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Influence of the forming pre-strain on the fatigue performance of upset bulge formed tubes

BECHLER Jan[1,a *], WEBER Florian[1,b], BULZAKOVSKI Tose[2,c],
VÖLLMECKE Jörg[2,d], SULAIMAN Hosen[2,e] and TEKKAYA A. Erman[1,f]

[1]Institute of Forming Technology and Lightweight Components, TU Dortmund University,
Baroper Str. 303, Dortmund 44227, Germany

[2]Faurecia Autositze GmbH, Garbsener Landstraße 7, Hannover 30419, Germany

[a]Jan.Bechler@iul.tu-dortmund.de, [b]Florian.Weber@iul.tu-dortmund.de,
[c]Tose.Buzalkovski@forvia.com, [d]Joerg.Voellmecke@forvia.com,
[e]Hosen.Sulaiman-dr@forvia.com, [f]Erman.Tekkaya@iul.tu-dortmund.de

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Abstract. Safety-relevant components in the automotive industry must fulfill stringent requirements for performance, particularly in endurance. The height adjustment system in a car seat is one example. The height adjustment system is made up of sheet metal parts which are joined with steel tubes through axial compression – also referred to as upset bulge forming. As a result of the forming process, initial cracks occur at the inner bending radius of the tubes which, along with the forming history, decrease the fatigue life by 450%. The aim of this study is to identify whether the initial cracks occur due to shear bending generated by the process or elastic springback. The influence of the elastic springback on the crack initiation is investigated through bending experiments of DP600, Al99.5, and 1.4301. To prevent elastic springback, the specimens are secured with screws post-bending and are removed afterwards. The bending radius is investigated with respect to the equivalent plastic strain to determine a minimum without failure. Cyclic tests of bulges with two different forming histories are tested to investigate the influence of the forming pre-strain on the fatigue behavior. In all bent materials, initial cracks occur at the inner bending radius where the elastic springback increases the initial cracks and Scanning Electron Microscopy (SEM) analysis confirms shearing as the cause. It was also found the grain shape and orientation have a significant influence on the crack propagation in the forming zone of the tube through the upset bulging process.

Introduction

The automotive industry is under constant pressure to increase performance, while decreasing the weight and cost of components. One of the most applied methods to achieve the objective is to use high-strength steels. In order to reduce the cost and to maintain the performance of the product, forming instead of welding processes are used in the assembly. Forming processes avoid the degradation of the assembly performance, which is often the case in welding due to the process temperatures when joining dissimilar materials. For safety-relevant components, it is especially important to ensure the performance over the entire lifetime of the vehicle. The height adjustment system is one example of a formed, safety-relevant component where it is made up of sheet metal parts which are joined with a tube. A bulge is formed in a first step by axial compression. The part is then placed onto the bulge and a second bulge is formed, finally joining both tube and sheet metal part (Fig. 1 a)).

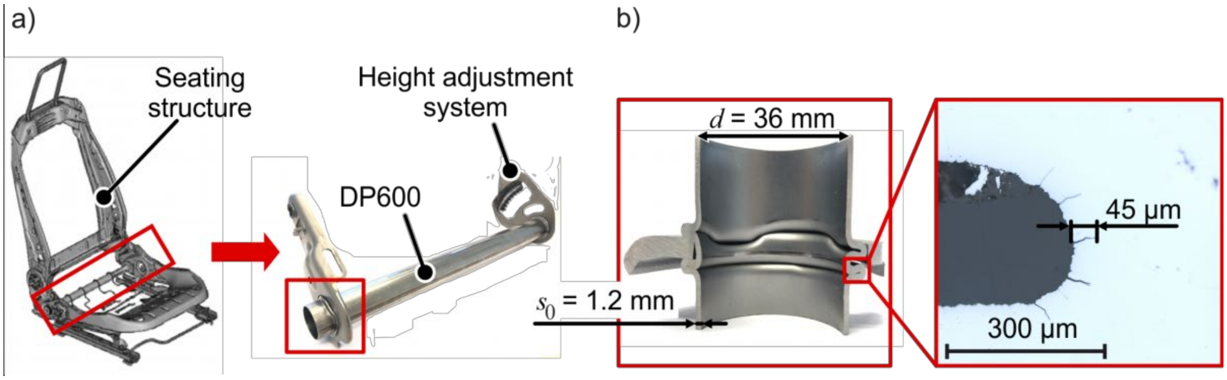

Fig. 1 a) Height adjustment system and b) The resulting initial cracks due to forming.

