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Influence of residual stresses induced by forming on the hot cracking sensitivity of laser welding processes of AlMgSi aluminum alloy

Peter Stritt*, Christian Hagenlocher, Rudolf Weber, Thomas Graf

Institut fuer Strahlwerkzeuge (IFSW), Pfaffenwaldring 43, 70569 Stuttgart, Germany

Abstract

In industrial production forming processes are often followed by joining processes such as laser welding. In most cases forming processes like deep drawing create residual stresses in the work piece. The influence of those residual stresses on laser welding processes in terms of hot crack formation and the resultant weld quality are major outcomes of the presented paper.
Cups of 6080 aluminum alloy were produced by deep drawing and the resultant residual stresses were determined by experiment and simulation. Knowing the local stresses, welding experiments were performed on the formed part and compared with welding experiments on flat aluminum sheets, which were stress free before welding.
Several known publications related the hot cracking sensitivity to the local stresses during the dendritic solidification of the melt. The experiments showed that the addition of residual bending stresses caused by forming increased the hot cracking sensitivity. This can be derived from analysis of high-speed images during the welding process and the metallographic analysis of the weld seam after the welding process. Finally these results were evaluated in the context of existing theories on hot crack formation.

Keywords: Laser welding; aluminum; hot crack; residual stress; forming

* Peter Stritt. Tel.: +49-711-685-69740; fax: +49-711-685-59740.
E-mail address: peter.stritt@ifsw.uni-stuttgart.de.

1. Introduction

The processing chain in industrial production often consists of forming processes of flat sheets, followed by cutting and joining processes such as welding. Fig. 1 shows a sketch of the described typical processing chain.

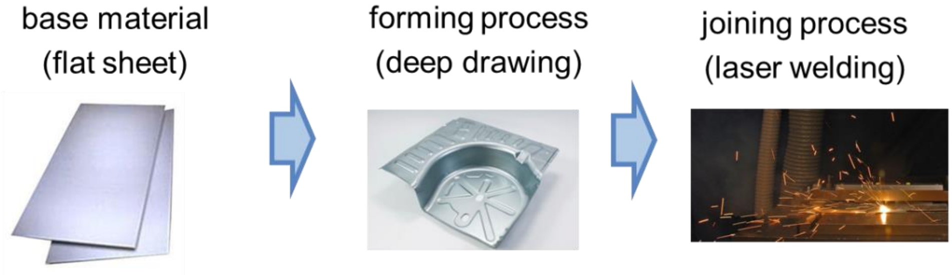

Fig. 1. Typical processing chain showing the consecutive forming and joining processes.

One major challenge during laser welding of 6000 series aluminum alloy is the prevention of hot cracks. However, the influence of the preceding forming processes, such as deep drawing, on the weld hot cracking sensitivity is not well known so far.

To investigate these relations, cups of 6080 aluminum alloy were deep drawn. Because of inhomogeneous forming events and the shape constraint of the cup shape, those cups possess residual stresses. The influence of these residual bending stresses on the hot cracking sensitivity has been experimentally investigated.

2. Basics of deep drawing and hot cracking

2.1. Deep drawing process

Following the processing chain the flat sheet is formed to certain shapes, which happens most common by a deep drawing process. A sketch of the deep drawing process is shown in Fig. 2.

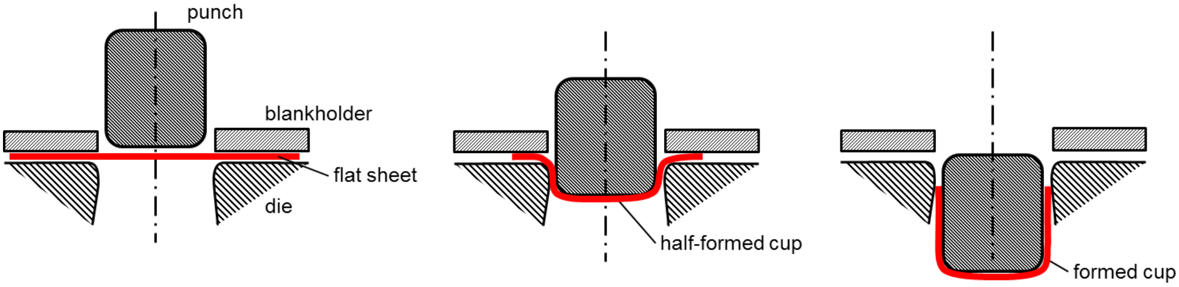

Fig. 2. The successive steps of the deep drawing process of cups.

