A fracture mechanics investigation on crack growth in massive forming

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Abstract. To understand the crack growth in massive forming and to consequentially avoid crack growth in workpieces, it is necessary to investigate its dependence on the crack depth and thus on the state of hydrostatic stress. Prior work shows that the crack opening displacement (COD) for shallow cracked tension specimens with low stress triaxiality is twice as high as for deep cracked specimens with high stress triaxiality.

This work examines the crack growth in compression specimens with pre-cracked cylindrical upsetting samples. The compression samples were cut in the stress symmetry plane in order to observe crack initiation and crack growth by a single specimen technique. In this way it is possible to observe blunting, crack initiation and crack growth inside the upsetting specimens. The resulting COD does not differ significantly from the values achieved in tension samples with short surface cracks.

Introduction

In forming workpieces, both the crack depths, the state of stress and the stress triaxiality, respectively, strongly deviate from the stress condition that occur in mechanical loading or standard fracture mechanics specimens used to predict the fracture toughness [1, 2].

Matsoukas *et al.* [3] showed that shallow cracks with low triaxiality exhibit a much higher critical crack opening displacement than deep cracks with high stress triaxiality. This result was confirmed by our prior work [4], where various tension samples with different crack depths were tested in order to achieve large differences in the stress state. The fracture toughness for shallow cracked tension samples with low stress triaxiality was twice as large as for samples with deep cracks and high stress triaxiality.

In this work the influence of crack depth in compression samples has been investigated. In order to simulate failure modes in massive forming cylindrical upsetting specimens with vertical fatigue cracks were tested. The results have been compared with the results gained from tension samples [4].

Material

The experiments were carried out with the austenic steel X5NiCrTi26-15 (Böhler T200), which is used e.g. in aviation industry or as turbine blade material. The 0.2 % offset yield strength of the used steel as received is 750 MPa and the tensile strength about 1280 MPa. The specimens were prepared from a rod with a diameter of 60 mm in a way that the crack propagated in C-R direction (following ASTM notation [5]). Experiments were carried out at room temperature.

In prior work the dependence of the COD on the crack depth in tension samples were examined [4]. Cylindrical tension samples with circumferential cracks were ruptured under tensile load. COD versus crack propagation curves for different crack depths were gained from stereoscopic scanning electron microscope (SEM) images [6, 7].

Rice [8] suggested to determine the COD value as the displacement at the intersections of a 90° vertex with the crack flanks. Because of the shape of the crack tips in those cylindrical tension samples, this vertex touches the crack flanks tangentially. This vertex was shifted to a crack propagation of 0.2 mm in order to get a distinctive value and hence becomes independent on the crack tip geometry. This new COD value is called $COD_{Rice0.2}$.

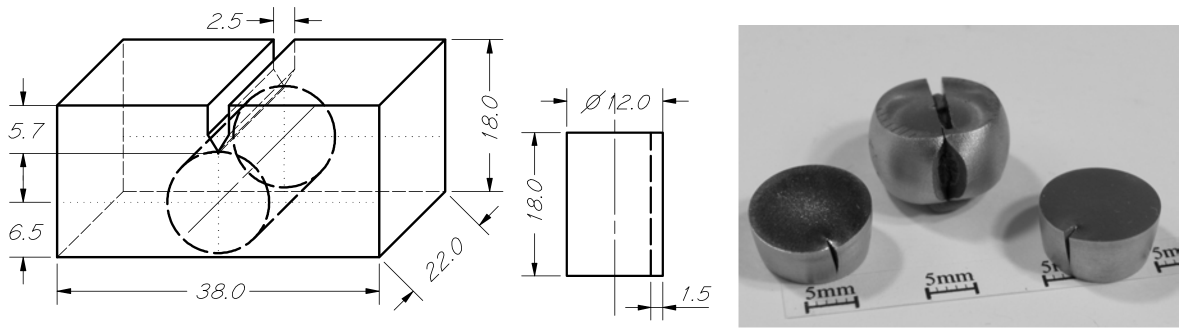
Tab. 1 shows the experimentally gained $COD_{Rice0.2}$ values for tension samples with different crack depths. $COD_{Rice0.2}$ values for deeply cracked specimens showed a strong increase by a factor of two in comparison to specimens with shallow cracks.