Investigations of the process limits showed that initial cracks occurred at the inner bending radius [1] (Fig. 1 b)). Furthermore, the initial crack length increased with further axial compression of the tube. It was presumed the elastic springback was the root cause of the initial cracks. The analysis of the microstructure showed that the initial cracks occurred mostly at the grain boundaries. Therefore, [2] concluded that the cracks initiated by shear bands and that the elastic springback supported the crack initiation. The development of shear bands for sheets was numerically analyzed for pure bending [3]. For this, periodic imperfections were implemented at the surface of the outer and inner bending radius. The surface imperfections led to undulations both at the tensile and compression sides of the sheet. The shear bands developed at the point of strain concentrations due to the undulations. Triantafyllidis et al. [3] suggested that notch-like protuberances on the compressive side of the sheet served as a failure initiation. In impact compression tests of aluminum tubes, similar initial cracks occurred compared to the upset bulge-forming process [4]. Microscopic analysis revealed that the bending led to undulations, which led into folds and sharp discontinuities with further bending. The bending load reversal led to failure due to the sharp clefts and creases. Haley and Kyriakides [4] suggested that even unloading due to elastic springback caused the local fracture. Furthermore, the numerical implementation of the surface roughness in the compression test caused undulations and finally high equivalent plastic strains occurred at the inner bending radius in the area of initial cracks.

The forming at elevated temperatures of 700 °C prevented the formation of initial cracks at the inner bending radius in upset bulging [5]. For this, the tube was inductively heated and subsequently formed. Microscopy analysis of the bulge cross-section showed that for 500 °C little and for 600 °C and 700 °C no initial cracks occurred. The fatigue lifetime of the hot formed bulge was 450% higher compared to the formed bulge at room temperature in a subsequent cyclic tensile test in axial direction.

From the literature, a possible root cause may exists where local instabilities cause undulations and can lead to cracks where the elastic springback may support the crack initiation. However, until now it is not clear whether the elastic springback or the shear bands cause the initial cracks. Furthermore, the initial cracks and the forming history have an influence on the fatigue life, but their interaction is unknown. Therefore, the main objectives of this paper are to analyze whether the cracks occur due to shear fracture or due to the elastic springback and how the microstructure affects the fatigue life. At first, cyclic tests were interrupted to analyze the crack propagation. The fracture surface was investigated by SEM to link the crack propagation to the microstructure. Secondly, bending experiments and microscopic analysis with DP600, Al99.5, and 1.4301 sheet materials were performed to investigate the influence of elastic springback on the initiation of cracks. To prevent elastic springback, the specimens were secured with fasteners post-bending.

Influence of the forming pre-strain on the fatigue behavior

The height adjustment system comprises of a tube material of DP600 and two sheet metal parts with comparable material properties, where one of the sheets has a gearing to adjust the height. The interlocking of the bulge into notches of the sheet allows the transmission of torque (Fig. 1 a)). The tubes were manufactured by cold rolling of sheet material. The yield strength of the tube was determined by a tensile test with an A_{80} specimen, lasered from the tube [6]. The outer diameter of the tube was $d_a = 36$ mm, the total length was l = 460 mm and the tube was thickness s_0 = 1.2 mm. The flow curve of the sheet material was derived from an A_{80} tensile specimen of the material DP600 from a different batch with an initial sheet thickness of s_0 = 1.5 mm for the comparison of the flow curves. Since the manufacturing of the tube was a bending operation the equivalent plastic strain was calculated by Eq. 2. Here, y is the half of the initial sheet thickness and the bending radius r_m is the half of the initial diameter of the tube. Shifting the tube's flow curve by the equivalent plastic strain of $\bar{\varepsilon} = 0.039$, caused by the bending operation, shows a sufficient agreement with the flow curve of the sheet material (Fig. 2). Therefore, for future analysis the forming history of the tube must be taken into account.

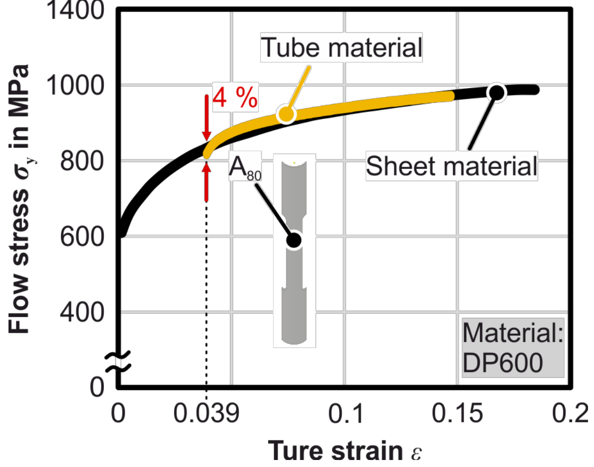

Fig. 2 Flow curve of the DP600 tube and sheet material.

