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Influence of Partial Penetration Laser Hybrid Welding Parameters on the Solidification Cracking for Thick-Walled Structures

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Abstract

In this study, the impact of the important laser hybrid welding parameters regarding the solidification cracking formation is investigated. Experimentally, the welding processes were performed for specimens under critical restraint intensity, which promotes solidification cracking formation. The welding speed and the arc power were varied under the same restraint-intensity condition to study its impact on the solidification cracking phenomenon. The results showed that there is an influence of the welding speed and the arc power on the formation of solidification cracking. The welding speed shows a significant effect on the crack number; that is by decreasing the welding speed, the crack number decreased. The arc power shows a slight influence on the solidification cracking. Moreover, the experiments were accompanied by the numerical simulation to understand the behavior of the stress in the welds by varying the welding parameters.

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1. Introduction

For several years, solid-state lasers have been widely applied in metal processing. The high-power of the laser sources and the excellent beam quality allow structures with wall thicknesses of more than 10 mm to be welded in one pass. The high welding speed, low heat input, and low-distortion of the laser beam welding are all advantages that significantly contribute to increasing productivity during the fabrication of thick-walled constructions, reducing rework. However, by using the laser to weld steels with thickness above 10

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mm the risk of solidification cracking of materials increases by not carefully coordinated process parameters and mechanical conditions.

Due to the complex nature of the hot cracking phenomena, many hypotheses and theories have been presented in the past decades. Prokhorov [1], [2] assumed that the materials show a reduced deformation capacity in a specific temperature range, known as the Brittle Temperature Range (BTR). If the strain during solidification exceeds the deformation capacity hot cracks will occur. According to an in-situ observation of crack formation and numerical simulations, an approach describing the functional relationship between the resulting stresses in the weld and the hot cracking formation was presented by Zacharia et al.[3]–[5]. The researchers indicated that the transverse compressive stress immediately behind the pool prevents the formation of hot cracks. The hot cracks will form if a liquid film is present behind the weld pool, such as when the transverse stress changes from compressive to tensile within the mushy zone.

2. Experimental setup

Fine-grained structural steel plates (S690QL) with 15 mm thickness were used in the welding experiments. The joint partners were clamped to a device with known restraint intensity, as in Fig. 1 shown.

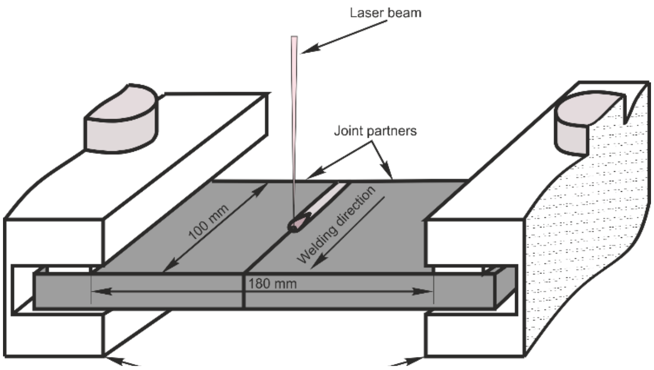

Fig. 1. Schematic illustration of the experiments

The concept of the intensity of restraint has been introduced by [6][7]. This represents the stiffness of the surrounding structure around the weld and its influence on stress development during solidification. The total restraint intensity of the presented experimental construction before welding was 20 kN/(mm mm), estimated according to [8][9].

To study the influence of the two empirical parameters of the partial penetration laser hybrid laser welding on the solidification cracking formation, test matrix with two factors and three stages was carried out. The laser power P_L was changed depending on the welding speed so that the welding depth remained constant. Since the literature indicates that a low welding speed reduces the cracks [10], welding tests were also carried out at a welding speed of 1 $m \cdot min^{-1}$ in addition to the test matrix. In these tests, the wire feed speed remained constant at 7.2 $m \cdot min^{-1}$ and the laser power was lowered to 7.5 kW to maintain the same weld depth. The test matrix and the varied welding parameters (welding velocity and wire feed rate) are listed in Table 1. Each experiment has been repeated three times.

