Fatigue Properties and Analysis of Fracture Surface and Crack Path of Ultrafine-Grained Structures produced by Severe Plastic Deformation

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ABSTRACT

In the recent years several manufacturing processes that introduce severe plastic deformation in materials were developed. Among these methods linear flow splitting allows bifurcation of thin metal sheets at ambient temperature due to high hydrostatic pressures. The flanges produced by this process present an ultrafine-grained microstructure on the surface and a steep property gradient along the thickness. These flanges show a significantly higher yield stress in comparison to the as-received material state. Their application to lightweight structures exposed to fatigue loading requires the material characterisation also in terms of cyclic behaviour and fatigue properties.

For safety reasons, a better understanding of the mechanisms of crack initiation and crack propagation through this gradient is important, considering in particular the ultrafine-grained structures. In this paper, results of axial tests from the as-received material (H480LA) and the flange material with UFG microstructure are presented. Notched specimens (Kₖ=2.3) were loaded with constant amplitudes (loading axis perpendicular to the micro structural gradient) and with overloads. The stress-life curves show in the case of notched specimens an increase of stress amplitude at the knee point of ca. 25-30% at the flanges in comparison to the as-received material state. The metallographic structure and the fracture surface are investigated by SEM. These investigations reveal significant differences in the orientation of the crack plane in the flange and the as-received material state.
INTRODUCTION

The steadily increasing costs of raw materials and energy and the increasing quality required in industrial products lead to the research at new manufacturing processes that allow reduction of costs and at the same time the improvement of mechanical properties and stiffness. An effective way for increasing stiffness and strength is the realization of bifurcated structures. The application of this tactic allows a drastic reduction of weight and of material employment retaining at the same time the desired mechanical properties. A recently developed Severe Plastic Deformation process (SPD) to produce bifurcated profiles is the Linear Flow Splitting (LFS). This process allows the generation of stringers in integral style at ambient temperature. Thereby, the splitting roll engages incrementally \( \Delta y_{inc} \) into the band edge of a plain metal sheet, which is stabilized by two supporting rolls, and generates flanges in integral style up to the final profile geometry with the total splitting depth \( y_{tot} \) (Fig.1) [1].

![Fig. 1: linear flow splitting: process principle](image)

Such bifurcated profiles can be used as structural parts in several applications, for example to increase the stiffness of bodyworks and in the realization of linear guide rails. All these components can be strongly loaded during service, and for this reason the analysis of the mechanical behaviour of the material also with respect to fatigue is of fundamental importance.

Due to the massive deformation, an ultrafine-grained (UFG)-microstructure develops in the process zone. Thus an UFG-surface layer of several hundred microns thickness is created in the flanges (Fig. 2). The UFG microstructure exhibit a pancake like grain shape parallel to the flange surface with maximum grain dimension parallel to the \( z \)-axis and minimum grain dimension parallel to the \( y \)-axis.

![Fig. 2: Flange of the profile with UFG-surface layer](image)
With increasing distance to the flange surface, the microstructure becomes coarser and changes into a classically strain-hardened microstructure. Thus, a gradient in microstructure exists through the flange thickness. Despite this gradient, the flanges exhibit the typical mechanical properties of UFG-microstructures. In comparison to the as-received metal sheet, material H480LA, the strength is nearly doubled, but is accompanied by a decrease in engineering fracture strain and a low uniform elongation $A_g$ (Table 1). The combination of stiffness and strength of these profiles increases the potential for light weight applications.

Table 1: H480LA - Mechanical characteristics of as-received and flange material state

<table>
<thead>
<tr>
<th></th>
<th>$R_{p0.2}$ [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>$A_g$ [%]</th>
<th>$A$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-received</td>
<td>619</td>
<td>667</td>
<td>5.7</td>
<td>17</td>
</tr>
<tr>
<td>Flange</td>
<td>1088</td>
<td>1114</td>
<td>0.77</td>
<td>2</td>
</tr>
</tbody>
</table>

The higher strength of the flange material is also observed in the cyclic material properties, where an increase of the cyclic yield strength $R_{p0.2}'$ of about 60% in comparison with the as-received material state is determined [3]. Despite higher fatigue strength of the UFG microstructures, e.g. higher resistance to crack initiation, they exhibit higher crack growth rates compared to their coarse grained counterparts [4, 5].

In the operative conditions overloads can be expected due to misuse as well as accidental and unexpected events. These overloads can lead to the initiation of cracks that can result in a sudden and dangerous failure of the components. Therefore, the content of this work is the investigation of cyclic behaviour in presence of overloads of the LFS profiles containing a microstructural gradient. For the analysis of crack initiation and crack path, the fracture surfaces were investigated using SEM.

