

12th CIRP Conference on Photonic Technologies [LANE 2022], 4-8 September 2022, Fürth, Germany

# Influence of the weld pool geometry on solidification cracking in partial penetration high power laser beam welding

Nasim Bakir<sup>a,\*</sup>, Ömer Üstündag<sup>a</sup>, Andrey Gumenyuk<sup>a,b</sup>, Michael Rethmeier<sup>c,a,b</sup>

<sup>a</sup>Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, 12205 Berlin, Germany

<sup>b</sup>Fraunhofer Institute for Production Systems and Design Technology, Pascalstraße 8-9, 10587 Berlin, Germany

<sup>c</sup>Institute of Machine Tools and Factory Management, Technische Universität Berlin, Pascalstraße 8-9, 10587 Berlin, Germany

\* Corresponding author. Tel.: +49-30-8104-4622. E-mail address: [nasim.bakir@bam.de](mailto:nasim.bakir@bam.de)

## Abstract

Solidification cracking is still a serious problem in laser beam welding, especially in the welding of thick-walled plates. The influence of weld pool geometry on solidification cracking in partial penetration welding of thick plates is investigated within scope of this study. Therefore, a specific experimental setup of steel and quartz glass in butt configuration and on the side with high-speed camera were used to record the weld pool shape. In addition, the influence of laser inclination angle on the weld pool geometry and on solidification crack formation was investigated. The results show a bulge in the weld pool root, which is separated from an upper region by a necking region. This leads to a case where there are three different longitudinal region lengths with different solidification zones. This temporal sequence of solidification strongly promotes the formation of solidification cracks in the weld root.

© 2022 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of the international review committee of the 12th CIRP Conference on Photonic Technologies [LANE 2022]

*Keywords:* Laser beam welding (LBW); solidification cracking; partial penetration; weld pool shape

## 1. Introduction

Recently, a wide range of criteria for hot cracking have been developed and described according to the literature [1]. Since the problem of hot cracking is very complex and depends on the interaction of a wide variety of factors, these criteria often build on each other or are quite similar in their approach. One of the earliest strain-based criteria is Pellini's "strain theory of hot tearing" [2]. This means that, the metallurgy of the material decides whether a material is susceptible to hot cracking, but the actual occurrence depends on mechanical factors. As soon as a critical strain is exceeded, cracking occurs. This can happen if the liquid film during solidification persists longer than usual. Sulphur, for example, can cause this effect. In this way, strain rates have longer time to cause a crack. The theory of the technological strength of metals during the crystallisation process was developed by Prokhorov [3]. He combined the

deformation capacity of the solidifying metal with thermomechanical influences during welding. Hot cracks will occur if the strain during solidification exceeds the deformation capacity. Apblett et al. [4], 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 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, [5]. The ROF-ROS model is probably one of the most famous models among the hypotheses based on balance equations. In this model, Feurer deals with the relationship between the rate of feeding (ROF) and the rate of shrinkage (ROS) [6]. During solidification, gaps are to be filled by the subsequent flow of residual melt. This is the case as long

as ROF is greater than or equal to ROS. However, if ROS becomes larger than ROF, hot cracks can occur.