Table 1. the test matrix and the partial penetration Laser Hybrid welding parameters

v_s in m·min^{-1}	P_L in kW	v_d in m·min^{-1}
1.5	9.5	6.7
1.5	9.5	7.2
1.5	9.5	7.7
2.0	10	6.7
2.0	10	7.2
2.0	10	7.7
2.5	12.5	6.7
2.5	12.5	7.2
2.5	12.5	7.7
1.5	9.5	8.7
1.5	8.5	10.7
1	7	7.2

A plane strain two-dimensional model was employed to perform the thermomechanical simulation. All out of plane strain components acting are to be neglected. The thermo-physical material properties were taken from [11].

The stress-strain diagram was taken from the Sysweld material database [12] and the data was supplied for S355J2G3 and scaled for the S690QL. The material was assumed to follow an elasto-plastic law with isotropic hardening behaviour (von Mises plasticity model). The phase transformation is also considered in the model. The numerical simulations were performed for the welding parameter which provided an influence on the crack formations

3. Results and Discussion

In Fig. 2 are the X-ray images for the specimens welded under 7.2 m·min^{-1} wire feed speed and welding speeds of 1 m·min^{-1}, 1.5 m·min^{-1}, 2 m·min^{-1} and 2.5 m·min^{-1}. Here it can clearly be observed that the width of the weld seam head decreases greatly as the welding speed increases, i.e., from (a) to (d). The cracks in the x-ray images are indicated with circles

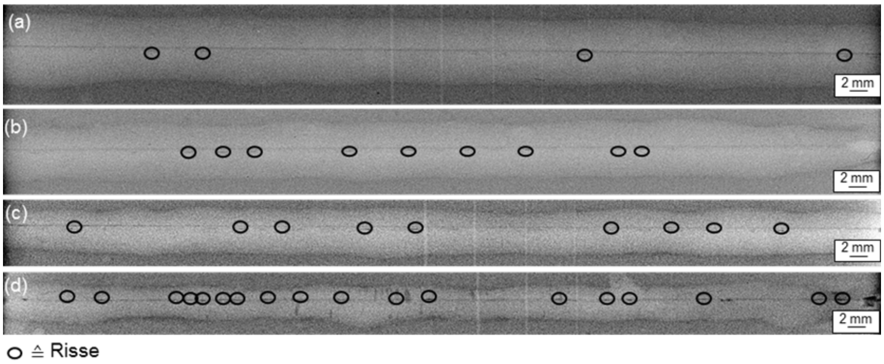

Fig. 2. X-ray images for specimens welded at the wire feed speed of 7.2 m·min-1 and the welding speeds of (a) 1 m·min-1, (b) 1.5 m·min-1, (c) 2 m·min-1 and (d) 2.5 m·min-1

Fig. 3 shows the number of cracks over the wire feed speed (a) and welding velocity (b). Although the number of cracks decreases as the wire feed speed increases, the number of cracks is slightly reduced, as shown in Fig. 3 (a). Also, it can be clearly seen that by increasing the wire feed speed from 8.7 m·min^{-1} to 10.7 m·min^{-1}, the number of cracks remains approximately the same. It must be mentioned here that the influence of the arc power on the crack formation depends strongly also on the welding depth.

