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Numerical study of the bulging effect in deep penetration laser beam welding

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Abstract

This article is devoted to the study of the bulging effect in deep penetration laser beam welding. The numerical results of the investigations are based upon experimental results from previous studies to reveal the relationship between the bulging effect and the hot cracking formation, as well as the mixing of alloying elements in the weld pool. The widening of the molten pool in its center area can be observed in full penetration as well as in partial penetration welds on 8 mm and 12 mm thick structural steel plates, respectively. The weld pool shape is extracted from the simulations to evaluate the extent of the necking of the solidification line as well as the bulging phenomena and its influence on the hot cracking phenomena. Relying on an earlier numerical study utilizing a fixed keyhole, simulation models considering a dynamic keyhole are developed thereto. Additionally, the mixing behavior of alloying elements during partial penetration is investigated. The link between the bulge and the studied phenomena is found to be significant.

Keywords: deep penetration laser beam welding ; welding simulation ; solidification cracking ; bulging effect

1. Introduction

The high-power laser beam welding technology is an established tool with steadily increasing capabilities in joining thick sheets, e.g. in the manufacturing of thick-walled pipelines for the oil and gas industry. The available laser powers of up to 100 kW for solid-state lasers allow the single pass welding of up to 50 mm thickness (Bachmann et al., 2016, Zhang et al., 2011) and thus show the great potential of this technology in

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comparison to traditional arc welding technologies which often require several passes to achieve the same welding depth. Additionally, the laser beam welding process offers even more advantages like its high efficiency, high achievable welding speed, high depth-to-width ratio, and narrow heat-affected zone (Ready and Farson, 2001).

Nevertheless, the laser beam welding technology shows different phenomena especially in the high thickness regime which are hardly investigated until now. One of those is the widening of the solidification line in the rear of the weld pool and its cross section often referred to as the bulging effect (Artinov et al., 2018, Artinov et al., 2019). It was found that this effect can play a significant role in the formation of weld defects like hot cracking and porosity development due to the locally delayed solidification of the melt. Moreover, studies of the same group also show that the transfer of filler wire in hybrid welding conditions can be restrained due to the bulging effect (Meng et al., 2020). This causes a limited mixing of the elements which leads to regions with different concentrations of the added filler material in the weld bead and can baffle the mechanical homogeneity of the final weld.

The first occurrence of the bulging phenomena in the literature is related to the electron beam welding, accounting the observed hot cracking with the delayed solidification phenomena (Shida et al., 1979). Later, experimental evidence was given to the interaction of the weld pool widening and the susceptibility to hot cracking also in hybrid laser-GMA welding (Barbetta et al., 2015). Artinov et al., 2020 have shown, that the bulging effect enhances the three most dominant driving factors of the hot cracking phenomena, namely the thermal cycle, the mechanical loading, and the local microstructure.

Another consequence of the widening of the weld pool is the corresponding narrowing of the vertical flow channels inside the weld pool whereby a limitation of the mixing of additional alloying elements inside the melt could be observed, see Meng et al., 2021. Thereby, a significant detrimental effect on the weld seam quality, e.g. in terms of Charpy impact toughness, was shown in Üstündağ et al., 2019.