The microscopic analysis of a representative bulge of the height adjustment system reveals initial cracks with a length of 45 µm (Fig. 1 b)). Due to the complexity of the bulging process of the height adjustment system, single formed bulges were analyzed microscopically and cyclically. Two different formed bulges were examined to investigate the influence of forming pre-strain. One bulge was opened and therefore had lower forming pre-strain at the inner bending radius of $\bar{\varepsilon}_{\mathrm{Exp.}}$ = 1.19 and the other one was closed and therefore had higher pre-strain $\bar{\varepsilon}_{\mathrm{Exp.}}$ = 1.25 (see Eq. 1). The high pre-strain at the inner bending radius occurs due to the compressive stress state during upset bulge forming, which postpones the onset of failure. Cracks at the inner bending radius indicate the surpassing of the materials compressive fracture limit in this area rather than its respective tensile limit at the outer radius. The crack lengths were measured by analyzing three formed bulges at three positions 120° shifted around the circumference and averaged. The sheet thickness was examined to verify an orthogonal cut and no oblique measure of the crack length. The opened bulge has a crack length of 24 µm (Fig. 3). This length increases by a factor of 2.8 up to 67 µm for the closed bulge. Higher axial compression of the tubes leads to an increase in crack length, confirming the results from [1]. Furthermore, the initial crack length of the height adjustment system lies in the range of the single formed bulges, which justifies the simplification to a single formed bulge.

The cyclic experiments were performed in a servo-hydraulic testing machine from Walter + Bai AG LFV-100-HH. The clamping jaws were designed to hold the tube material with mandrels. The fatigue tests were conducted with a load of 10 kN and a frequency of 10 Hz. The fatigue lifetime was averaged over three samples.

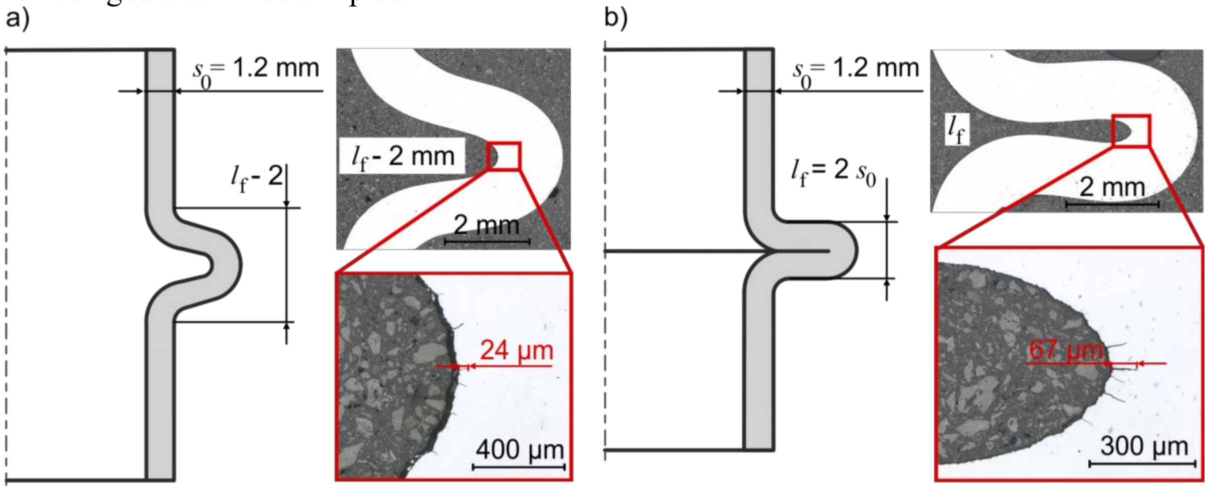

Fig. 3 Influence of the pre-strain in the simplified bulge geometry for the a) Opened and b) Closed configuration.

The fatigue life of the closed bulge is 742 cycles and for the opened bulge is 4092 cycles (Fig. 4 a)). The forming pre-strain decreases the fatigue life for the different bulges by a factor of 5.52. This confirms the influence of the forming history [1]. Because of the difference in the initial crack length, which differs by a factor of 2.8, the question arises if differences in crack length cause the discrepancy. Therefore, the development of the crack length was analyzed by interrupted cyclic tests. The tests were interrupted at 2.5%, 7.5%, 20%, 50%, 80%, and 95% of the fatigue life for each single formed bulge. For the closed bulge, the initial crack length was 67 µm. Under the cyclic load, this length increases rapidly after 18 cycles to 278 µm (Fig. 4 b)). After the increase in length, the crack propagation stabilizes until the remaining cross section is too small to bear the load and forces rupture. In contrast, in the opened bulge, the crack propagation is stable until the forced rupture appears. Furthermore, the slope in the region of the stable crack propagation is higher for the closed than for the opened bulge which indicates that besides the instantaneous increase in crack length, the crack propagates faster in the closed bulge.