**Experimental investigations**

In order to evaluate the effects of overloads in notches, single-side-notched specimens were manufactured with material taken both from flanges and from parts of the profile where the material is approximately in an as-received state (Fig. 3a). The specimen geometry is shown in Figure 3b. Dimensions are expressed in mm.

![Fig. 3: Position of the specimens from flange – black - and from the as-received state - red (left) and specimen geometry (right).](image-url)
The specimens were tested in a servo-hydraulic test rig under axial load (loading direction parallel to the x axis) under two load ratios with and without overloads. In the case of overloads, a periodic tensile overload with overload ratio \( OLR = 60\% \) was introduced. For both load ratios \( R_S = -1 \) (fully reversed loading) and \( R_S = 0 \) (pulsating loading) the overload ratio was defined according to Eq. 1 [6].

\[
OLR = \left( \frac{S_{OL} - S_a}{S_a} \right) \cdot 100
\]  

(1)

In Eq. 1, \( S_a \) denotes the maximum stress in constant amplitude loading cycles and \( S_{OL} \) the overload peak. The overload was introduced in the middle of each block of 1000 cycles, which means the first overload was applied after 500 cycles and afterwards with a pace of 1000 cycles. Representative spectra for the load ratio \( R_S = -1 \) und \( R_S = 0 \) are shown in Figures 4a and 4b respectively.

![Fig. 4: Loading spectrum with overloads by load ratio \( R_S = -1 \) (left) and \( R_S = 0 \) (right).](image)

The tests were carried out till the specimen failure, with run-out limit fixed at \( 5 \cdot 10^{6} \) cycles. The fracture surfaces were analyzed using a scanning electron microscope with an accelerating voltage of 20 kV and a working distance between 15-16 mm. The crack surface of specimens of as-received and flange material states of both tested load ratios \( R_S = -1 \) and \( R_S = 0 \) (with and without overload) are investigated.

RESULTS

Fatigue Tests

The stress-life curves derived in the fatigue tests are depicted in Figures 5 - 8 and summarised in Table 2. After the knee-point a constant slope of the Wöhler-curve \( k' = 44.9 \), correspondent to a decrease of 5\% per decade was assumed [7].
Fig. 5: Stress-life curves for as-received material state with and without overloads by load ratio $R_s = -1$.

Fig. 6: Stress-life curves for as-received material with and without overloads by load ratio $R_s = 0$.

Fig. 7: Stress-life curves for flange material with and without overloads by load ratio $R_s = -1$. 
Fig. 8: Stress-life curves for flange material with and without overloads by load ratio $R_S = 0$.

### Table 2: summary of fatigue results.

<table>
<thead>
<tr>
<th></th>
<th>Slope $k$</th>
<th>Knee point $N_k$</th>
<th>Nominal fatigue strength at the knee $S_{n,k}$ [MPa]</th>
<th>Scatter band $1/T_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_S = -1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As-received</td>
<td>5.5</td>
<td>$5 \cdot 10^5$</td>
<td>166</td>
<td>1.14</td>
</tr>
<tr>
<td>with OL</td>
<td>5.8</td>
<td>$5 \cdot 10^5$</td>
<td>157</td>
<td>1.18</td>
</tr>
<tr>
<td>Flange</td>
<td>10.7</td>
<td>$5 \cdot 10^5$</td>
<td>219</td>
<td>1.30</td>
</tr>
<tr>
<td>with OL</td>
<td>7.3</td>
<td>$5 \cdot 10^5$</td>
<td>193</td>
<td>1.24</td>
</tr>
<tr>
<td>$R_S = 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>As-received</td>
<td>6.2</td>
<td>$5 \cdot 10^5$</td>
<td>156</td>
<td>1.18</td>
</tr>
<tr>
<td>with OL</td>
<td>7.7</td>
<td>$1 \cdot 10^6$</td>
<td>143</td>
<td>1.11</td>
</tr>
<tr>
<td>Flange</td>
<td>9.9</td>
<td>$5 \cdot 10^5$</td>
<td>197</td>
<td>1.29</td>
</tr>
<tr>
<td>with OL</td>
<td>9.3</td>
<td>$1 \cdot 10^6$</td>
<td>162</td>
<td>1.31</td>
</tr>
</tbody>
</table>

In the case of flange material, the scatter of experimental results is much higher than the scatter in the as-received state. In general overloads have a negative influence on the fatigue life and the flange material is more negatively influenced by the application of overloads. In the case of $R_S = 0$ the overloads result also in a change of the position of the knee point.

**Metallographic analysis**

The detailed and systematic examination of the fracture surfaces reveal that the fracture modes of the as-received and the flange material differ significantly, independent from the load ratio or the occurrence of overloads. According to the linear elastic fracture
mechanics, the as-received material state shows a fatigue fracture behavior of mode I, e.g. the crack front is normal to the loading axis (Fig. 9).

