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EVALUATION OF FOUR FRACTURE CRITERIA IN COMPRESSIVE LOADING CONDITIONS

Summary: Suitability of various fracture criteria in the case of compressive loading conditions are performed in this work. Four fracture criteria were investigated: constant fracture strain, EWK, Oh and Xue-Wierzbicki. The first two are already implemented in PamCrash v2005.1, while the latter two had to be programmed as a user material. These models were applied to the technological process of bolt-head trimming. The digital simulation was compared with the experimental results. Constant strain fracture had insufficient results because calibration conditions were not consistent with the simulation. Xue-Wierzbicki is a versatile criterion, but it is not suitable for compressive loading conditions either. Good conformity was observed with EWK and Oh criteria.

Key words: ductile fracture, element elimination, explicit FE simulation

1. INTRODUCTION

Digital simulation of the fracture process is an intensively studied field with applications in automotive, aerospace and the metallurgical industry. Although a great number of fracture criteria were developed, none of them is universal. The aim of this work is to investigate selected criteria in case of compressive loading conditions. This type of loading is typical for technological operations, which uses material failure as a production technique (machining, drilling and trimming). In these conditions, many failure criteria have insufficient results and the research has to be done to achieve reliability, which allows using digital simulation in industrial practice.

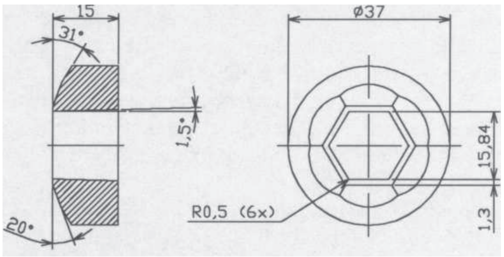

Fig. 1. Trimming matrix OK16
Rys. 1. Matryca okrawająca OK16

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The manufacturer of the trimming matrices (Fig. 1) was interested in digital simulation of the bolt head trimming process, which is the last stage in high strength bolt production. Previously, the bolt crank is created by extrusion and the upper part is compressed to form the round head. The trimming process is very complex and there is no valid theory to support it, so the computer simulation could give a closer insight into the processing nature and design of trimming tools and devices could be more efficient, the tools more durable and the overall process faster and therefore more effective

2. EXPERIMENT

Verification of the computer simulation results were made by comparison with the experiments carried out in cooperation with our industrial partner.

A mechanical press was operated to stop the movement of the tool in predefined positions (Fig. 2), so that the evolution of process could be observed. The samples were then passed on for metallographic analysis. They were cut longitudinally in the middle section, polished and etched; so that the structure of the material can be seen (Fig. 3). Shear bands are clearly visible as well as the corresponding stepped shape of chips. Cracks were found in the shear bands.

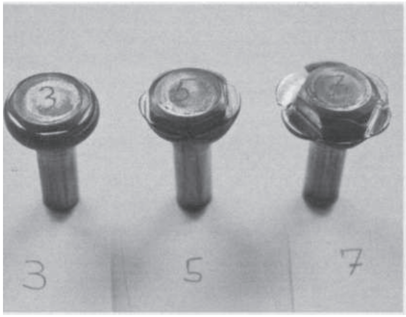

Fig. 2. Partially cut samples
Rys. 2. Próbki okrawane stopniowo

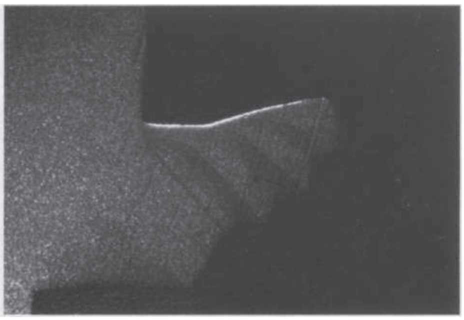

Fig. 3. Slip bands with cracks
Rys. 3. Linie poślizgu z pęknięciami

3. COMPUTER ANALYSIS

The computational model of bolt head trimming was optimized by test problems by choosing the contact type, contact stiffness and hourglassing control type. Firstly, the 3D case was solved, but even with a very coarse mesh, the calculation was very time consuming. It was necessary to reduce the computer time cost. Since PamCrash does not support 2D elements, only a thin slice of 3D material model was created. There was only one layer of solid bricks in the transversal direction with boundary conditions for plan ar strain. The layer thickness was determined to obtain a cubic shape of elements in the cutting region, which offers the best numerical properties. The whole model had 12700 nodes and 6150 elements.

Material of the bolt is a special bolt steel AISI S 17400. Its flow curve was determined from the compression test. In the simulation it was modeled by an elastoplastic material with the von Mises yield surface, isotropic hardening and failure criteria described in the next section. Trimming tool is made up from high strength tool steel 19 830 (Czech standard), which has a yield strength in compression of $R_{et} = 3500$ MPa; so that the elastic behavior was assumed in the whole loading range. The table material was rigid. Scheme of computer model is shown in Fig. 4.

