at the process start.

For these parameters, the weld root quality of the circumferential joint in the start area fulfilled the requirements of EN ISO 12932, *Welding — Laser-arc hybrid welding of steels, nickel and nickel alloys — Quality levels for imperfections*, evaluation class B — Fig. 8B.

The welding thermal cycle was measured during the welding process in the circumference of the welding specimen, including the overlap area, with the help of thermocouples. The thermocouples were placed at the weld root side of the welding specimen at a distance of approximately 2 mm from the butt joint to precisely determine the welding thermal cycle. The distance of the thermocouples to the starting point of the weld was about 5 mm. The measurement scheme used is shown in Fig. 9A. The welding thermal cycle in the overlap area during welding is shown in Fig. 9B.

According to the measurement scheme used, a temperature peak of approximately 400°C could be measured at the starting point of the circumferential weld. During the welding process, the temperature at the measured point decreased due to the three-dimensional heat distribution. As the temperature curve shows, the weld start area cooled to 200°C in approximately 11.5 s, which corresponds to the welding time of the whole circumferential weld. This residual temperature served as preheating for the overlap area during the completion of the circumferential weld. Therefore, while defocusing the laser beam, the laser power

Fig. 11 — The outer appearance, cross sections in different layers of the overlap area, and an x-ray image of a pipe segment. Hybrid laser-arc welds on 10-mm-thick pipe rings made of steel API 5L X100Q, $P_L = 12.5 \text{ kW}$, $v_w = 2.0 \text{ m min}^{-1}$, and $v_{\text{wire}} = 11 \text{ m min}^{-1}$ (I 225 A, U 29 V).

was reduced from 12.5 to 11.5 kW at the end of the process to prevent overheating and the formation of excessive droplets. The comparison of the weld root formation of a circumferential weld with a non-optimized and an optimized laser power at the end of the process is shown in Fig. 10A and B, correspondingly. The droplet could be effectively eliminated by a combination of defocusing and adjusting the laser power.

Figure 11 shows the outer appearance, cross sections at different lengths of the overlap area, and an x-ray image of a pipe segment. It can be seen that a cup-shaped weld profile was generated using the defocusing technique without any pores or cracks in the material thickness. A 40-mm defocusing of the laser beam in the Z direction over a short overlap length of 15 mm and an adjustment of the laser power avoided the mentioned problems. With a crater-filling program that is integrated in the arc power source, the shrinkage void on the upper surface (Zone III) was filled in 0.9 s with a wire feed speed of 4.5 m min^{-1} .

Welding Simulation

The welding simulation was performed for the stress state for two overlap cases (15 mm and 30 mm). Before that, the model was compared with cross sections and the temperature measurement. Figure 12 compares cross sections between the simulation and experiments of the weld in the pipe circumference (Fig. 12A), shortly after using the crater strategy (Fig. 12B), and in the crater zone (Fig. 12C). The heat source parameters were varied till an error less than 5 % was reached.

Figure 13 shows the comparison between the actual temperature measurement and the simulation in the crater zone. Very good agreement can also be observed here.

Figure 14 shows the transverse stress in the crater area before complete solidification of the weld pool for two overlap lengths.

Fig. 12 — Comparison of cross sections between the simulation and experiment of the weld in the pipe circumference (A), shortly after using the end crater strategy (B), and in the crater zone (C).

Fig. 13 — Comparison of the temperature course between the simulation and the actual measurement in the crater zone.

Fig. 14 — Transversal stress distribution on the symmetry plane. A — 15-mm-long overlap; B — 30-mm-long overlap.

Fig. 15 — The stress curves for the two overlap lengths 15 and 30 mm at the points marked in Fig. 14.

Figure 15 shows the stress courses as a function of temperature at the evaluation points shown in Fig. 14 for 15 mm and 30 mm overlap lengths.

Discussion

Welding Trials on Flat Samples

As the results showed, a short overlap area length of 5 mm was characterized by the formation of a relatively small drop on the weld root side — Fig. 5. However, there was a shrinkage void in the middle of the drop, which was similar to the case when the laser was abruptly switched off. This observation provided an indication that the 5-mm-long overlap was too short to use the defocusing effect. The optimal length of the overlap area was found at the range between 10 to 20 mm. There was a transition from complete joint penetration to incomplete joint penetration mode within the overlap area, which indicated that the defocusing was effective. Drop formation was minimized and the welds were classified in the highest evaluation group B according to EN ISO 12932 with regard to weld root quality. Increasing the

overlap length resulted in the appearance of larger drops at the weld root of the welded specimens. A potential cause for this effect was the formation of a larger remelted zone with a melt flow movement oriented against the welding direction. The excessive heat accumulation led to solidification of the melt at the weld root of the joint in the form of a large drop. In particular, drop formation took place at the end of the circumferential weld (i.e., at the transition from complete joint penetration to incomplete joint penetration when the circumferential weld gets closed). The volume of the droplet was closely related to the surface tension and the heat input, which is in good correspondence with the results in Refs. 24 and 25. In general, too high of a heat input or ramping too slow out of the process heat leads to the formation of larger drops. On the other hand, ramping too fast out of the process heat can lead to weld root undercuts. It is necessary to say that welding in the 2G horizontal position can prevent the formation of weld root droplets. In the research of Lai et al., no weld root drops were observed when welding in the horizontal position (Ref. 31). With this method in practice, it is important to ensure that the welding task allows the process to be carried out in the horizontal position.

