17th International Conference
ENGINEERING MECHANICS 2011
Svratka, Czech Republic, 9 – 12 May 2011

DUCTILE FRACTURE CRITERIA IN PREDICTION OF CHEVRON CRACKS

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Abstract: *Seven ductile fracture criteria are applied to simulation of cold forward extrusion and their performance in prediction of chevron cracks is presented. The criteria are implemented as user material subroutine (VUMAT) into ABAQUS/Explicit code and their calibration is based on tensile testing of several types of tensile specimens. Ability of the criteria to predict material damage in forward extrusion is tested under various combinations of process parameters.*

Keywords: ***Fracture criteria, calibration, forward extrusion, chevron cracks.***

1. Introduction

During forward extrusion of long products, their cross-section is reduced by extensive plastic deformation. Chevron cracks which originate on the symmetry axis represent a typical extrusion-related damage, which is not too frequent, but dangerous due its invisibility on the product surface. Process parameters such as die cone angle, area reduction ratio and friction have significant effect on the stress triaxiality η and equivalent plastic strain which are the main factors influencing damage. Definition of the frequently used criteria like Rice-Tracey, Xue-Wierzbicki (Rice & Tracey, 1969; Wierzbicki & Xue, 2006) and others are based on these quantities. This paper contains a qualitative analysis of the ability of selected fracture criteria to describe the influence of process parameters on the damage cumulation.

All the analyzed criteria were implemented into ABAQUS/Explicit by user subroutine, their parameters calibrated from independent tensile tests and applied to extrusion simulation. In case of reaching critical value of damage, crack initiation is simulated by deleting appropriate finite elements.

2. Implementation and calibration of seven fracture criteria

There are two basic mechanisms of ductile failure of metals. Shear mechanism is prevailing for triaxiality close to zero, whereas growth and coalescence of voids is typical for tensile loading with large positive values of triaxiality. Chevron cracks are caused by the second mechanism, generated at the symmetry axis in the process zone of extruded material.

To describe the damage evolution under different stress-strain history represented by different stress triaxiality, four different tensile test specimen geometry of steel no. 41 2050.3 were used for fracture criteria calibration. Besides a standard smooth tensile specimen, three others with notch radii 5 mm, 2.5 mm and 1.2 mm were used. Multilinear model of stress-strain curve was used in all the simulations. To identify the flow curve, a trial-and-error strategy with the MLR correction as described in (Borkovec, 2008) and (Mirone, 2006) was used. Experimental results of tensile tests and their computational simulations with identified flow curve are compared in Fig. 1 for two of the specimens.

Analysis of mesh sensitivity of the flow curve identification showed that element size less than 0.15 mm is necessary to reach negligible effect on the force response. The difference between computed and experimental curves in all the simulated tests is less than 10%. This was accepted as a

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reasonable correspondence if we take into account the variability of geometry and material properties among various specimens.

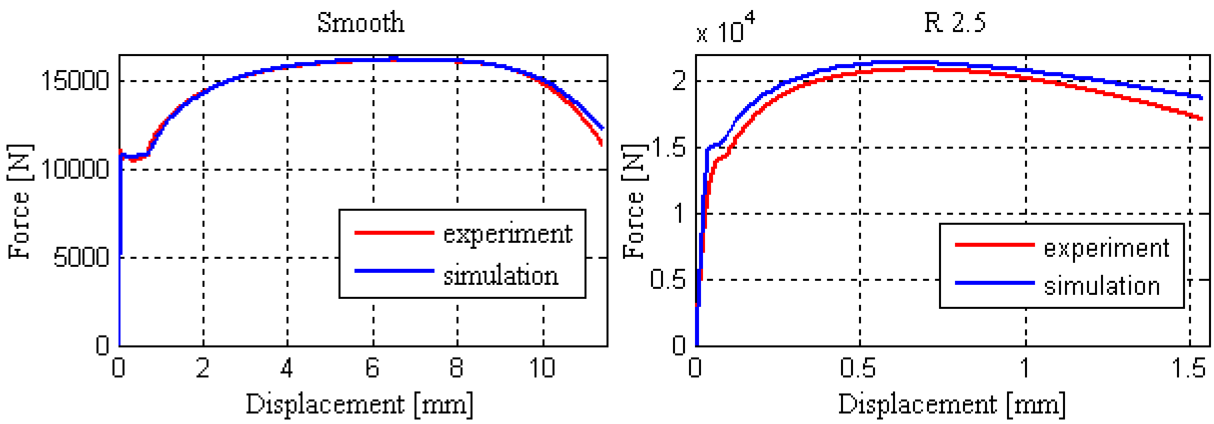

Fig. 1: Tensile test results – standard (left) and notched (right) specimen with radius 2.5 mm.