During the drawing process the material of the flat sheet experiences a bending process, while the material flow passes the die radius. The formed cup is restricted to shape constraint, so there is only a limited spring back possible. Thereby and because of inhomogeneous forming events during the bending it possess residual stresses. These residual stresses are mostly bending stresses as depicted in Fig. 3.

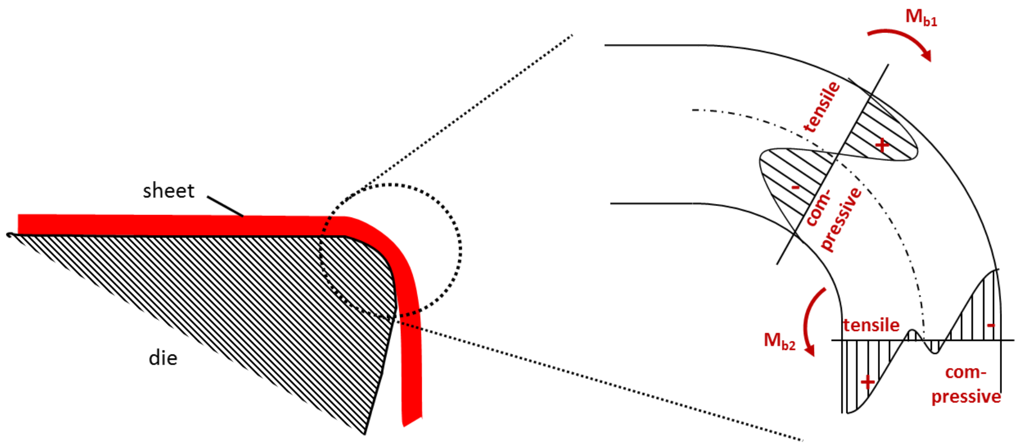

Fig. 3. The resultant bending stresses during the cup forming process [according to Behrens 2007, Lange 1990 and Saito 1979].

The bending process, while passing the die radius, creates compressive stresses near the outer cup surface and tensile stresses in direction of the inner cup surface. After passing the die radius the material is forced to bend in the other direction, because of the cup's closed circular shape. As depicted in Fig. 3 after forming the inner cup surface possesses compressive stress and the outer cup surface tensile stress in axial direction of the cup. Thus being the described residual bending stresses in the formed cup.

2.2. Hot cracks during close edge laser welding

As reported in several publications hot-cracking during laser welding of 6000-series aluminum mainly occurs in close edge configuration [Hilbinger 2001, Stritt 2012 and Weller 2013]. The edge-deformation due to heat accumulation leads to a mechanical strain on the solidifying liquid of the weld pool resulting in the known hot cracks [Hilbinger 2001 and Stritt 2012].

This hot-cracking phenomena in aluminum welds has also been correlated to the local thermomechanical stresses perpendicular to the welding direction acting in the solidification zone of the weld [Chihoski 1972,1979; Zacharia 1993,1994 and Shibahara 2001].

3. Experimental setup

Two experimental setups depicted in Fig. 4 and Fig. 5 were realized. The first setup (Fig. 4) was used for flat sheet welding, whereas the second setup (Fig. 5) was used for cup welding.