The phenomenon occurring in the weld pool have been identified as potentially promoting the formation of defects during the solidification phase, e.g. hot cracking. Shida et al [7] found a correlation between weld pool geometry and solidification cracking as they investigated the effects of welding parameters in electron beam welding (EBW) on weld quality. However, they observed a small cavity in the rear part of the weld pool caused by the variation of the focus position during electron beam welding. The observed cavity has a significant influence on the formation of solidification cracks. In addition, it has been shown in electron beam welding that a bulge in the molten pool in the middle part leads to a local delay of the solidification behaviour and thus increases the susceptibility to cracking in this region [7]. Gebhardt et al [8] observed a similar phenomenon during laser beam welding of thick components. They called it bulging in the weld seam. In their numerical models, a significant influence of the studied bulging of the temperature field is attributed to the mechanical stress distribution, which then contributes to the formation of hot cracks during solidification in the mushy zone. Barbetta et al [9] confirmed a close correlation between the bulge in the weld and the occurrence of solidification cracks, as the solidification crack was always associated with a bulge and thus a change in the temperature distribution. Bakir et al [10] and Artinov et al [11] showed that the bulging effect amplifies the three most important factors that determine the susceptibility of the component to initiate cracking, namely the thermal cycle, the time-related mechanical stress and the local microstructure. This effect represents a geometric feature of the molten pool shape and plays a critical role in the formation of defects such as solidification cracks. Monitoring the dynamics of the keyhole and the molten pool during welding is a challenging task. For this purpose, the keyhole or the melt could be observed in-situ using X-ray images of the melt pool [12, 13]. An observation technique based on recording the keyhole and the melt pool through a quartz glass plate has become widespread in recent years and is relatively close to reality. This experimental setup has already been used by Li et al [14] to investigate the plasma and keyhole behaviour in high power deep penetration welding of stainless steel with fibre laser. Zhang et al [15] also successfully used the butt configuration of fused silica and zinc to investigate their behaviour during laser beam welding.

The purpose of this study is to investigate the influence of weld pool geometry on crack formation during laser beam partial penetration welding. Moreover, the laser inclination angle and its impact on the weld pool and thus on crack formation was studied. The present study is a completion of the last investigation on weld pool geometry in high power laser beam welding in partial penetration welding [16].

## 2. Experimental setup

Welding experiments were carried out in butt joint configuration of 25 mm thick mild steel sheet (S355J2) and 5 mm thick quartz glass. The emission wavelength and beam parameter product were 1070 nm and 11 mm x mrad,

respectively. Laser beam was transferred through an optical fibre with a core diameter of 200  $\mu\text{m}$ . A BIMO HP laser processing head was chosen, offering a magnification of 2.8, so that the laser beam could be focused on a spot with a diameter of 560  $\mu\text{m}$ . Side views of the weld pool were recorded using a Fastcam 1024PCI high-speed camera and an 808 nm interference band-pass filter with a bandwidth of 20 nm. The experimental setup is shown in Fig. 1.

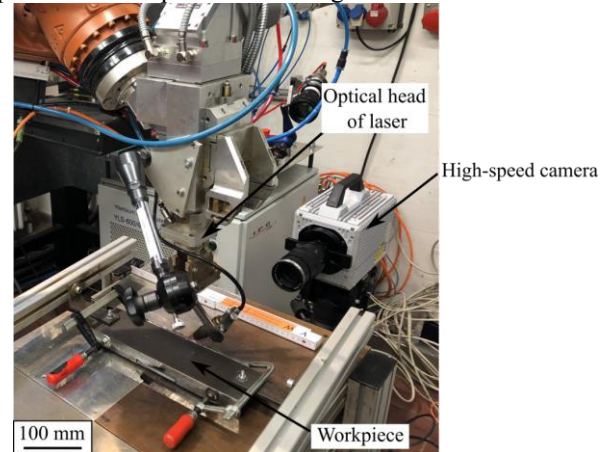


Fig. 1. Experimental setup for LBW in steel-glass configuration

The frame rate as well as the image size were 2000 fps and 1200 pixels to 1200 pixels, respectively. The steel-glass tests were carried out with a laser power of 12 kW and a welding speed of 1 m  $\text{min}^{-1}$ .

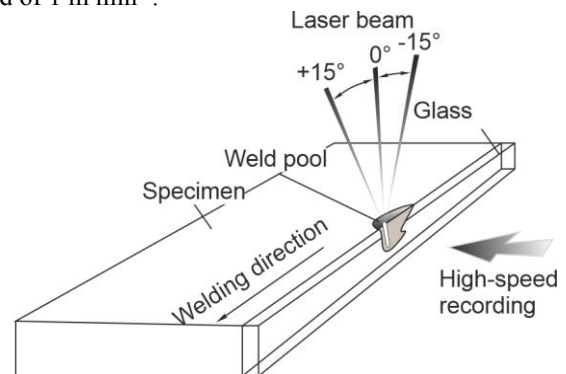


Fig. 2. Schematic representation of the investigated laser inclination angles.