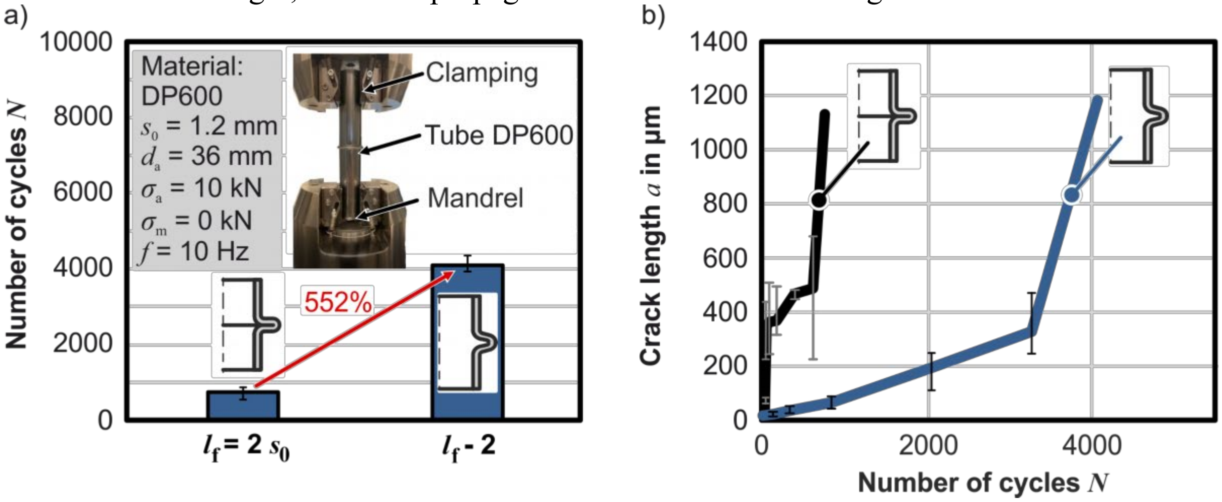

Fig. 4 a) Fatigue lifetime of the opened and closed bulge and b) The difference in crack propagation

The difference in the crack propagation was investigated by SEM of the fracture surface after failure. At the inner bending radius, both bulges show shear fracture (Fig. 5). The results show that the initial crack initiate due to shear fracture at the inner bending radii. In radial direction from the inner radius, the closed bulge shows shear fracture directly followed by trans- and intergranular fracture. At the outer bending radius a ductile fracture surface with cup and cone occurs. According to Atkins [7] the lack of remaining ductility caused the brittle failure in terms of trans- and intergranular failure. In contrast to this, the opened bulge shows the shear and the ductile fracture surfaces in the same order without brittle failure. Therefore, the difference in the fatigue lifetime was caused by the different fracture modes which is influenced by the forming pre-strain.