Table 1: Dependence of $COD_{Rice0.2}$ on the crack depth values derived from a CT specimen and cylindrical tension specimens with circumferential cracks of different depths [4].

crack depth [mm]	17 (CT)	5.7	3.1	0.7	0.4	0.2
$COD_{Rice0.2}$ [µm]	60	70	85	125	140	125

Cylindrical Upsetting Specimens

A standard experiment in massive forming is the upsetting of cylindrical specimens. To examine the crack growth in this geometry a vertical pre-crack was introduced in such a sample by manufacturing the upsetting specimen from a standard pre-fatigued single edge notched bend (SENB) specimen. This production procedure is sketched in Fig. 1.



(a) (b) (c)

Figure 1: Sketched procedure to manufacture a cylindrical upsetting specimen with a vertical pre-crack (b) from a SENB specimen (a); (c) shows a compressed specimen and two halves of a split sample.

A tested sample, which was compressed to half its original height, is shown in the center of Fig. 1.c. The contact surfaces of the sample and the upsetting dies were sandblast to obtain high friction, and thereby strong bulging. The upsetting process leads to a growth of the pre-crack. The crack growth is highest in the center of the sample because there are the highest circumferential stresses. After the compression the sample was split vertical and the fracture surfaces were examined by stereoscopic SEM images. In this way it was just possible to analyse the final state of the crack, but not to gain information about the crack initiation and crack growth, due to the vertical plastic deformation of the wake of the crack.

In order to gain such information with a single specimen technique, the prepared cylindrical upsetting samples were cut horizontally in the stress symmetry plane and put together in such a way that again a continuous crack existed. This split samples were compressed step by step, and SEM images of the cracks were taken for each step. The compression lead to symmetric growth of the crack in both halves of the samples (Fig. 2) and it was possible to observe blunting, crack initiation and crack growth inside these split samples (Fig. 3).

For a sample with a 1.5 mm deep fatigue crack, shown in Fig. 3, a critical COD of about 80 μm was measured. Table 2 shows the measured COD versus crack propagation extracted from Fig. 3. It is remarkable that this value for a 1.5 mm deep crack is in a comparable range to the $COD_{Rice0.2}$ value for a 1.5 mm deep pre-cracked tension sample (see Tab. 1) where a value of about 100 μm is expected (see Tab.1).

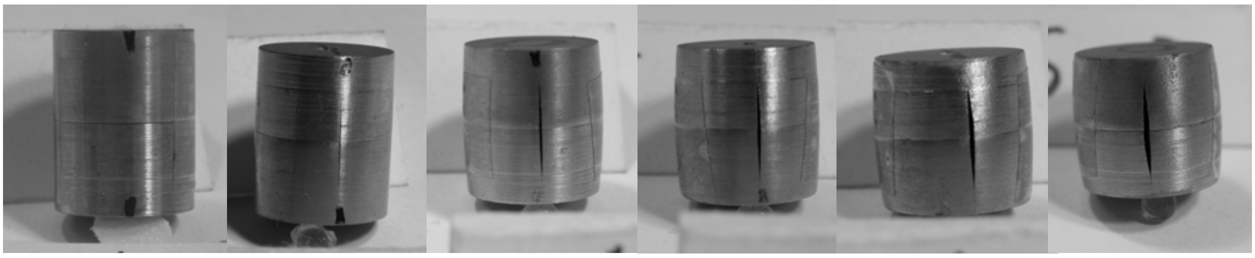


Figure 2: Split upsetting sample, stepwise compressed from h_0 = 15.3 mm by Δh = 0.6, 1.0, 0.3, 0.7, and 0.3 mm (from left to right).

