Lasers in Manufacturing Conference 2021

Observation of the weld pool shape in partial penetration welding and its influence on solidification crack formation for high-power laser beam welding

Nasim Bakir[a,*], Ömer Üstündag[a], Andrey Gumenyuk[a,b], Michael Rethmeier[c,a,b]

[a]*Bundesanstalt für Materialforschung und -prüfung, Unter den Eichen 87 , 12205 Berlin, Germany*
[b]*Fraunhofer Institute for Production Systems and Design Technology, Pascalstraße 8-9, 10587 Berlin, Germany*
[c]*Institute for Machine Tools and Factory Management, Technische Universität Berlin, Pascalstraße 8-9, 10587 Berlin, Germany*

Abstract

Solidification cracking is still a particular problem in laser beam welding, especially in the welding of thick-walled plates. In this study, the influence of weld pool geometry on solidification cracking in partial penetration welding of thick plates is a subject of discussion. For this purpose, a special experimental setup of steel and quartz glass in butt configuration and lateral with high speed camera was used to capture the weld pool shape. Additionally, laser beam welding experiments were carried out to compare the crack positions and the cross section with the high-speed camera observations. The results showed a bulge in the weld pool root separated from the upper region by a nick area. This leads to the fact that three different longitudinal lengths with different solidification areas are taking place. This temporal sequence of solidification strongly promotes the solidification cracks in the weld root.

Keywords: Laser beam welding; weld pool shape; solidification craking; partial penetration; bulging

1. Introduction

Solidification crack formation is influenced by the interaction of mechanical, thermal and metallurgical factors during welding, Cross et al., 2008. Apblett et al., 1954 hypothesize that solidification cracking occurs due to a critical strain at a temperature slightly above the solidus temperature. A thin film of liquid is present between the dendrite structures, which leads to the formation of hot cracks if the highly localized strains in

* Corresponding author. Tel.: +49-30-8104-4622
E-mail address: Nasim.bakir@bam.de.

the liquid films exceed their critical limits. This liquid film contains impurities, low melting eutectic as well as iron sulfide (FeS), which has a solidus temperature of 988 °C, Cross, 2005. Prokhorov, 1956, 1976, and Prokhorov and Gavrilyuk, 1962 found that cracks are formed in a temperature range between the solidus temperature and the liquidus temperature, the so-called brittle temperature range (BTR). Hot cracks will occur if the strain during solidification exceeds the deformation capacity. Studies by Zacharia et al., 1994, showed a functional relationship between the resulting stresses in the weld and the formation of hot cracking, which was presented via in situ observations and numerical simulations. A metallurgical model based on the ratio of the cooling-related volume deformation, the so-called rate of shrinkage (ROS), and the rate of feeding (ROF) for closing the cavity, was represented by Feurer, 1977. Hot cracks are formed if the shrinkage rate exceeds the feeding rate.

The weld shape geometry also plays a significant role in the formation of solidification cracks. A large depth to width ratio often leads to the formation of centerline cracks for high-power laser-based welding processes. The center of the weld solidifies at last and therefore contains large columnar-shaped grains, which impinge on each other. Thereby, voids between the grains arise, which cannot be filled with the molten filler being added from above. Numerical and experimental analyses by Bakir et al. 2018 show that a bulging region is created in the centerline due to the Marangoni vortex on the surfaces. Solidification cracks are expected in the bulging region. This phenomenon is more frequent for partial penetration welds. Gebhardt et al. 2013, 2014 show that cracks are formed close to the weld root. As the wire feed speed increased, the number of cracks could be reduced at hybrid laser-arc welding (HLAW). Growth in penetration depth due to an increase of the laser power showed the opposite effect. The welding speed, which was variated in a range between 1.7 m min^{-1} and 3.2 m min^{-1}, showed no significant influence on the crack number. Schaefer et al., 2017 demonstrated that crack formation can be eliminated for partial penetration HLAW using a higher optical magnification of 2.67. They also showed that the focal position of the laser beam affected the melt flow during laser welding of steel, the keyhole shape and the weld pool geometry, Schaefer et al., 2017. However, these modifications of the melt flow were mainly on the upper half of the weld pool.