To investigate the influence of the laser inclination angle on the weld pool geometry, two other inclination angles were considered in addition to the perpendicular to the specimen surface. Fig. 2 shows the investigated inclination angles 0° the case where the laser beam is perpendicular to the specimen surface and 15° in both the clockwise and counterclockwise directions. Further experiments on steel in the butt joint configuration were also carried out with the different inclination angles. The same welding parameters were also used for these experiments.

## 3. Results and discussion

The observations obtained using the high-speed camera show that the dimensions of the weld pool depend on the penetration depth. For the evaluation of the high-speed images,

the displacements in the melt-glass interface were estimated and then the velocities calculated with the optical flow algorithm according to the Lucas-Kanade method. Fig. 3 shows the velocity vectors for a sequence of LBW specimens. These analyses allow the flow directions and their velocities to be clearly identified. Furthermore, the shape of the melt pool can be estimated as a virtual transition boundary between non-zero and near-zero velocities.

The region near the melt pool surface takes a teardrop shape. A bulge area and its evolution over time were observed approximately in the weld root. The melt was driven in two main flows 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 and is mainly driven by the recoil pressure and the Marangoni stress effect at the melt surface. The second circulation takes place in the lower half of the melt pool. The liquid metal flows downwards 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 circuits then join in the middle of the depth of the melt pool, forming a narrow region that separates them. The fluid in the narrow region, which comes together from the upper and lower sections of the melt pool, is driven back to the vicinity of the keyhole by the two mentioned vortices.

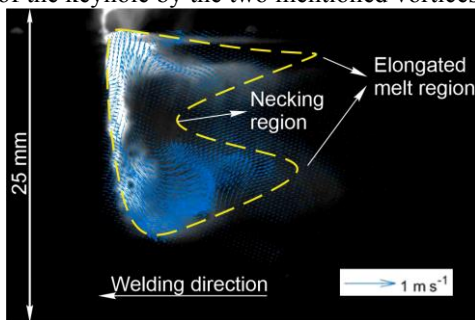


Fig. 3. Velocity vectors estimated using optical flow algorithm.

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 issue is how this bulging can promote solidification cracking. The problem in this case is that the molten pool does not solidify continuously from the root to the surface, but in three steps. To illustrate this, three consecutive solidification times are taken in Fig. 4. and the corresponding cross-sections are shown schematically on the right. At moment T1, immediately after the keyhole, the weld pool is completely formed.

This corresponds to what can be seen when a cross-section is taken in a joint. At time T2, solidification has already begun. Here it can be recognised that the solidification in the necking region is much faster because this region is much shorter. At time T3, the area of the necking has completely solidified and splits the melt pool into two parts, which later solidify separately.

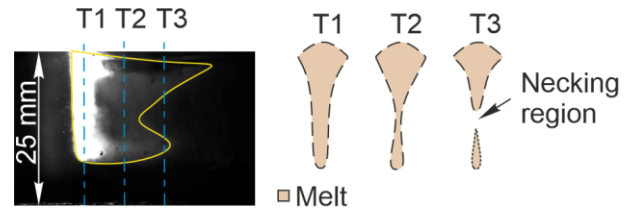


Fig. 4. Schematic representation of the molten pool (in cross-section) at three consecutive intervals during solidification

On the one hand, there is a trapped and melt-filled region that is under tensile stress in the opposite direction of dendrite growth at the end of solidification, as schematically shown in Fig. 5. These tensile stresses occurring in the bulge region could be the result of the restraint condition of the welded parts or the shrinkage of the relatively cold material around the weld root. On the other hand, this bulge leads to the accumulation of impurities in the final phase of solidification and forms low-melting phases such as (FeS), which also contribute to solidification cracking.

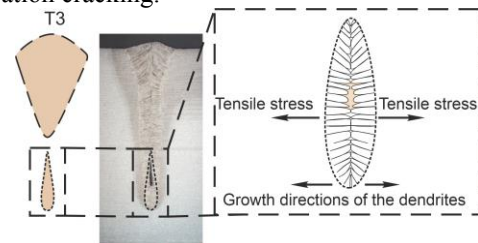


Fig. 5. Schematic diagram explaining how bulging assists in solidification cracking.