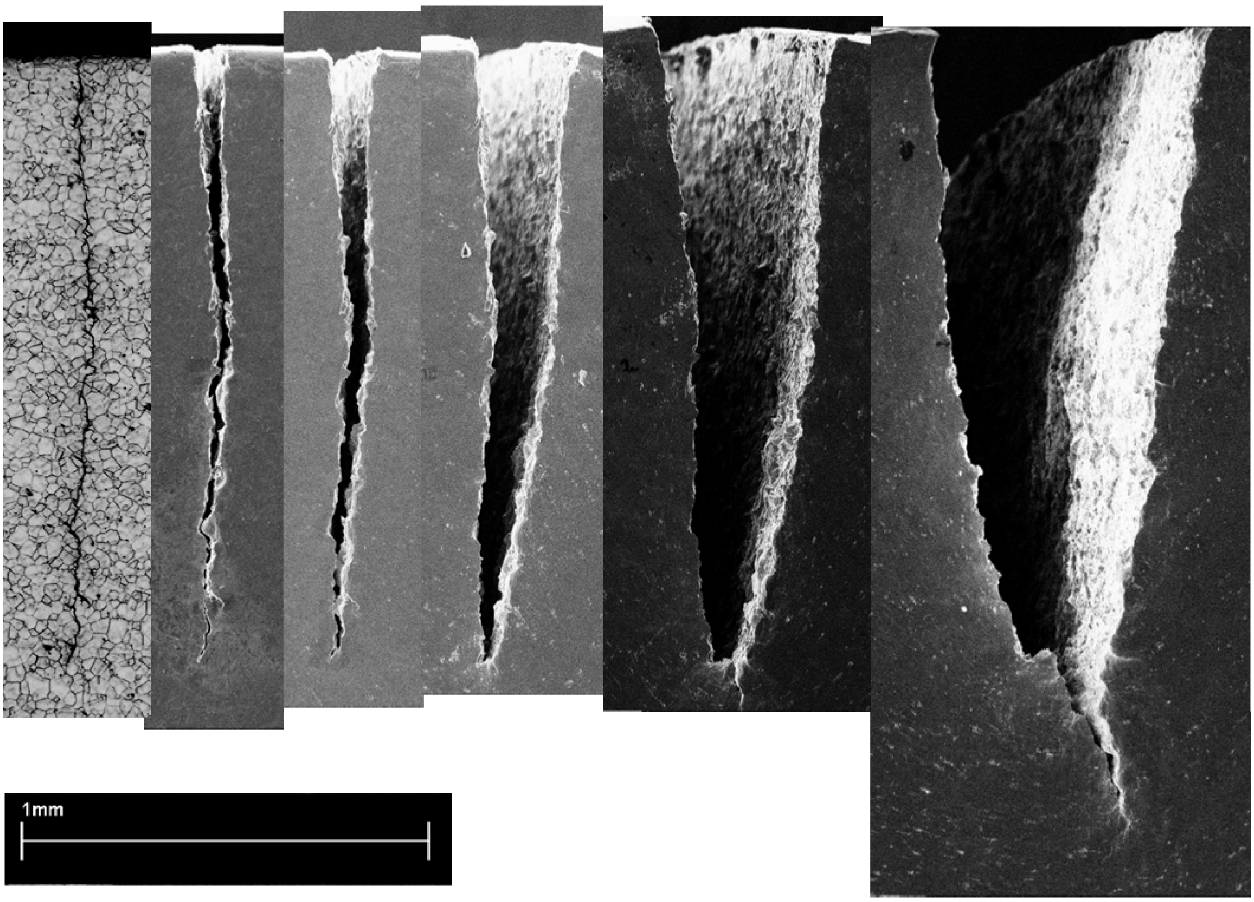


Figure 3: Blunting, crack initiation and crack growth in a split cylindrical upsetting specimen with a 1.5 mm deep fatigue crack. Leftmost a light optical micrograph of the non deformed specimen, followed by SEM images of the deformed specimen, upset from h_0 = 17.9 mm by Δh = 1.1, 0.7, 1.1, 1.1, and 0.8 mm.

Table 2: COD versus crack propagation from the split upsetting specimen with a 1.5 mm deep fatigue crack.

crack propagation [µm]	0	140	435
COD [µm]	40	80	235

Conclusion

By the technique of split compression samples, cut in the stress symmetry plane, it is possible to observe crack initiation and crack growth with a single specimen technique. This brings the big advantages of saving testing time and material.

In the split compression sample with a 1.5 mm deep vertical crack a critical COD of about 80 µm was measured. This value does not deviate significantly from the one obtained in tension samples with the same crack depth [4].

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