The data from four independent tensile tests are used in calibration of selected fracture models according to Tab 1. Unknown fracture criteria parameters are found in MATLAB by least-squares minimization in the following form:

$$\min_x \sum_{i=1}^{4} f_i^2(C), \tag{1}$$

where, for example, in case of the Cockcroft-Latham fracture criterion the calibration constant $C = C_{CLO}$ and minimized function is given by equation:

$$f_i(C) = C_{CLO} - \int_0^{\bar{\varepsilon}_i^f} \frac{\langle \sigma_{1i} \rangle}{\bar{\sigma}_i} d\bar{\varepsilon}_i^p . \tag{2}$$

Calibrated parameters of each fracture model are listed in Table 1. Due to aim of this study, only the parameters relevant for tensile loading damage were identified in case of complex fracture models like CrashFEM and EWK.

Tab. 1: The parameters for the different criteria calibrated to fit the tensile tests.

Criterion	***Formula***	***Parameters***
Rice - Tracey (Rice & Tracey, 1969)	$C_{RT} = \frac{1}{1.65}\int_0^{\bar{\varepsilon}^f} \exp\left(\frac{3}{2}\eta\right) d\bar{\varepsilon}^p$	$C_{RT} = 1.36$
Cockcroft - Latham (Cockcroft & Latham, 1968)	$C_{CL} = \int_0^{\bar{\varepsilon}^f} \langle \sigma_1 \rangle d\bar{\varepsilon}^p$	$C_{CL} = 802$
Cockcroft - Latham - Oh (Oh et al., 1979)	$C_{CLO} = \int_0^{\bar{\varepsilon}^f} \frac{\langle \sigma_1 \rangle}{\bar{\sigma}} d\bar{\varepsilon}^p$	$C_{CLO} = 0.976$
Johnson - Cook (Johnson & Cook, 1985)	$\bar{\varepsilon}^f = [D_1 + D_2 \exp(D_3\eta)][1 + D_4 \ln \dot{\varepsilon}^*][1 + D_5 T^*]$	$D_1 = 0.182$, $D_2 = 4.23$ $D_3 = 2.75$, $D_4 = 0$, $D_5 = 0$
EWK (Wilkins, 1981)	$D_C = \int_0^{\bar{\varepsilon}^f} \frac{1}{\left(1 - \frac{\sigma_m}{P_{\lim}}\right)^{\alpha}} \left[1 - \sup\left(\frac{S_2}{S_3}, \frac{S_2}{S_1}\right)\right]^{\beta} d\bar{\varepsilon}^p$	$D_C = 5.7$, $P_{\lim} = 1820[MPa]$ $\alpha = 4.19$, $\beta = 0$

Xue – Wierzbicki (Wierzbicki & Xue, 2006)	$\bar{\varepsilon}^f = k - [k - C_3 \exp(-C_4\eta)]\left[1 - \lvert\xi\rvert^n\right]^{\frac{1}{n}}$ Where $k = C_1 \exp(-C_2\eta)$	$C_1 = 3.07$, $C_2 = 1.86$ for axisymmetric case $\xi = 1$
CrashFEM (Borkovec, 2008)	$\bar{\varepsilon}_d^f = d_0 \exp(-3c\eta) + d_1 \exp(3c\eta)$ tensile loading only	$d_0 = 2.56$, $c = 0.42$, $d_1 = -0.07$

3. Influence of process parameters on extruded material damage

By repeated simulation of the extrusion process with different reduction and die cone angle, their influence on material damage can be quantified by different fracture criteria as shown in Fig. 2. The contours in Fig. 2 show damage values actually reached from appropriate criterion equations given in Tab. 1. Typical pattern can be found in all fracture models with a single exception of slightly different results of Johnson-Cook criterion.