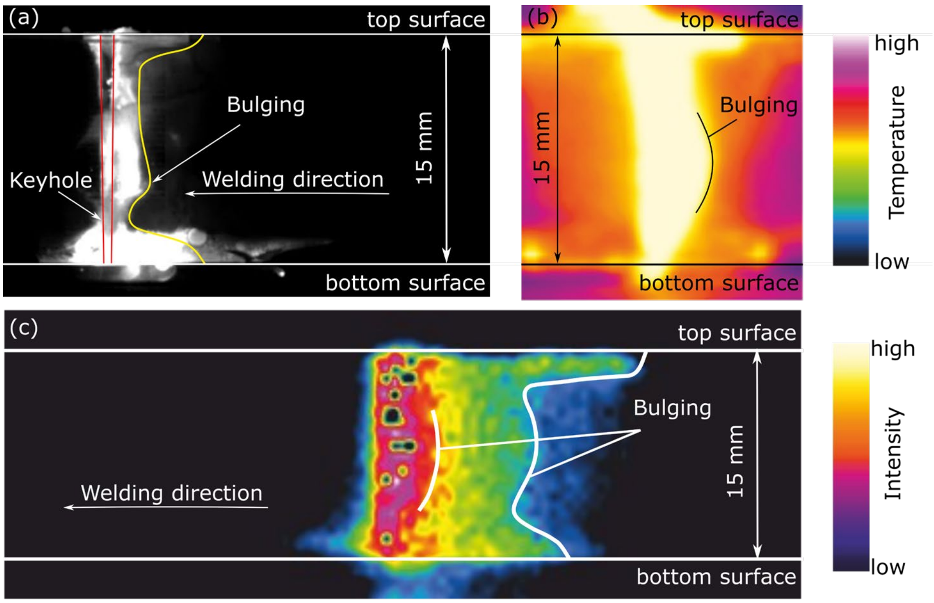

Fig. 1. Different experimental views of the longitudinal section through a quartz glass according to Artinov et al., 2019 using (a) a high-speed camera; (b) a thermo camera; (c) an infrared camera; Original images: © 2021 Reprinted with permission from the Laser Institute of America. All Rights Reserved.

The present numerical study is motivated through a series of experiments published in Artinov et al., 2019, giving evidence of the bulging effect in deep penetration laser beam welding by different experimental observation techniques of the weld pool, see Fig. 1. Welding experiments of 15 mm thick structural steel S355 in butt joint configuration with a transparent quartz glass plate were conducted with a welding speed of 2 m/min, a laser power of 18 kW, a focal position of -5 mm, and a focal diameter of 0.56 mm. An additional laser illumination technique described in detail therein was used to allow for a direct observation of the weld pool by means of a high-speed camera, a thermo camera, and an infrared camera. Their results show a distinct widening of the isothermal lines in the melt pool area that was associated to a local delay in the solidification behavior and thus increasing the susceptibility to hot crack formation in the bulging region. The location of the bulge was confirmed to coincide with those of the occurring cracks and it was also visible in the metallographic cross sections (Bakir et al., 2018).

Between the bulging area and the weld pool surfaces a necking area was observed which limits the potential flow of melt along vertical directions in the weld pool. This might deteriorate the dilution when using filler material. This was also investigated in detail in Meng et al., 2021.

However, the optical inaccessibility of the process can only offer partly insights into the mechanisms of the formation of the described bulging and necking phenomena. Hence, this study aims for a numerical investigation of those.

2. Numerical modelling

The main assumptions for the simulations with a dynamic keyhole evolution are summarized in the following. More details thereto are given in Artinov et al., 2021. A ray tracing algorithm according to Cho et al., 2012 was implemented in the commercial CFD code Ansys Fluent considering the main physical aspects for the heat input into the material to be welded, e.g. multiple reflection and Fresnel absorption at the keyhole surface along the route of the laser radiation. Semak and Matsunama, 1997 developed a model to account for the role of recoil pressure during laser beam welding which was used in this investigation. The influence of the vapor induced stagnation pressure and shear stresses acting on the keyhole surface was accounted for according to the model of Muhammad et al., 2018. Other main physical effects, e.g. Marangoni convection, buoyancy, latent heat of fusion, and temperature-dependent material properties up to the vaporization temperature were considered as well.

2.1. Bulging formation in partial and full penetration welds

The simulations for the assessment of the bulging effect in deep penetration laser beam welding were conducted with the low-alloy ferritic steel S355. The welding speed was 2 m/min, the laser power was set to 7.5 kW, and the focal position at the upper surface of the specimen. Exemplary results of the partial penetration welds can be seen in Fig. 2.