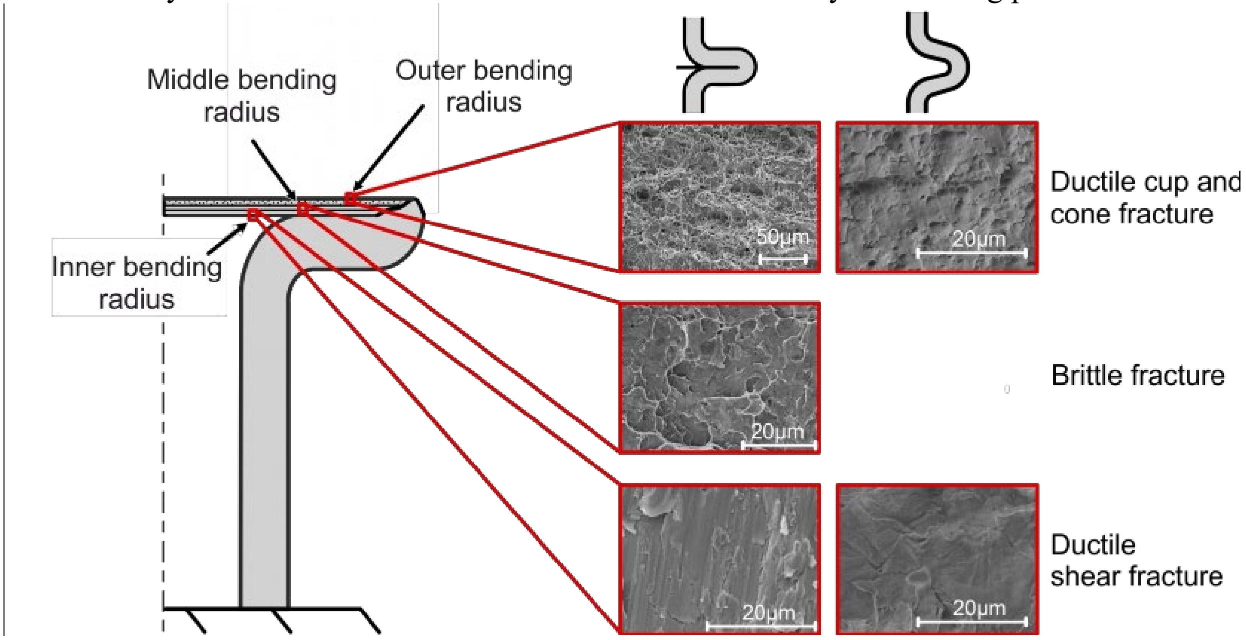

Fig. 5 Fracture surface analysis of the opened and closed bulge after the fatigue test

The influence of the microstructure on the fracture mode was further analyzed by microscopic investigations and the results are schematically depicted in Fig. 6 a). The results of the microscopic investigations can be seen in Fig. 6 b). The grains are elongated at the inner bending radius orthogonal to the surface due to the compressive state. The grains become more globular towards the inner of the bulge and elongated at the outer bending radius due to the tensile stress state. At the inner bending radius, the grains are more elongated in the closed bulge compared to the open bulge because of the higher compressive stress state. Higher grain elongation is equivalent to higher forming pre-strains. Therefore, the remaining ductility of the material of the closed bulge is lower than of the open bulge. Microscopic analysis of the grain size distribution of the closed bulge interrupted at 95% (704 cycles) of the overall fatigue life for the closed bulge, show a less tortuous fracture path at the inner bending radius and the path becomes more tortuous towards the inner of the bulge (Fig. 6 b)). At the inner bending radius, the crack grows uniformly in the radial direction and becomes more tortuous in the area where the grains are more globular.

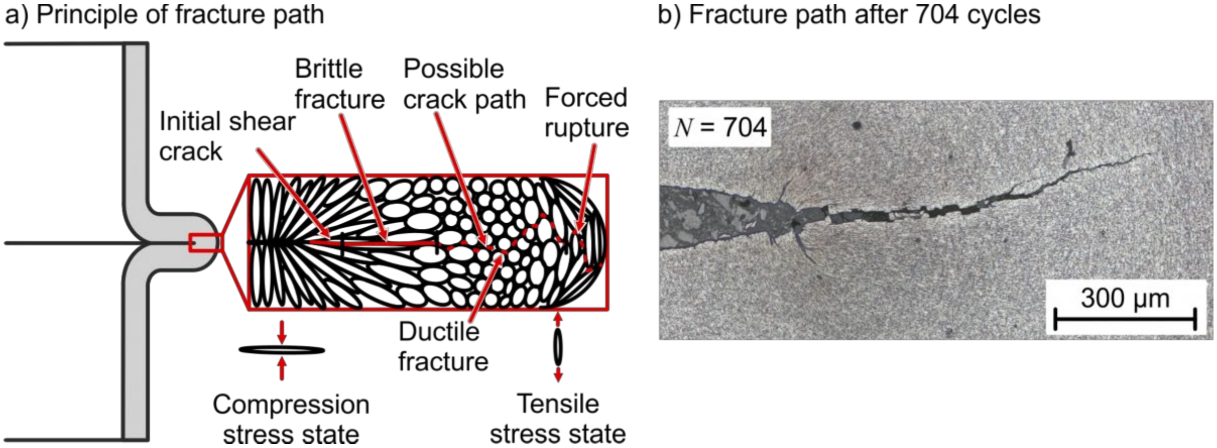

Fig. 6 a) Basic principle of the fracture path in upset bulge formed tubes and b) Microscopic image of the fracture path.

Influence of the springback onto the crack initiation

To investigate the influence of elastic springback on the initiation of cracks, sheets were bent and fastened by a screw as shown in Fig. 7. The sheet specimens had the length l = 100 mm, width b = 40 mm and thickness s_0 = 1.5 mm. The materials were high strength steels DP600, pure AL99.5 and austenitic stainless steel 1.4301. Subsequentially, the specimens were cut open near the screw and analyzed microscopically. This methodology allowed the comparison of the same crack in the fastened and unfastened configuration.

All materials show initial cracks in the fastened configuration at the inner bending radius (Fig. 7 b)). The aluminum has a crack with 131 µm in length, the DP600 with 97 µm and the 1.4301 with 45 µm. SEM analysis of the fracture surfaces confirm shear fracture as the cause for the initial cracks (Fig. 7 c)).