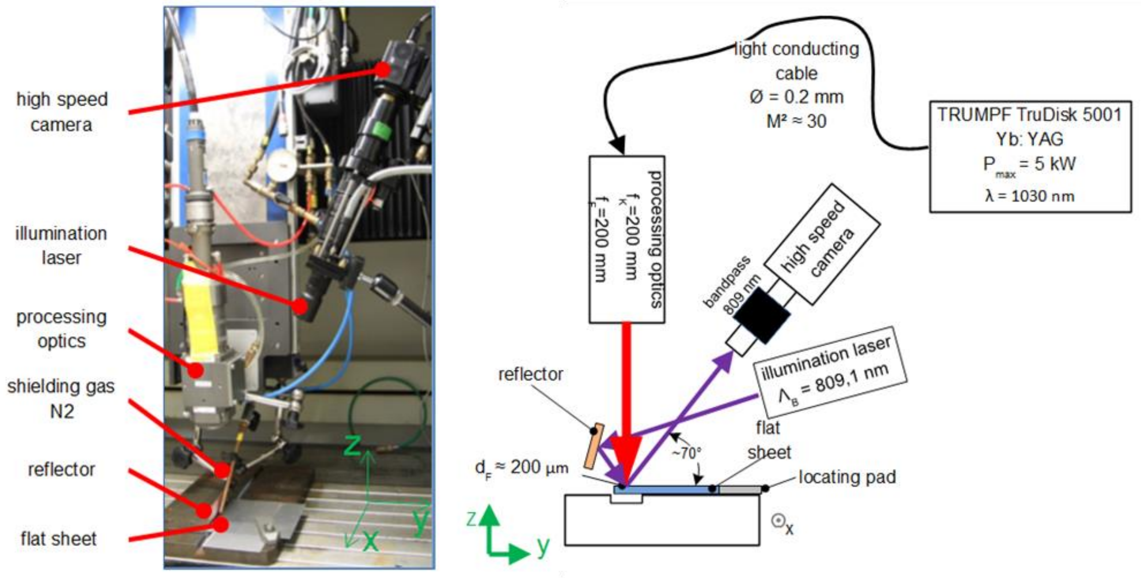

Fig. 4. Experimental setup for flat sheet welding experiments.

As shown in Fig. 4 the flat sheet welding experiments were performed with steady laser focus position, while the sample is laterally moved by a linear axis underneath the laser optics. The locating pad in y-direction was utilized for sample positioning, whereby the edge distance of the welding process could be varied.

For welding tangential seams in close edge position in the formed aluminum cups a second experimental setup according to Fig. 5 has been realized.