The center crack formation mechanism in the overlap area, at the transition from a complete joint penetration weld to a partial

joint penetration weld, is based on the assumption that the formation of the center cracks is caused by an unfavorable weld shape and present stresses. It is closely related to the crystallization of the weld metal and to the weld shape. The cold (chilled down) material with high yield strength below the molten material in the partial joint penetration weld acts like a local restraint and prevents weld shrinkage. This results in increased local stresses, which promote the formation of solidification cracks in the material thickness.

Welding Trials on Circular Samples

In a circumferential weld, the start and end areas of the weld remain inside the welded component and are not offset outside the component. The specific feature of circumferential joint welding, therefore, is that defects at the beginning of the weld can overlap with defects at the weld end when the weld is closed. For this reason, a defect-free weld root at the weld start is a decisive precondition for a defect-free closing of the weld end. The beginning of a laser hybrid weld is characterized by the formation of a weld root drop if the ramp times of the laser and the arc are not coordinated. Simultaneous activation of the laser beam and ignition of the arc at the start of the process causes the arc to produce an unfavorably high pressure on the unstable keyhole, and the melt is forced downward as soon as complete joint penetration is formed. In other words, the ignition of the arc at the same time as a steep increase in laser power leads to unstable melt flow in the weld pool, and weld root droplets can form. This means the ignition points of both energy sources have to be separated from one another in time.

When closing the circumferential HLAW weld, it is also important to coordinate the parameters of both welding processes used. Here, the overlap length AB (Fig. 3) is an important variable since parameter adjustments are made only within this length. As shown by Lai et al., a defect-free process termination was achieved at an overlap length of 80 mm (Ref. 31). However, with a pipe diameter of 127 mm used in the present research, this length would correspond to about $\frac{1}{5}$ of the weld circumference and therefore appears unnecessarily long. From a practical point of view, it makes sense to keep the overlap area as small as possible. This also prevents the unnecessary re-melting of a large volume of material when closing the weld. According to the previous welding tests carried out on flat specimens, the length of the overlap area should be kept between 15 and 20 mm for a material thickness of 10 mm.

It has to be taken into account that in addition to defocusing the laser beam, the laser power has to be adjusted when closing the circumferential weld. This necessary parameter adjustment results from the heat accumulation taking place in the pipe body during the execution of the circumferential weld. This residual heat serves from one side as preheating, which has a positive effect on crack prevention. From the other side, it can lead to overheating of the overlap area.

The arc power has a significant influence on crack formation during HLAW of the circumferential welds. Investigations by Gebhardt on the HLAW of 14.5-mm-thick circumferential welds made of S460NH showed that crack-free welds could be achieved at an increased wire feed rate of greater than 12 m min^{-1} (Ref. 35). These recommendations are applicable to circumferential welds. In the present work, the adjustment of the arc power at the end

of the weld was effectively applied. In particular, the use of the crater-filling program helped end the welding process without crater defects such as shrinkage voids or cracks.

Welding Simulation

In general, tensile stresses are seen in the overlap area, confirming the assumption that stresses play a key role in the formation of solidification cracks. In addition, the overlap length influences the resulting stresses, as the stresses in the case of a 30-mm overlap are higher than in a 15-mm overlap. This difference can be attributed to the different incomplete joint penetration welding mode lengths, since incomplete joint penetration welding produces high stresses in the weld root (Ref. 18), which lead to an accumulation of tensile stress in the final crater zone. This means the longer the overlap length, the higher the accumulated stresses and the higher the risk of solidification cracking. The difference of stress development after solidification can be clearly seen, as was mentioned, when the stress increases faster immediately after solidification in the case of the 15-mm overlap — Fig. 15.

When interpreting the simulation results, it can also be stated that an adaptation of the partial joint penetration weld to the cup shape (see Fig. 12B and C) can lead to the avoidance of center cracks. Exactly these cases were realized by defocusing the laser beam. The circumferential welds performed in this research show that the cup-shaped welds led to a flawless overlap area.

Conclusions

Different strategies were tested using HLAW of 10-mm-thick pipe segments to avoid crater imperfections such as cracks, pores, and shrinkage voids. With an adjustment of the time course between the welding parameters of each welding process (laser beam welding and gas metal arc welding), the imperfections in the start of the welds were successfully avoided. An ignition of the arc after reaching the nominal value of the laser beam power was necessary to avoid weld root imperfections in the start. It was demonstrated that defocusing the laser beam at the end of the process and the resulting cup-shaped formation of the weld had a major influence on the formation of cracks. With a high defocusing of 40 mm in the Z direction in a short overlap length of 15 mm, mid-thickness cracks and pores were avoided. The simulation results showed tensile stress concentration in the overlap zone, which, in addition to the melt pool shape, contributed to the initiation of solidification cracks. Additionally, it was demonstrated that the length of the overlap had an influence on the stress. This means the longer the overlap, the higher the stress, which can lead to the formation of cracks. This corresponds to the experimental results. For the avoidance of a crater or shrinkage void on the top surface, a sufficient time of approximately 1 s at a wire feed speed of 4.5 m min^{-1} was necessary to fill the crater after switching off the laser beam power.

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