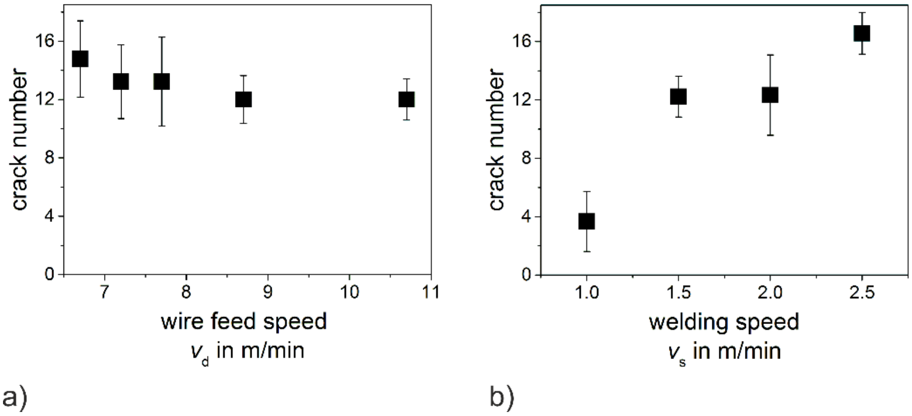

Fig. 3. Results of the cracks number under variation the wire feed speed (a) and the welding speed (b) with standard deviation

The results by varying the welding speed have provided clearer evidence of its influence cracking phenomena. In Fig. 3(b), the number of cracks increases as the welding speed increases. Only at welding velocities of 1.5 m·min^{-1} and 2 m·min^{-1}, the number of cracks does not change.

To clarify the influence of the welding speed, numerical simulations were performed for the welding speeds 1 m·min^{-1} and 1.5 m·min^{-1}, where a clear impact on the number of cracks can be observed. The heat sources parameters, which used thermal analyses were optimized to achieve a good match between the experiments and the model. These parameters were adjusted until an error of less than 5% was obtained. Fig. 4 shows shows the comparison of the weld pool obtained from the FE analyses and the weld cross section.

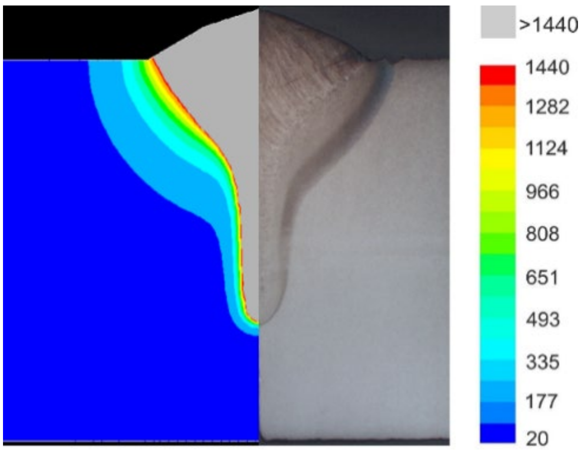

Fig. 4. Comparison of the fused zone between experiment and FEM

The transversal stress distribution and vertical stress distribution in the weld root for a specimen welded with 2 m·min^{-1} are shown in Fig.5. A concentration of stress at the root of the weld can be observed.
The transversal and vertical stress evolution versus the temperature during cooling at the weld root are shown in Fig. 6 Transversal and vertical tensile stress development could be observed immediately after solidification, continuing to rise until reaching a value of 80 MPa and 120 MPa, respectively. The high tensile stress in the weld root can be attributed to the thermal stress (after solidification) and the restraint to

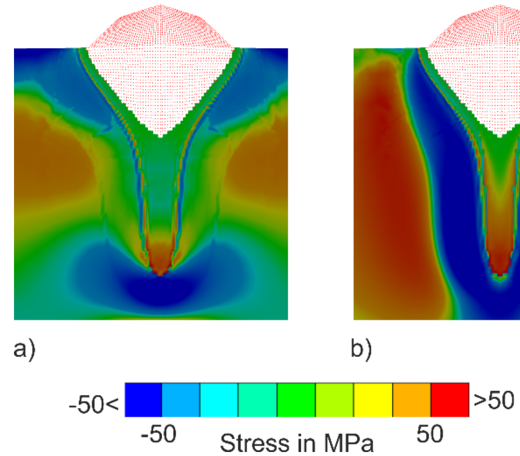

Fig. 5. Transversal (a) and vertical (b) stress distribution in the weld root shortly after the solidification for specimen tested with welding velocity 2 m·min^{-1}.

shrinkage by the surrounding cold material. This explains the usual crack form in the weld root, which is possible to take a vertical or horizontal position or to take the shape of a cross under the influence of both stress components, as shown in Fig. 7.