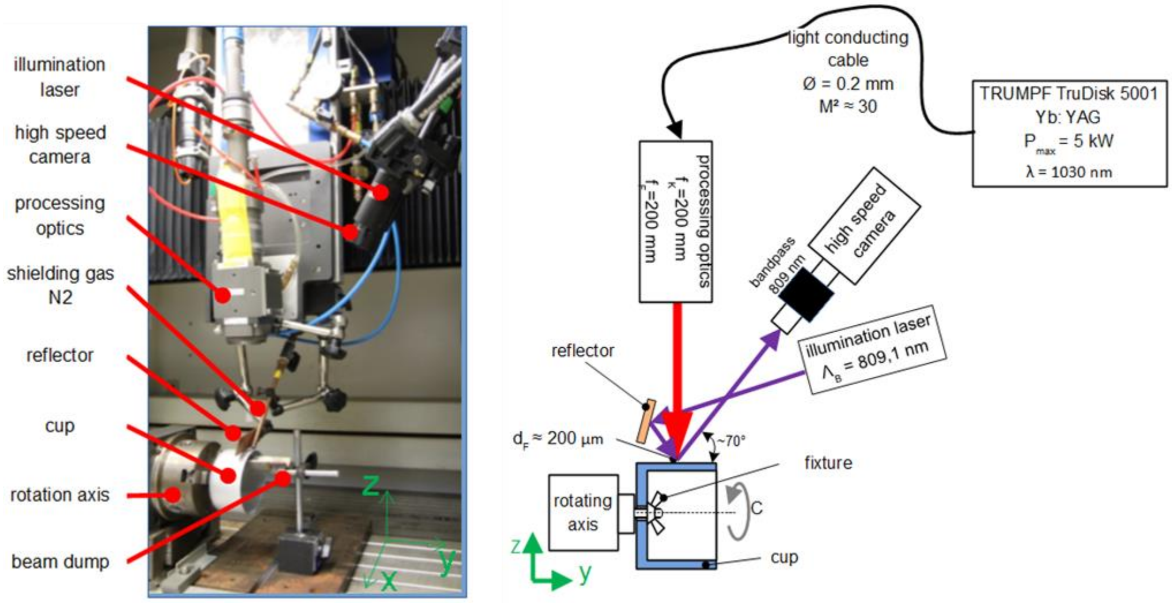

Fig. 5. Experimental setup for cup welding experiments.

The formed cups were rotated underneath the processing head during the welding process of the tangential welds.

Both welding processes were observed with a high-speed camera, utilizing an 809 nm laser for illumination and filtering this wavelength for the observations. Nitrogen (N_2) was used as shielding gas to prevent the weld from oxidation and increase the visibility of cracked weld surfaces. The laser optics was inclined to avoid damage caused by back reflected light.

The parameters used for laser welding were:

- a laser power of 1 kW,
- a fiber core diameter of 200 µm,
- a focal spot diameter of 200 µm,
- a feed rate of 3 m/min,
- the material: 6080 AlMgSi aluminum alloy,
- with a sheet thickness of 1 mm,
- N_2 as shielding gas,
- and the focal position: 0 mm relative to the sample surface.

4. Results and Discussion

4.1. Hot cracks during flat sheet welding

As a reference, the welding process was performed on the flat sheet according to the experimental setup depicted in Fig. 4. Varying the edge distance and measuring the average crack length, the bars in Fig. 6 are obtained. They show a high crack susceptibility at 2 and 3 mm edge distance.

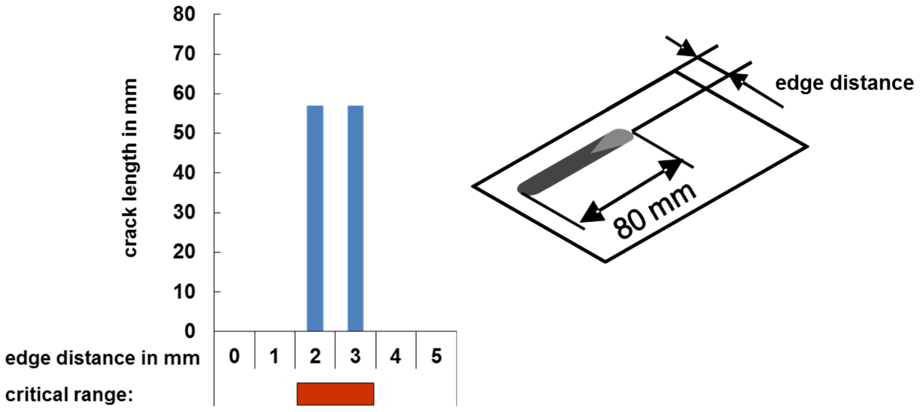

Fig. 6. Resultant crack length retrieved from close edge laser welding experiments of flat sheets.

4.2. Residual stresses in the formed cup

The residual stresses in the formed cup were determined by modelling the forming process [Hagenlocher 2015]. The Solutions has been verified by experimental measurements, using the, method of splitting the cups in rings and tongues, as suggested by Siebel [Siebel 1954] which allows to derive the local intensity of stresses. In Fig. 7 the axial bending stresses $\sigma_{b,axial}$ in the cup, being perpendicular to the tangential welding direction, are shown according to the position relative to the cup base.