The upper part of the weld pool is dominated by the Marangoni flow and a correspondingly elongated weld pool surface can be observed. As can be seen in the evolution of the weld pool, the weld pool length varies depending on the dynamic behavior of the keyhole due to its transient fluctuations. They themselves depend on the absorbed amount of thermal energy and subsequent mechanical effects of the recoil pressure. A bulge starts to form at the very beginning of the weld (Fig. 2a) well before reaching its maximum penetration depth. It was found that bulging occurs transiently, but more frequently at penetration depths above 5 mm in the weld center area which was experimentally proven to be the location of the appearing hot cracks (Artinov et al., 2019). The reason of the development of a bulging area can be found in the interaction of the subsurface backflow of material as a consequence of mass conservation in the upper part of the weld pool and the pushing

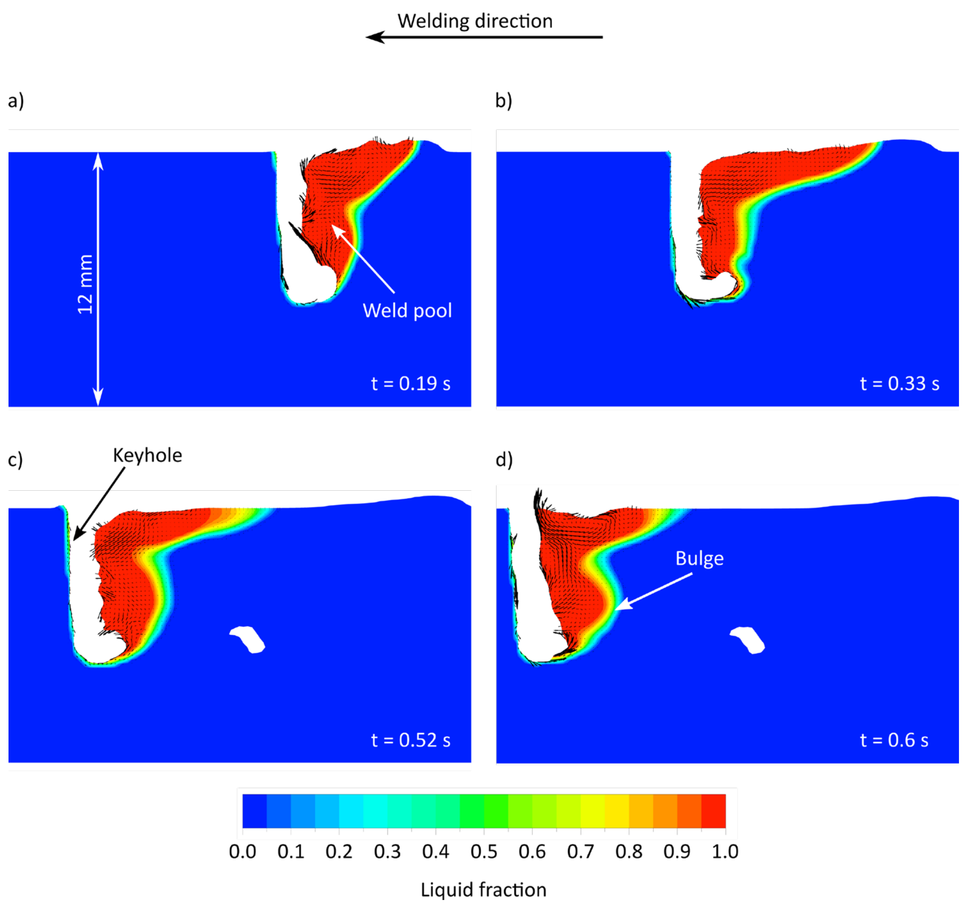

Fig. 2. Calculated weld pool shape on the longitudinal plane during partial penetration welding of 12 mm thick S355 low-alloy steel (laser power 7.5 kW, welding velocity 2 m/min, focal position at the upper surface).

force of the recoil pressure that tends to move the liquid to the rear of the melt pool at its bottom. Consequently, a narrow region in between both areas develops that separates the circulation region at the weld pool top from the elongated bulging region below. The described behavior could be observed for various thicknesses shown exemplarily in Fig. 2 for a penetration depth of approx. 7 mm.