Fig. 6 shows the comparison of the melt pool geometry between the three inclination angles  $+15^\circ$  and the reference case  $0^\circ$ . Based on the high-speed recordings, it can be observed that the geometry of the melt pool in the case of the  $-15^\circ$  inclination angle includes the three regions found in the reference case. The bulge, the necking region and the elongated region at the surface. In addition, the bulge region appears to be longer than in the reference case, which should also increase the risk of cracking. In contrast, in the  $+15^\circ$  case, the melt pool takes on a different shape and looks like a triangle. In this case, it appears that the bulge and the necking are no longer visible. This should have a positive effect on reducing solidification cracking.

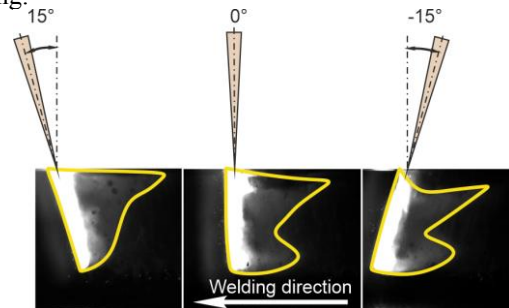


Fig. 6. Comparison of the melt pool geometry with the three investigated laser inclination angles.

This is clearly confirmed by looking at the results of the influence of the inclination angle on the cracking in butt joint experiments in which this study was carried out. Fig. 7 shows the number of cracks against inclination angle of the laser beam. There is a clear and direct correlation between the inclination angle and the number of cracks.

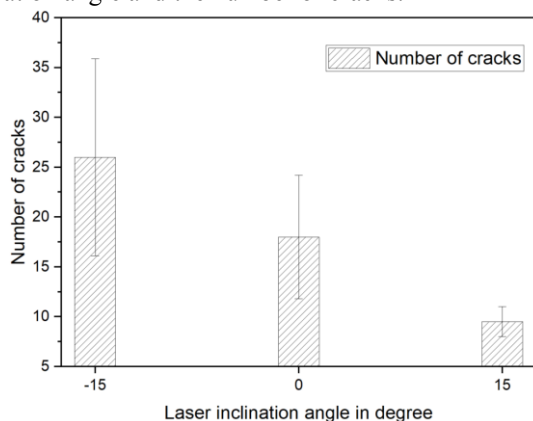


Fig. 7. Dependency of the number of cracks on the laser inclination angle.

From this it can be concluded that inclining the laser beam in the welding direction reduces or eliminates the bulge formation and reduces the number of cracks, which is observed.

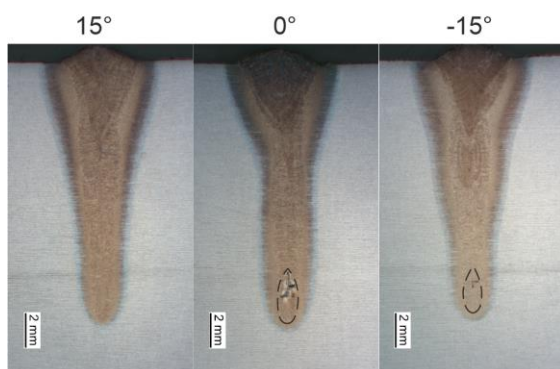


Fig. 8. Comparison of the melt pool geometry with the three investigated laser inclination angles.

Fig. 8 shows cross-sections of three welded specimens with the investigated inclination angles. Solidification cracks can be observed in the weld root in the case of the  $-15^\circ$  and  $0^\circ$  inclination angles. Furthermore, a drop-shaped solidification in the weld root similar in Fig. 5 can be recognised.

#### 4. Conclusion

In the present study, steel-glass experiments were carried out to observe the geometry of the molten pool with a high-speed camera. The high-speed images and optical flow analysis show that two main flows take place in the vortices. By driving the melt back from the front keyhole wall, the lower vortex causes an expansion of the melt pool called bulging. This bulge promotes cracking during solidification by forming a trapped region filled with melt and the accumulation of impurities in

the final solidification phase, resulting in low-melting phases that are under tensile stress at the end of solidification. The laser inclination angle exhibited a significant influence generally on the weld pool geometry and especially on the formation of bulges in the weld pool root. The inclination of the laser beam in the welding direction reduces or eliminates bead formation and also reduces the risk of cracking in the weld root for partial penetration welding.