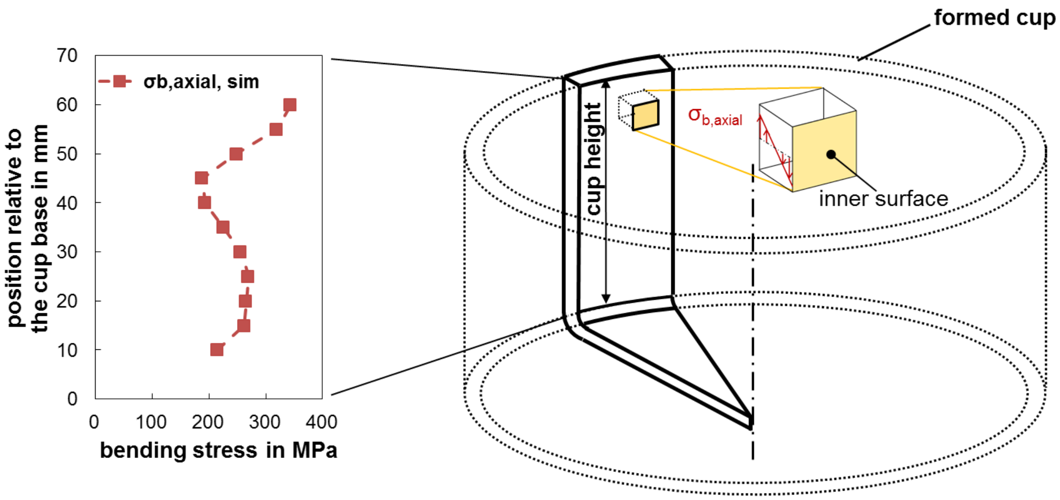

Fig. 7. Resultant axial bending stresses in dependence of cup height.

As can be seen the local bending stress varies depending on the position relative to the cup base. Thereby after laser cutting the cup to a certain height, the close edge welding process is exposed to different sizes of bending stresses.

4.3. Comparison of flat sheet welding and formed cup welding

At 3 mm edge distance both, the flat sheets and the formed cups were welded with the welding parameters named in in section 3. An image of the welding process of flat sheet (a) and a formed cup (b) is shown in Fig. 8.

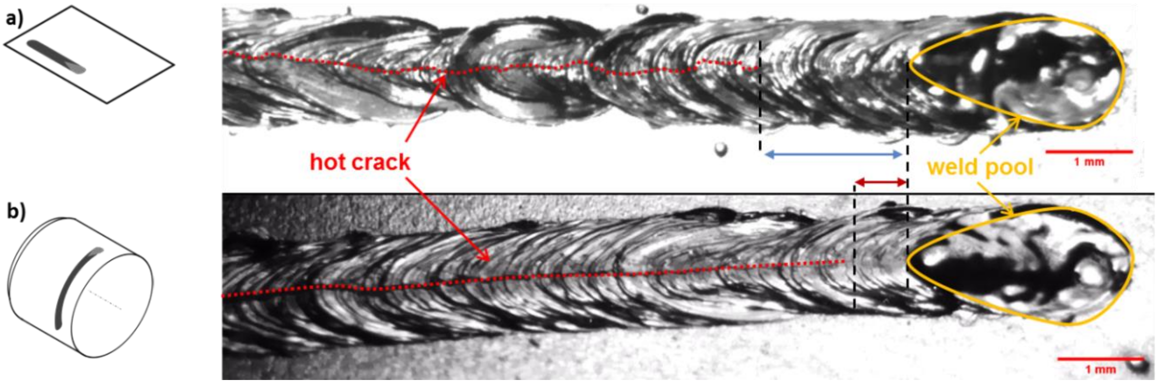

Fig. 8. (a) Image of a high speed sequence of flat sheet welding with the hot crack marked as dashed red line. The blue arrow defines the distance of crack visibility and weld pool end. (b) Image of a high speed sequence of formed cup welding with the hot crack marked in as dashed red line. The red arrow defines the distance of crack visibility and weld pool end.

The two shown welding processes show centerline hot cracking. One difference, which can be noticed, is the position of crack formation. In Fig. 8 (a), the flat sheet welding, the crack initiation occurs further behind the visible weld pool than in Fig. 8 (b). This behavior is exposed more obvious, when showing the distance of crack initiation as bars, like in Fig. 9.