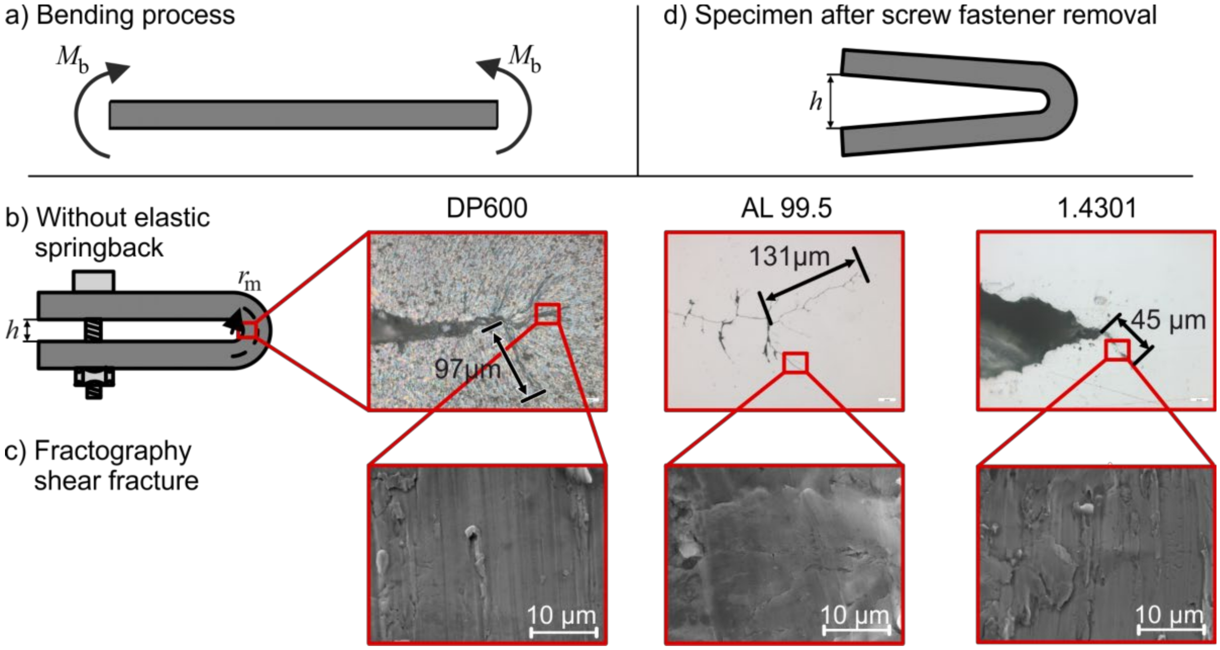

Fig. 7 a) Bending of the specimen, b) The initial crack in the fastened configuration without elastic springback, b) The SEM analysis of the resulting shear fracture surface and d) The increase in gap height after the elastic springback.

The influence of the elastic springback on the crack length was analyzed. For this, five bending specimens of the material DP600 with different forming pre-strain were examined with respect to initial cracks. The different forming pre-strains were determined by different bending radii. The bending radii ranged from completely closed r_m = 0.75 mm to opened r_m = 2.14 mm. The elastic springback was quantified by measuring the height at the end of the specimen (Fig.7 d)). The height of the bent specimen increases by 1% – 4%, which is a change of a thousandth millimeter, from the fastened to the unfastened configuration due to the elastic springback (Fig. 8a)). Furthermore, the crack length increases for the majority of the specimens from the fastened to the unfastened configuration. The growth in crack length varies from 10% to over 100% increase, which is a change of a hundredth of a millimeter (Fig. 8b)). Only one specimen does not show an increase in crack length. One explanation could be the increase of a crack further into the material, which was not visible. However, even small elastic springback can cause a severe increase in crack length.