According to Bakir et al., 2018, one can expect a highly increased susceptibility to hot cracking in the bulging area which is caused by observed high values of tensile stress there in combination with compressive stresses in the narrow regions in its vicinity.

Results of the shape of the weld pool for the full penetration case of 8 mm thick low-alloy steel are shown in Fig. 3. The laser power was set to 7.5 kW, the welding velocity and the focal position were kept constant at 2 m/min and at the upper surface.

The characteristics of the weld pool geometry during the process in the upper part is very similar to the partial penetration case shown in Fig. 2. Like for the upper surface a vortex in opposite direction forms, which enhances the surface flow away from the keyhole. Again, a subsurface flow changes the isothermal lines narrowing of the solidification line occurs once the penetration depth reaches the bottom of the weld pool.

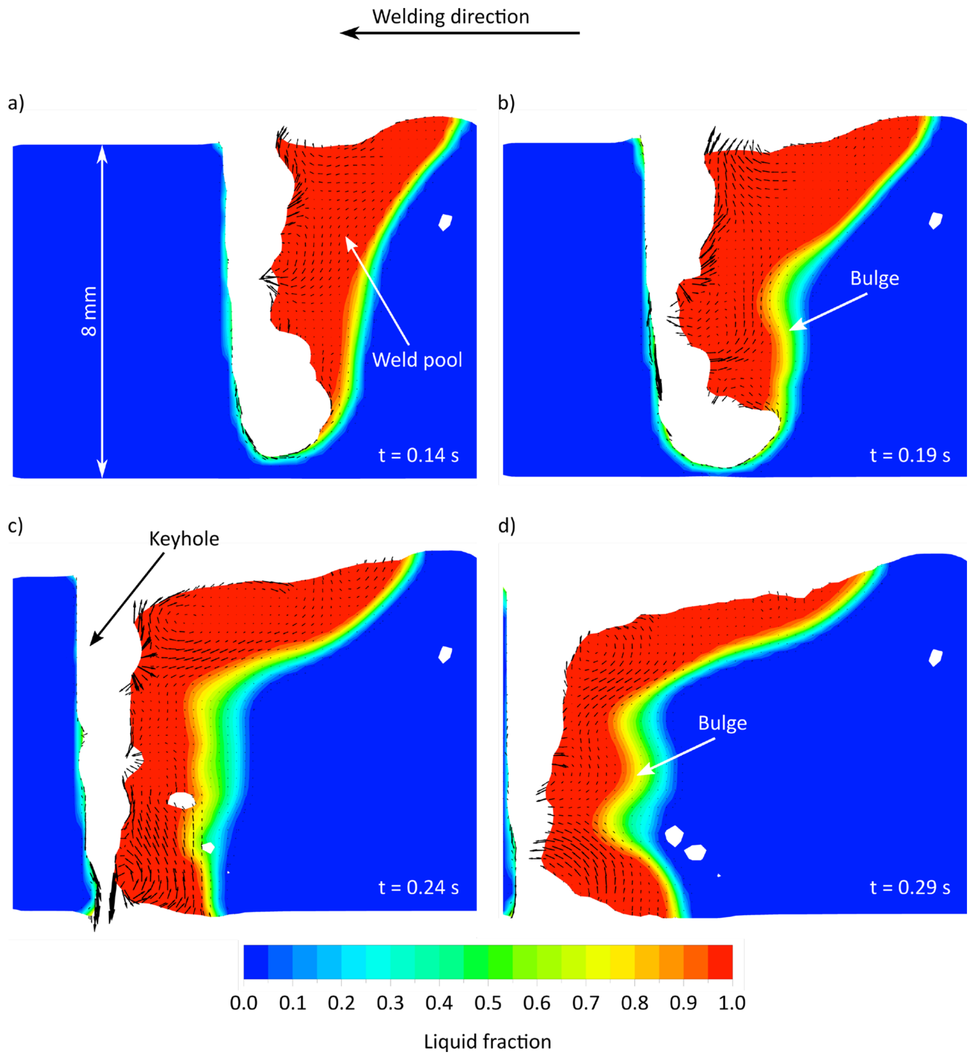

Fig. 3. Calculated weld pool shape on the longitudinal plane during full penetration welding of 8 mm thick S355 low-alloy steel (laser power 8 kW, welding velocity 2 m/min, focal position at the upper surface).