![Fracture surface of an as-received specimen](image)

**Fig. 9:** Fracture surface of an as-received specimen ($R_S = 0, S_a = 225$ MPa)

The crack initiation is located at the notched side (Fig. 9, right side) followed by an transcry stalline crack propagation and finally results in a ductile residual fracture. The application of an overload results in the same fracture appearance, however the portion of residual fracture increases.

In contrast, the flange material with the UFG surface layer (Fig. 10) exhibits a fatigue fracture which deviates from that obtained for the as-received material state. Starting from the notch, the crack propagates at the flange surface (with UFG-microstructure) transcry stalline under mode I, whereas the fracture surface at the underside of the specimens (classically work-hardened material) tilts up to an angle between 40-60° (tilting edge marked with red dashed line) and thus the mode of fatigue fracture behavior changes. Noticeable for the flange surface with the UFG microstructure are the secondary micro cracks, which occur parallel to the loading axis (Fig. 10, right).

![Fracture surface of a flange specimen](image)

**Fig. 10:** Fracture surface of a flange specimen ($R_S = 0, S_a = 250$ MPa).

The application of an overload leads to the same kind of fracture surface, e.g. a tilted transcry stalline crack path and different fracture appearances of the flange surface and
the underside of the specimen. Additionally, the overloads cause a significant appearance of striations (Fig. 11). These striations range through the complete specimens thickness, but the crack front curvature is opposite to that which could be expected.

Fig 11: Fracture surface of a flange specimen with overload ($R_S = 0$, $S_a = 175$ MPa)

DISCUSSION OF RESULTS

Considering the tests with constant amplitudes, the fatigue results show for notched specimens higher fatigue strength of the flange material state in comparison with the as-received state. The fatigue strength at the knee-point is ca. 30% higher for the flange material. The mean-stress sensitivity remains for both states at relatively low levels ($M = 0.06$ for as-received material and $M = 0.11$ for flanges), and is higher for the flange material due to the higher ultimate tensile strength [8]. In comparison with the un-notched specimens [9] the mean-stress sensitivity is lower for the as-received material state, which presents a higher ductility, in presence of notches [10]. The mean stress sensitivity with and without notches is constant at a value $M = 0.11$ for the flange material.

With regard to overloads, Figures 5 and 6 show for the as-received material a relatively low sensibility to overloads. The so-called endurance limit is reduced by about 5% with load ratio $R_S = -1$ and by 10% by $R_S = 0$.

In the case of flange material (Fig. 7 and 8), the sensitivity to overloads is higher, almost double in comparison with the material in as-received state (reduction of the so-called endurance limit of ca. 13% by $R_S = -1$ and 22% by $R_S = 0$).

The fracture surfaces of the fatigue tested as-received material and flange material states reveal that the gradient in the flange material has a significant influence on the crack growth. While the as-received and homogenous coarse grained material show crack propagation under mode I, the fracture surface of the flange material with UFG layer and the grain size gradient exhibit a mixed failure character in terms of a tilt between 40-60° and a change of the fracture mode I to fracture mode II. The crack front curvature of the striations compared to the crack growth direction (Fig. 11) indicates faster crack propagation in the flange surface with UFG microstructure compared to the classical hardened material in the specimen underside. The crack front curvature of the
striations compared to the crack growth direction (Fig. 11) indicates faster crack propagation in the flange surface with UFG microstructure compared to the classical work-hardened region. Though further investigations are required to confirm this aspect, it would be plausible with respect to the lower resistance to fatigue crack growth which is typical for UFG materials [11, 12].

The secondary cracks in the UFG region (Fig 10, right) occur parallel to the flange surface, e.g. along the strongly elongated grain interfaces of the pancake structures. The tearing of these interfaces during the cyclic loading (even with the loading axis parallel to the elongated pancakes), indicate a weakening of the grain boundaries due to the linear flow splitting process. However, the secondary cracks exhibit no influence on the fatigue crack growth, since the fatigue crack grows in perpendicular direction and thus within the smallest grain dimension of this microstructure.

CONCLUSION

The flanges from the material H480LA manufactured by LFS are due to the presence of a gradient structure with UFG structure suitable for light-weight application because of their higher strength. The occurrence of overloads is nevertheless more damaging in comparison with the as-received material. Considering also the higher scatter band in the fatigue results in the specimens taken out from the flanges (Tab. 2), a more attentive design of components where the flange material is used is required, especially if frequent overloads are expected during service.

With respect to the fracture surface and crack path, the analyses reveal a strong difference between the behavior of as-received and flange material state. Since these gradient structures are relatively new, further studies are required in order to better understand and to model the material behavior in presence of cracks.

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REFERENCES