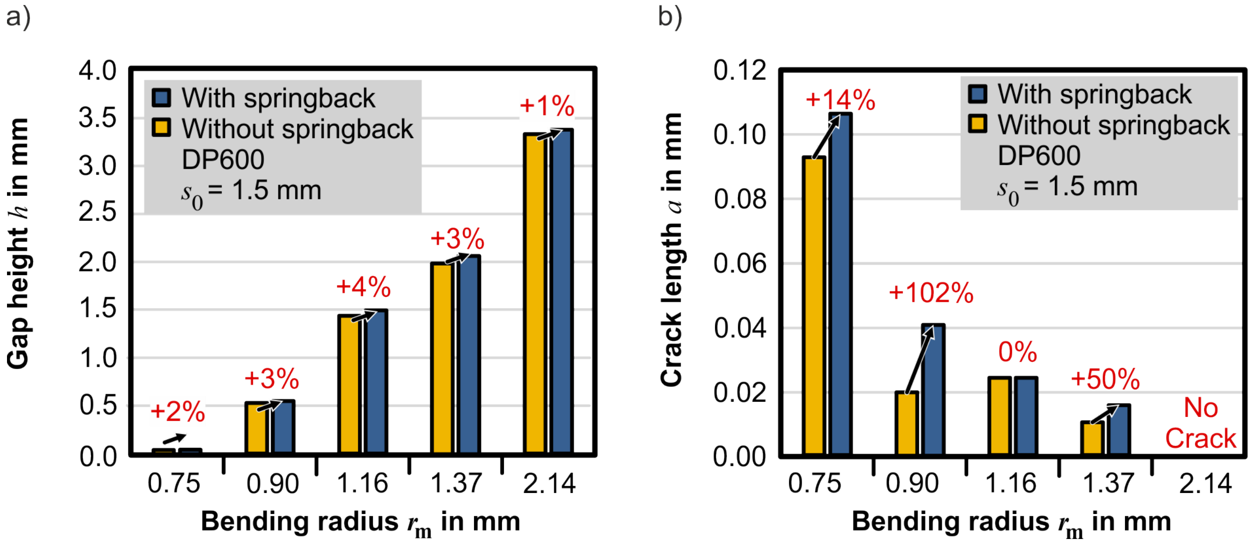

Fig. 8 Influence of the elastic springback a) On the gap height and b) On the crack length.

Prediction of initial crack for bending specimens

The highest bending radius of r_m = 2.14 mm showed no initial cracks whereby the next smallest bending radius of r_m = 1.37 mm had initial cracks. Therefore, a limit of the smallest bending radius between r_m = 2.14 mm and r_m = 1.37 mm must exist where no initial crack occur. For this, the experimental equivalent plastic strain $\bar{\varepsilon}$ was calculated from the bending samples by the change of grain size

$$\bar{\varepsilon}_{\text{Exp.}}=\sqrt{\frac{2}{3}\left(\ln\left(\frac{d_1}{d_0}\right)^2+\ln\left(\frac{d_2}{d_0}\right)^2+\ln\left(\frac{w_1}{w_0}\right)^2\right)}, \tag{1}$$

whereby d_0 is the initial diameter, d_1 is the changed length and d_2 the changed width of the grain. The change in width w direction of the sheet is calculated by the volume constancy.

Additional bending specimens were analyzed and the equivalent plastic strain $\bar{\varepsilon}$ was plotted over the bending radius r_m normalized by the initial sheet thickness s_0 (Fig. 9 b)). The equivalent plastic strain $\bar{\varepsilon}$ increases for smaller and decreases for higher bending radii r_m. Specimens with initial cracks are marked with a red cross. The bending experiments do not show a clear limit at which strain initial cracks occur. Therefore, the shear strain γ from shear test is evaluated by the so-called time-dependent method to determine the equivalent plastic strain $\bar{\varepsilon}$ – normally used to determine the forming limit curve of sheet metal components [8] (Fig. 9 a)). The shear strain γ and the equivalent plastic strain $\bar{\varepsilon}$ were evaluated over time. The shear strain γ value increases over time and at the onset of failure γ accelerates. The onset was determined by fitting a first linear line

L_1 in the region of homogeneous deformation. The second linear line L_2 was fitted from the last two recorded points [8]. The intersection of the L_1 and L_2 determined the onset of shear failure and the equivalent plastic strain was evaluated by the onset of shear failure. The shear test determines a failure limit of $\bar{\varepsilon}_{\mathrm{SL}} = 0.78$. The $\bar{\varepsilon}_{\mathrm{SL}}$ determines the failure strain between the specimen of $r_{\mathrm{m}} = 2.14$ mm ($\bar{\varepsilon}_{\mathrm{Exp.}} = 0.65$) and $r_{\mathrm{m}} = 1.37$ mm ($\bar{\varepsilon}_{\mathrm{Exp.}} = 0.84$) and is therefore in good agreement. Furthermore, the closed $\bar{\varepsilon}_{\mathrm{Exp.}} = 1.25$ and opened $\bar{\varepsilon}_{\mathrm{Exp.}} = 1.19$ bulge lie above the determined shear limit.

However, the determination of the equivalent plastic strain $\bar{\varepsilon}_{\mathrm{Exp.}}$ from the change of grain size for many bending experiments is time and cost consuming. The equivalent plastic strain $\bar{\varepsilon}$ for bending experiments can also be analytically determined at the inner bending radius

$$\bar{\varepsilon}_{\mathrm{A.}} = \frac{2}{\sqrt{3}} \left| \ln\left(1 + \frac{y}{r_m}\right) \right|, \tag{2}$$

whereby y is the half of the initial sheet thickness starting from the neutral fiber of the bending radius. It is assumed that the neutral fiber does not shift. The analytical method is valid as long as pure bending moments are applied and the sheet thickness does not change. However, for small bending radii, shearing causes initial cracks and which alters the sheet thickness.