2. Experimental setup

Welding trials in butt joint configuration of 25 mm thick structural steel plate (S355J2) and quartz glass were conducted. The emission wavelength and beam parameter product were 1070 nm and 11 mm x mrad, respectively. The laser radiation was transmitted through an optical fibre with a core diameter of 200 µm. A laser-processing head BIMO HP has been selected, which provides a magnification of 2.8 so that the laser beam can be focused into a spot with a diameter of 560 µm. Side views of the molten pool were taken with help of a highspeed camera Fastcam 1024PCI and interference band-pass filter at 808 nm and band width of 20 nm. The experimental setup is shown in Fig. 1. The frame rate and the frame size were 2000 fps and 1200 pixels to 1200 pixels, respectively. The steel-glass experiments were carried out with a laser power of 10 kW and a welding speed of 1 m min^{-1}. The welding tests were carried out at the same speed with the laser power increased to 16 kW.

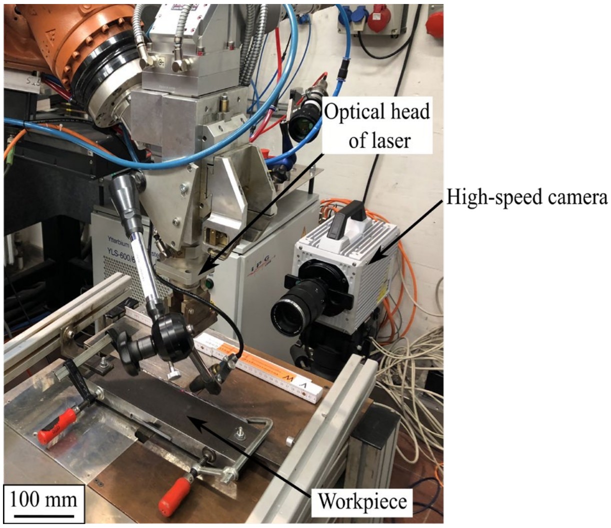

Fig. 1. Experimental setup for LBW in steel-glass configuration.

3. Results & discussion

The experiment was performed using 10 kW laser beam power at a welding speed of 1 m min^{-1}. The observations show that the dimensions of the weld pool are depending on the depth. For the evaluation of the high-speed recordings the displacements in the melt-glass interface were estimated and then the velocities were calculated using the optical flow algorithm according to Lucas-Kanade method. Fig. 2 shows the velocity vectors for a sequence of LBW specimen. These analyses can clearly show the flow directions and their velocities. Also, the shape of the molten pool can be estimated as a virtual transition boundary between non-zero and nearly zero displacements. See the yellow line in Fig. 2.

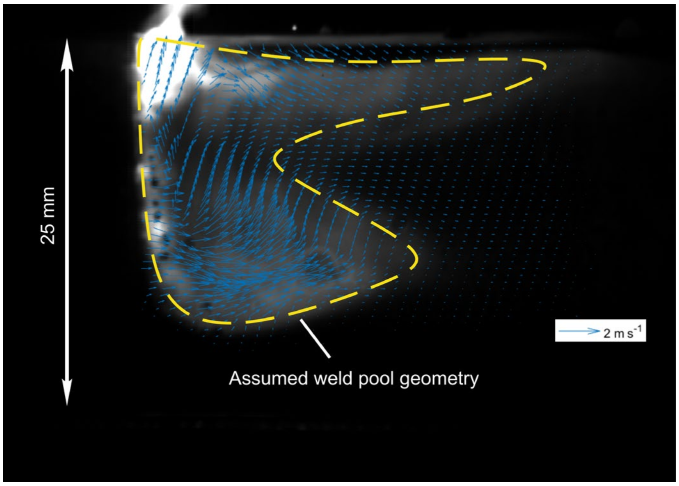

Fig. 2. Velocity vectors estimated using optical flow algorithm.