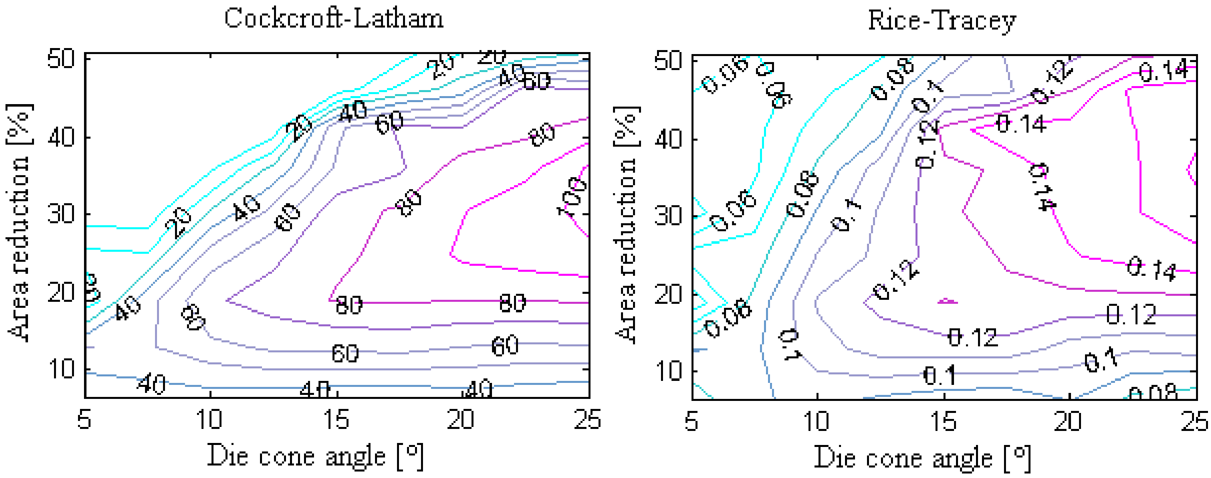

Fig. 2: Influence of process parameters on damage obtained from selected criteria.

The results show maximum values of damage for increasing die cone angles and medium reductions – about 30-40%. Similar results were obtained in (Saanouni, 2004; McVeigh, 2005). On the other hand the Johnson-Cook criterion shows that maximum values of damage compared to other criteria are located in the area of smaller die cone angles and smaller reductions. In terms of security and forming forces it is then preferable to use small angle of reduction. Repeated analysis also shows that it is more dangerous to reach final reduction of the product in several successive small reductions than doing it all in one extrusion run.

4. Simulation of chevron crack development

Initiation and growth of ductile fracture is described by deletion of elements, where the level of damage surpasses critical fracture parameters, specified in Table 1. Element size is the same as it was for calibration to eliminate mesh sensitivity. Results obtained with the Cockroft-Latham-Oh criterion are given in Fig. 3, other criteria produced very similar results. We can see that the simulation is corresponding to real chevron crack discontinuous character and arrow-like shape oriented in the direction of material flow. Because of relatively large ductility of material, first cracks are developed at area reduction reaching 61%. We can also see that cracks are generated only if the total reduction 61% is obtained in four consecutive partial reductions. If the same reduction is reached in only three larger reduction steps, material remains intact. This is in correspondence with literature and practical industrial experience – most dangerous are the last, although small finishing reductions.

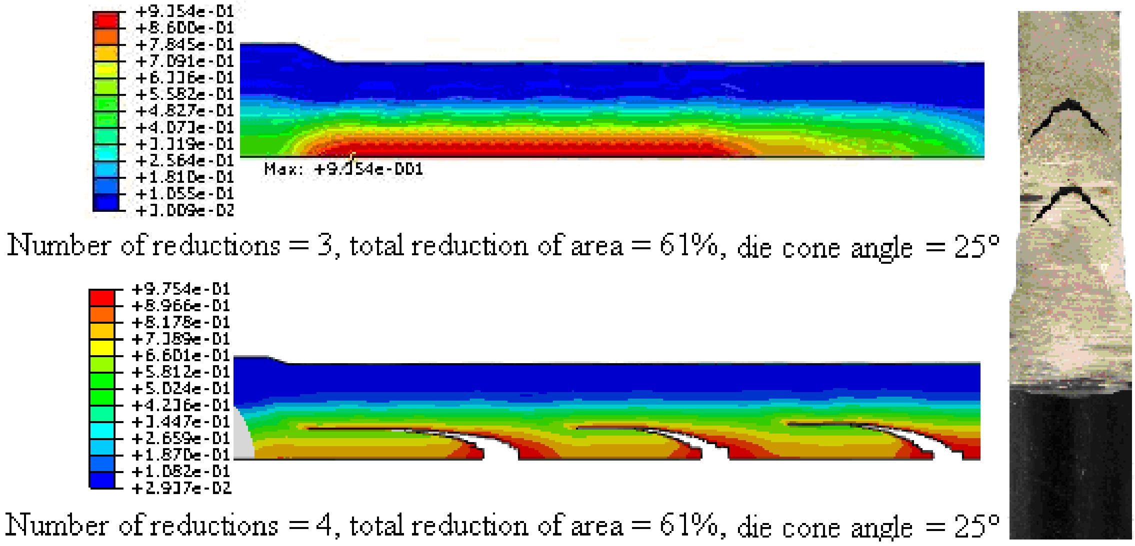

Fig. 3: Shape of chevron crack by using the model Cockcrof-Latham-Oh.

5. Conclusions

Complex problem of calibration and application of several fracture criteria to simulation of cold forward extrusion of long products was presented. Obtained results show good correspondence between simulated and real position, distribution and shape of chevron cracks. Computational analysis thus presents appropriate tool to predict potential problems with forward extrusion processes and can be helpful to prevent them already in the process design stage. Nevertheless, following research steps should be directed at least towards precise prediction of cracks shape and frequency, influence of friction and element-size dependence of the FE results.

Acknowledgement

Financial help of the grant projects GA101/09/1630 and FSI-S-10-12 is gratefully acknowledged.

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