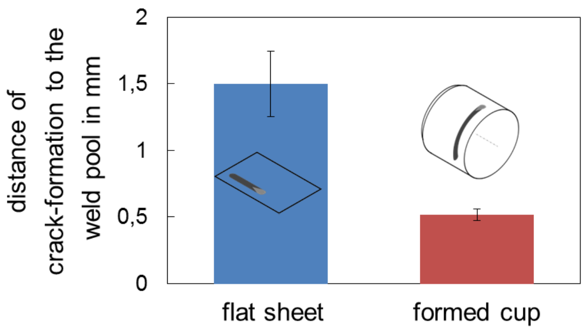

Fig. 9. Distance of crack-formation to the end of the weld pool during flat sheet welding (blue) and cup welding (red).

The distance of crack initiation to the weld pool end in flat sheet welding is almost three times higher than the distance of crack initiation in the welding process of the formed cup. This is an indication, that the formation of hot cracks must be influenced when welding the deep drawn cups.

Further, to compare the two welding situations the edge distance was increased to 4 mm. The ratio of crack length to weld length has been calculated to evaluate the hot crack susceptibility. The retrieved ratios are depicted in Fig. 10.

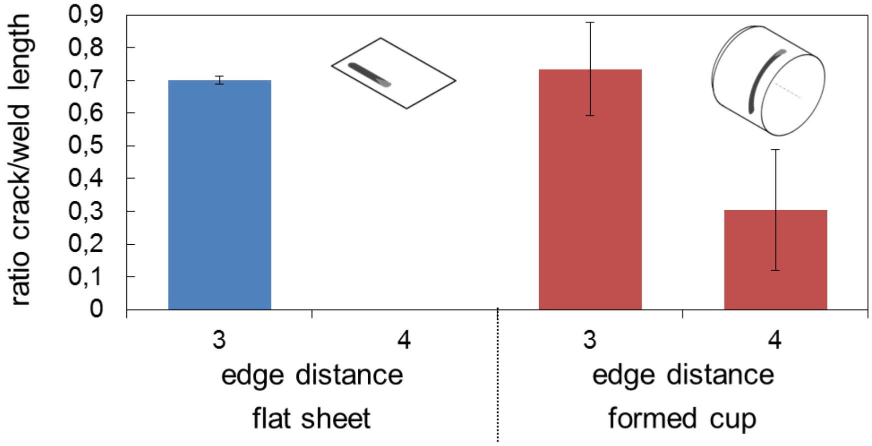

Fig. 10. Ratio of crack length to weld length for flat sheet welding (blue) and formed cup welding (red), at edge distances of 3 and 4 mm.

It can be derived from the depicted results, that the critical edge distance has increased in case of the cup welding from 3 to 4 mm compared to flat sheet welding. This indicates that the additional bending stresses in the formed cup increase hot crack susceptibility.

To investigate whether the actual size of the bending stresses influences the hot cracking susceptibility, the tangential welds of the cups at certain edge distance and cup height position where performed after laser cutting the cup to the desired height. Thus, the size of the bending stresses is experimentally varied according to Fig. 11. At different positions relative to the cup base the definite bending stress values according to Fig. 6 and Fig. 11 are obtained.