The areas close to the weld pool surface take a teardrop-shape. A bulge-region and its temporal evolution were observed approximately in the weld root. Two main flow circulations moved the melt from the front to the back of the keyhole ensuring mass conservation. The first circulation occurs in the upper half of the melt pool depth, which is mainly driven by the recoil pressure and the Marangoni stress on the melt surface. The second circulation is located in the lower half of the melt pool. The liquid metal flowed down from the front wall of the keyhole and then backwards and upwards along the liquid-solid interface, creating a circular flow at the bottom of the melt pool. The two circulations then join in the middle of the melt pool depth and form a narrow region that separates them. The fluid in the narrow region, which comes together from the upper and lower half of the melt pool, is driven back to the vicinity of the keyhole by the two mentioned vortices. Moreover, the backflows of the melt transport the cooled material into the middle region of the melt pool, thus further reducing the temperature in this region and forming a necking. The strong melt circulation in the keyhole root leads to the elongation of the melt pool in the longitudinal direction and thus to the formation of the bulge-region. The main flow lines are illustrated in Fig. 3 (a).

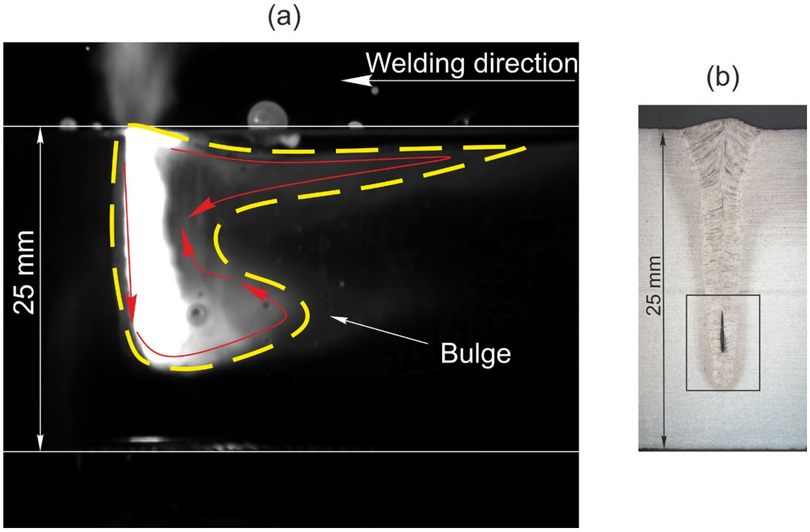

Fig. 3. a) Observed melt region and flow pattern in the longitudinal section through the quartz glass using a high-speed camera b) cross-section with solidification crack in the weld root.

This bulge promotes solidification cracking by forming a closed region filled with melt that is under tensile stress at the end of solidification, Bakir et al., 2018. This also leads to the accumulation of impurities in the final solidification phase and forms low melting phases such as (FeS), which as well contributes to solidification cracking. The tensile stresses in the bulge-region could be a result of the restraint condition of the welded parts or of the shrinkage restraint of the relative cold material around the weld root. Fig. 3 (b) shows an example for solidification crack within the bulge-region.

4. Conclusion

In this study, steel-glass experiments were conducted to observe the melt pool geometry using a high-speed camera. The high-speed recordings and optical flow analysis show that two main flows take place in form of vortices. The lower vortex drives the melt backwards from the front keyhole wall and thus causes an extension of the melt pool, which is called bulging. This bulging promotes solidification cracking by forming a closed area filled with melt and the accumulation of impurities in the final solidification phase, resulting in low-melting phases which are under tensile stress at the end of solidification.

Acknowledgements

The research project IFG 19582N/ P1241 "Investigation of influence the restraint conditions on hot cracking in laser and laser-hybrid welding of thick structure steels" from the Research Association for steel Application (FOSTA), Düsseldorf was supported by the Federal Ministry of Economic Affairs and Energy through the German Federation of Industrial Research Associations (AiF) as part of the programme for promoting industrial cooperative research (IGF) on the basis of a decision by the German Bundestag. The project was carried out at Bundesanstalt für Materialforschung und –prüfung (BAM).

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