#### Acknowledgements

The authors would like to thank Mr. Grunwald from the Division 8.3 (Radiological Methods) of the BAM for the X-ray images.

#### References

- [1] Eskin, D.G. und Katgerman, L.: A Quest for a New Hot Tearing Criterion. Metallurgical and Materials Transactions A, 2007. 38(7): S. 1511-1519.
- [2] Pellini, W.S.: *Strain Theory of hot Tearing*. Foundry: Management and Technology, 1952. 80: S. 125-133, 192, 194, 196 & 199.
- [3] N. N. Prokhorov, "The technological strength of metals while crystallizing during welding," *Welding Production*, vol. 9, no. 4, pp. 1-8, 1962,
- [4] Apblett, W. R., & Pellini, W. S. (1954). Factors which influence weld hot cracking. *Welding J.(NY)*, 33.
- [5] Cross, C.E.: On the Origin of Weld Solidification Cracking, in *Hot Cracking Phenomena in Welds*. 2005, Springer, Berlin, Heidelberg.
- [6] Feurer, U. (1977). Influence of alloy composition and solidification conditions on dendrite arm spacing, feeding and hot tearing properties of aluminum alloys. In *Qual. Control Eng. Alloys Role Met. Sci, Proc. Int. Symp* (pp. 131-145).
- [7] Shida, T., Okumura, H., and Kawada, Y., Effects of welding parameters and prevention of defects in deep penetration electron beam welding of heavy section steel plates. *Weld. World*, 1979. 17: p. 196-207.
- [8] M. O. Gebhardt, A. Gumenyuk, and M. Rethmeier, 2013 "Numerical analysis of hot cracking in laser-hybrid welded tubes," *Advances in Materials Science and Engineering*, vol. 2013, pp. 1–8
- [9] Barbetta, L., Weingaertner, W., Seffer, O., Lahdo, R., and Kaierle, S. Influence of molten pool geometry and process parameters on solidification cracks formation in hybrid laser-GMA welding of thick 5L X70 steel plates. in *ABCM International Congress of Manufacturing Engineering (COBEM), 8th Brazilian Congress of Manufacturing Engineering*, Salvador, Bahia, Brazil. 2015.
- [10] Bakir, N., Artinov, A., Gumenyuk, A., Bachmann, M., and Rethmeier, M., Numerical simulation on the origin of solidification cracking in laser welded thick-walled structures. *Metals*, 2018. 8(6): p. 406.
- [11] Artinov, A., Bakir, N., Bachmann, M., Gumenyuk, A., Na, S.-J., and Rethmeier, M., On the search for the origin of the bulge effect in high power laser beam welding. *Journal of Laser Applications*, 2019. 31(2): p. 022413.
- [12] Katayama, S., Kawahito, Y., and Mizutani, M., Latest progress in performance and understanding of laser welding. *Physics Procedia*, 2012. 39: p. 8-16.
- [13] Berger, P., Hügel, H., and Graf, T., Understanding pore formation in laser beam welding. *Physics Procedia*, 2011. 12: p. 241-247.
- [14] Li, S., Chen, G., Zhang, Y., Zhang, M., Zhou, Y., and Deng, H., Investigation of keyhole plasma during 10 kW high power fiber laser welding. *Laser physics*, 2014. 24(10): p. 106003.
- [15] Zhang, Y., Li, S., Chen, G., Zhang, H., and Zhang, M., Characteristics of zinc behavior during laser welding of zinc "sandwich" sample. *Optics & Laser Technology*, 2012. 44(8): p. 2340-2
- [16] Bakir, N., Üstündag, Ö., Gumenyuk, A., & Rethmeier, M. (2021). Observation of the weld pool shape in partial penetration welding and its influence on solidification crack formation for high-power laser beam welding. In *Lasers in Manufacturing Conference 2021* (pp. 1-5)