Like seen in the calculations in partial penetration mode, the development of the bulging area is present very frequently upon a distinct weld thickness. In the investigation of the full penetration welding case, the bulging phenomena was observed for 8 mm plate thickness, and its occurrence again increased for materials above 10 mm thickness. Predominantly, the position of the observed bulging phenomena varies around the middle of the plate thickness, in correspondence to previous studies (Bakir et al., 2018). Due to the dynamics of the keyhole which fluctuates according to the transient local heat input, the development of the bulging especially at the solidification front is a non-steady phenomenon that forms along the weld seam.

2.2. Influence of bulging on the mixing behavior of filler material

The same characteristics of the weld pool shape that was observed for partial penetration welding of low-alloy steel S355 could be reproduced for partial penetration welding of 10 mm thick austenitic stainless steel (Fig. 4). The base material in this study is AISI 304 with approx. 8.7 % Ni content and the filler metal is Inconel 625 with approx. 58 % Ni. The numerical model corresponds to this presented in section 2.1, but with a laser power of 6.5 kW, a welding velocity of 1.3 m/min, a wire feeding velocity of 2.1 m/min at an angle of 57° with respect to the optical axis, and a focal position 3 mm below the upper surface. Further details to the modelling can be found in Meng et al., 2021.

The strong backward flow along the top surface is mainly driven by both recoil pressure and the Marangoni shear stress leading to an elongation of the upper weld length. Near the keyhole, the effect of the momentum caused by its highly fluctuating nature due to the recoil pressure forces is even more important, see the strong velocity components there, e.g. in Fig. 4c. The laser beam moves forward with the welding speed at the same time and the recoil pressure tends to push the material to the sides, especially in the regions where the major