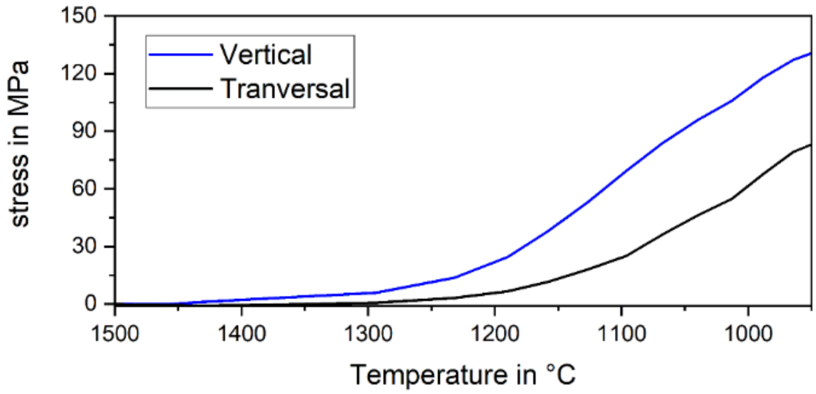

Fig. 6. The vertical and the transversal stress development at the weld root

Fig. 8 shows the stress development on the locations of the cracks for specimens welded with 1 m·min^{-1} and 2 m·min^{-1} over temperature. By comparison, the stress development for the two chosen welding velocities on the weld root a reduction of the stress can be recognized.

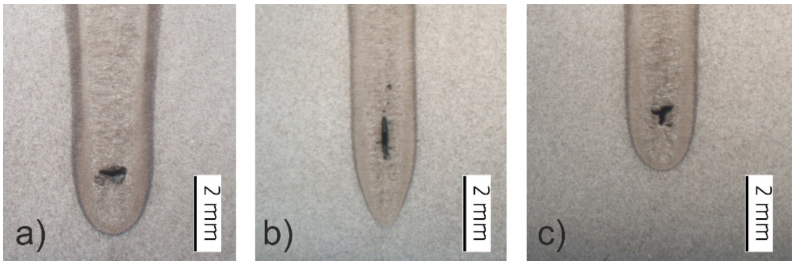

Fig. 7. Solidification crack forms in the weld roots (a) horizontal, (b) vertical and c(c) cross form

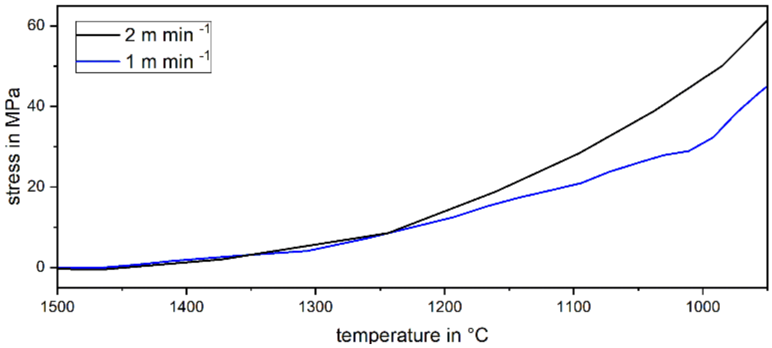

Fig. 8. Transversal stress evaluation on the weld root for the HLAW with welding velocity of 1 m/min and 2 m/min

4. Summary

In this study, the influence of the welding speed and the arc power on the solidification crack formation for partial penetration laser hybrid welded Thick-Walled plates were investigated.

Experimentally, a linear correlation between the welding velocity and the crack number was observed. That is by reducing the welding velocity the crack number was reduced.

The reduced welding velocity showed a strong impact on stress, as the model demonstrated a very lower stress amount in comparison to the reference case. The reduction of the welding speed could be a helpful technique to reduce the hot cracking.

The wire feed speed showed a very slight influence on the crack formation. That can be returned to the large distance between the critical region for cracking and the arc region.

Acknowledgements

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