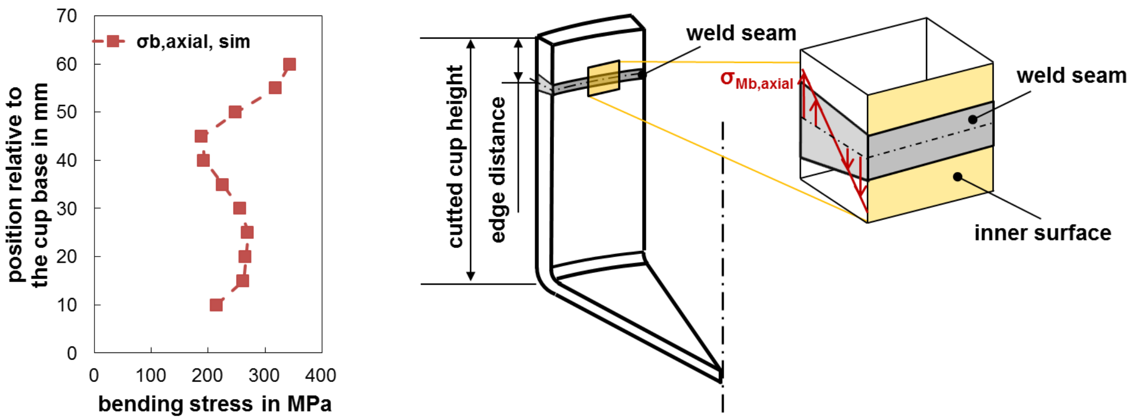

Fig. 11. Resultant axial bending stresses in dependence of cup height and the positioning of the tangential laser welds.

When varying the cup height, as described above, and welding at a defined edge distance of 4 mm, the resultant ratio of crack length to weld length is shown over the size of the bending stresses in Fig. 12.

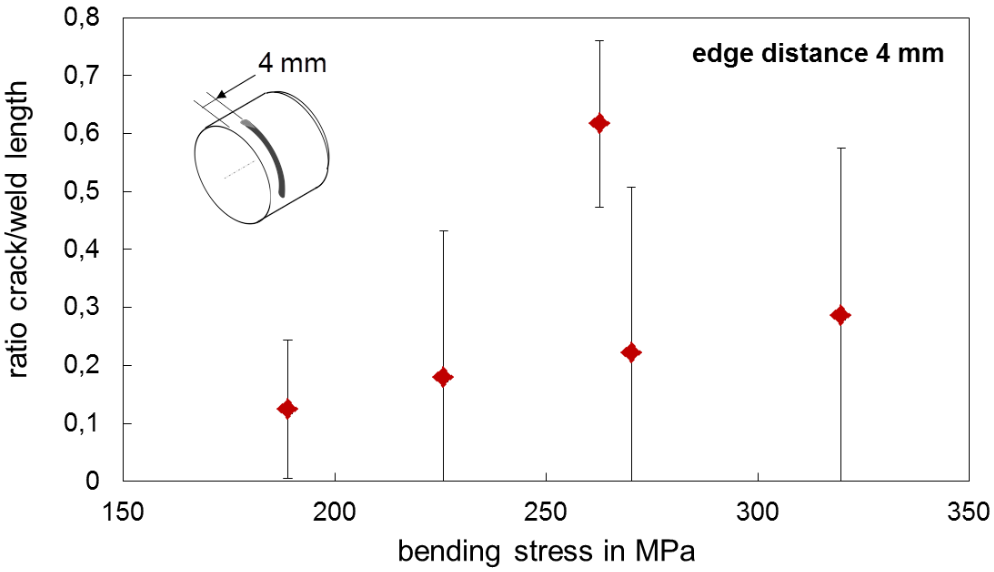

Fig. 12. The ratio of crack length to weld length over the local bending stress, retrieved when welding at different cup height at 4 mm edge distance.

The repetition of the experiments three times leads to the variance in Fig. 12. From these results no clear proof of the correlation of crack susceptibility, being defined by the ratio of crack length to weld length, with the bending stresses can be given. However, the trend of increasing crack susceptibility with increasing bending stresses can be seen.

5. Conclusion

It could be shown that residual bending stresses, perpendicular to the welding direction, influence the hot cracking behavior in close edge laser welding of 6000 series aluminum. This can be derived from the observed shift of the crack initiation towards the weld pool end when welding formed cups compared to flat stress free sheets. Further, the flat sheet welding experiments without any residual stress showed a critical edge distance of 3 mm, whereas for welding the formed cup the critical edge distance increases to 4 mm. The influence of residual stresses on the hot crack phenomena in welding supports the theories of stress based hot cracking. Therefore earlier preceding process steps like forming have to be considered for further investigation on the hot cracking susceptibility. This will improve the inherent cross-process knowledge.

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