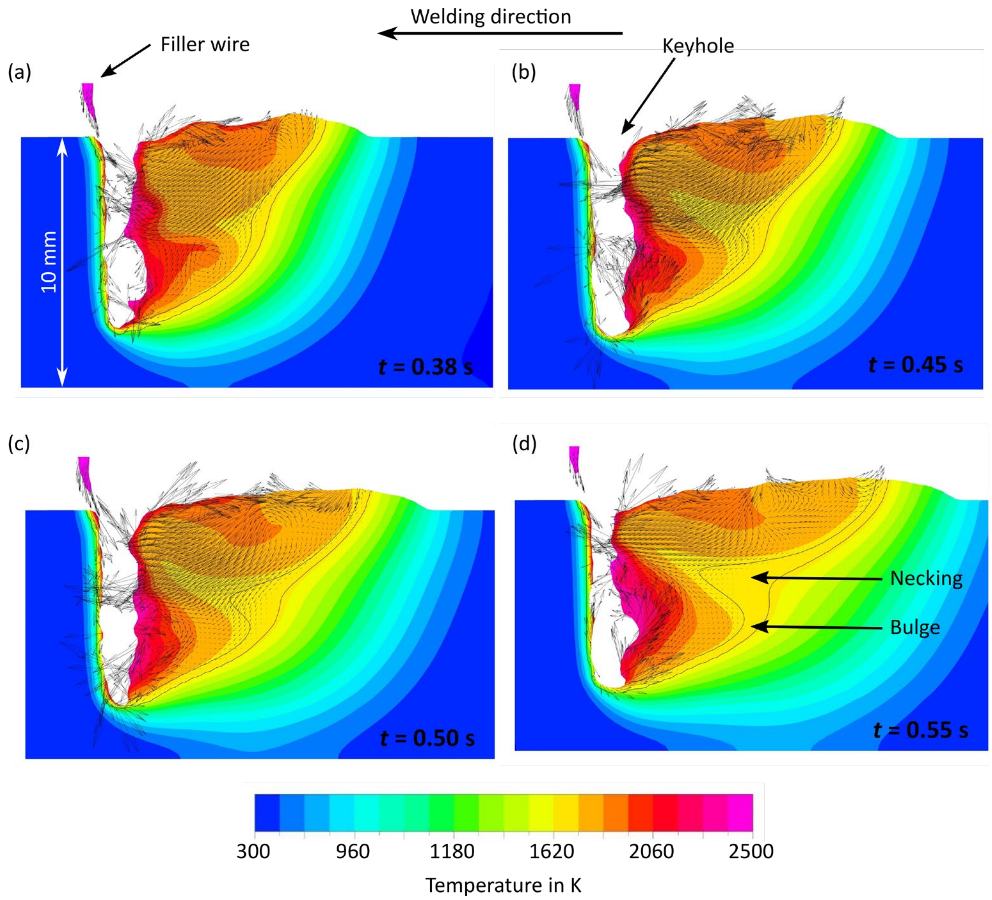

Fig. 4. Calculated temperature distribution on the longitudinal plane during partial penetration welding of 10 mm thick austenitic stainless steel AISI 304 with Ni-base fille wire (laser power 6.5 kW, welding velocity 1.3 m/min, focal position 3 mm below the upper surface).

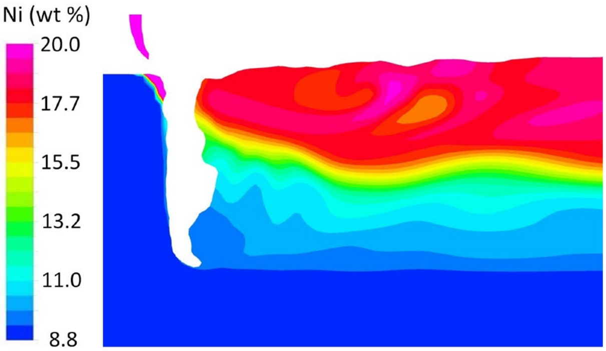

Fig. 5. Calculated Nickel concentration on the longitudinal plane during partial penetration welding of 10 mm thick austenitic stainless steel AISI 304 with Ni-base fille wire.

part of the thermal energy is absorbed and the evaporation of material is strongest. Thus, there is a counterflow being directed against the subsurface backflow due to the Marangoni-dominated upper surface flow. Consequently, a necking of the weld pool occurs which divides the weld pool in two areas: an upper area which is dominated by the Marangoni flow and a bulge region at the weld pool bottom. In between there is a necking area where the potential vertical flow channels are minimized. The flow direction of the subsurface flow attaches along the solidus line thus minimizing the vertical velocity component. Accordingly, there is a sharp boundary at the final stages of the weld between an upper Ni-rich region and a Ni-poor region below the necking area, see Fig. 5. This can cause obvious flaws of the final weld when the filler material was expected to have a metallurgical and preferably homogeneous effect, e.g. in terms of defect prevention or a strengthening of mechanical properties of the final weld.

3. Conclusions

The present numerical study was intended to reveal the formation of characteristic deformations of the solidification line during high power laser beam welding based on a former experimental investigation (Artinov et al., 2019) and its consequences for the susceptibility to hot cracking and the homogenization of added filler wire in the melt.

According to the experimental observations presented therein, the results of the simulations show that a distinct bulge appears in partial as well as in full penetration welding. In both cases, the penetration depths where bulging occurred in this study correspond to the range of penetration depths being known to be susceptible to hot cracking (Artinov et al., 2019; Bakir et al., 2018). The location of the observed bulging correlates very well with earlier experimental studies.

The occurrence of bulging is often accompanied by a necking region which deteriorates the potential vertical flow routes in the melt pool. Hence, the homogenous dilution of added filler material with a different chemical composition compared to the base metal can be dramatically impeded and the weld characteristics can be compromised.

Acknowledgements

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