The equivalent plastic strain $\bar{\varepsilon}$ was evaluated at the inner bending radius since the initial cracks occur there. The $\bar{\varepsilon}_{\mathrm{A.}}$ overestimates the experiments for small bending radii due to the violation of the previously named assumptions. For larger bending radii the analytically and experimentally determined $\bar{\varepsilon}_{\mathrm{A.}}$ are in good agreement with $\bar{\varepsilon}_{\mathrm{Exp.}}$. The intersection of the analytical determined $\bar{\varepsilon}_{\mathrm{A.}}$ and the shear limit $\bar{\varepsilon}_{\mathrm{SL}}$ determine a conservative lower limit of r_{m} to which specimen can be bend without initial cracks at the inner bending radius.

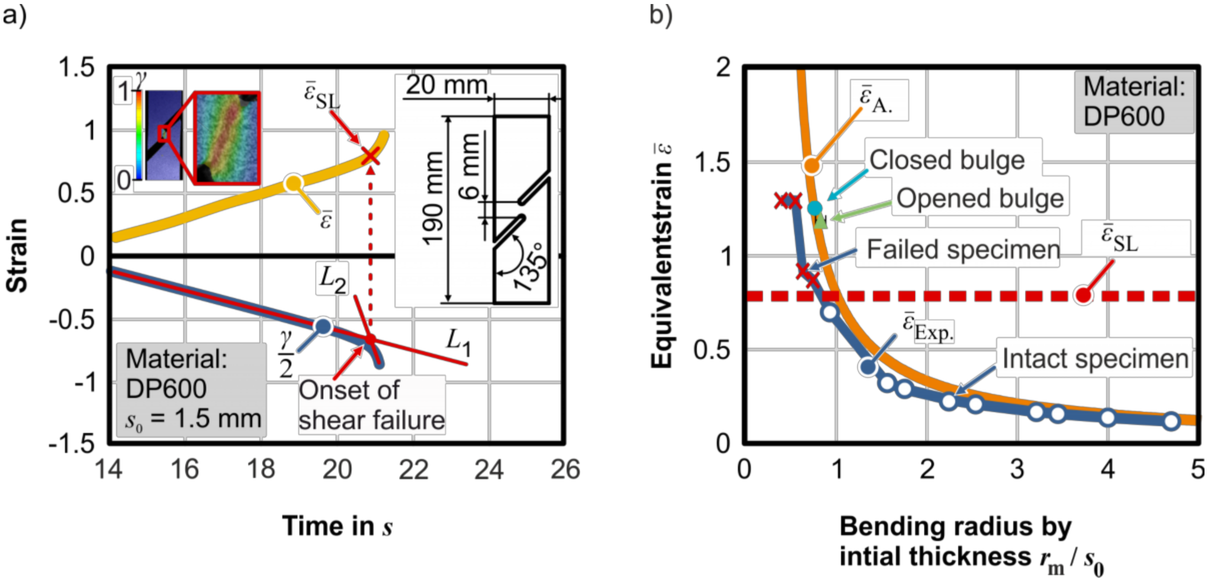

Fig. 9 a) Evaluation of the shear strains to determine the equivalent strain and b) Equivalent strain over bending radius evaluated at the inner bending radius

Summary and Conclusions

The aim of this study was to investigate the root cause of initial cracks at the inner bending radius and the influences of the forming history on the fatigue life of upset bulged tubes. For this, a closed bulge with higher forming pre-strain and an open bulge with lower forming pre-strain were investigated. The closed bulge had higher elongated grains than the opened bulge. The closed bulge had a decreased fatigue life by the factor of 5.52 compared to the opened bulge. From the results of the interrupted cyclic tests, in combination with the microscopic analysis, it can be said the grain size distribution in the form of highly elongated grains, in combination with a decreased ductility due to the forming pre-strain both enhance the susceptibility of brittle failure. Therefore, the bulge with the higher forming pre-strain is more susceptible to brittle failure, which decreases the fatigue lifetime.

The fastened bending experiments in combination with SEM analysis of the fracture surface proved shearing as the cause for the initial cracks at the inner bending radius. Furthermore, the elastic springback did not cause, but supported the initial crack length. Additionally, a conservative lower boundary of bending radius was determined by the comparison of analytically bending strain and the limit strain of the shear tests.

Future analysis will focus on the numerical prediction of the initial cracks in upset bulge forming or bending processes. Furthermore, attempts could be made to predict the complex fatigue behavior of upset bulge formed tubes.

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