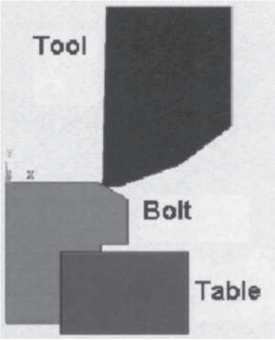

Fig. 4. Computer model scheme
Rys. 4. Schemat modelu komputerowego

Symmetrical boundary conditions were applied in the centre of the bolt and in the outer diameter of the tool. The table was fixed in all directions. Top side of the tool was prescribed to have displacement in y-direction with speed amplitude of $v = 0.2\ \mathrm{m\cdot s^{-1}}$.

The frictional coefficient between the parts was set to a value of 0.15.

4. FRACTURE CRITERIA

Four fracture criteria were used in this work. The first fracture criterion is **constant fracture strain,** the origin of which dates back to the beginning of the 20th century [3]. Material failure occurs when the equivalent strain reaches a critical value. This criterion is included in all commercial codes such as Abaqus, LS-Dyna or PamCrash, in spite of the well-known fact that the fracture strain varies with changing stress triaxiality factor. It is still popular especially for the first approximation, because it is simple to understand, calibrate and use. In this work it is used for comparative reasons.

The second model to be investigated is **EWK** which is abbreviation for ESI-Wilkins-Kamoulakos. According to this criterion, fracture occurs when the time integrated product of the equivalent plastic strain and two functions of the local stress distribution exceed a critical value D_c over a critical dimension R_c. The damage parameter is defined by:

$$D = \int w_1 w_2 d\bar{\varepsilon}^p \tag{1}$$

Weight parameter w_1 is related to the mean tensile stress and w_2 to the stress asymmetry:

$$w_1 = \left(\frac{1}{1 + aP} \right)^{\alpha} \tag{2}$$

$$w_2 = \left(2 - A\right), where\, A = \max\left(\frac{S_2}{S_3}, \frac{S_2}{S_1} \right) \tag{3}$$

where:

P	–	mean stress,
Si-S_3	–	principal deviatoric stress components (Si > S_2> S_3),
A, α, β	–	material constants, which can be determined by two different approaches.

The first way, by calibrating the model, is to perform a series of smooth and notched tensile tests followed by their numerical simulation. From the comparison the material parameters can be found. The second, and often used, is made possible by the automatic semi-analytical calibrator, incorporated into the PamCrash implementation of the EWK model. It can help to do the calibration in case the experimental data is not complex enough for complete parameter identification. Only basic information has to be inserted: stress-strain curve and tensile fracture strain. This method was also used in this work.

Oh criterion [4] was developed by modification of the Cockroft-Latham criterion for the bulk forming operations and therefore is applicable only to the range of negative and small positive stress triaxiality. According to this criterion, fracture occurs when the accumulated equivalent strain modified by maximum principal tensile stress reaches a critical value:

$$\int_0^{\bar{\varepsilon}_f} \frac{\langle \sigma_1 \rangle}{\bar{\sigma}} d\bar{\varepsilon} = C_{Oh} \tag{4}$$

where the expression <σ_1> is zero when σ_1 is negative. For positive values, <σ_1> is equal to σ_1.

Xue-Wierzbicki criterion was created recently at the Massachusetts Institute of Technology [6]. It works with the weighting function dependant on triaxiality η and Lode parameter ξ. It was created in the 3 dimension space (Fig. 5). Fracture criterion is defined by:

$$\int_0^{\varepsilon_f} \frac{d\bar{\varepsilon}}{F(\eta, \xi)} = 1 \tag{5}$$

where Lode parameter describing deviatoric stress state is:

$$\xi = \frac{27}{2} \frac{J_3}{\bar{\sigma}^3} \tag{6}$$

where J3 is the third invariant of deviatoric stress tensor. In the coordinate system, its value is $J_3 = S_1S_2S_3$. Lode parameter can have values from interval <-1, 1>; for uniaxial tension 1, for uniaxial compression -1 and 0 for pure shear.

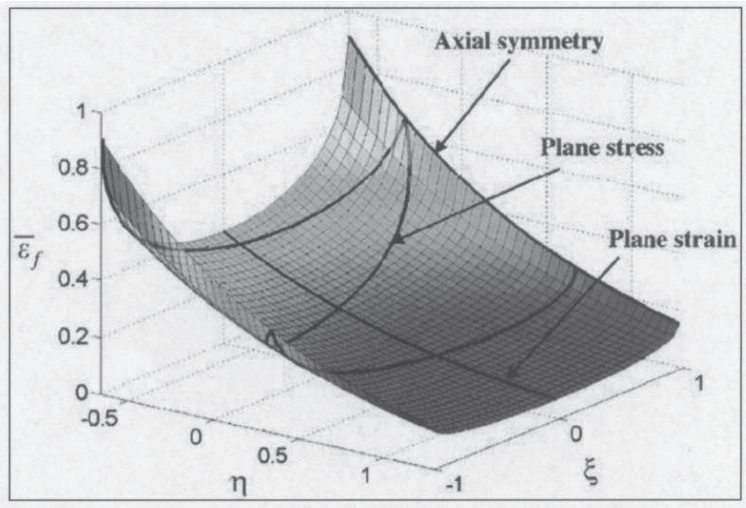

Fig. 5. Fracture weighting function depending on the stress tri-axiality and Lode parameter
Rys. 5. Zależność funkcji obciążenia pęknięcia od trójosiowych naprężeń i parametru Lode'a

Authors described the decreasing dependency of fracture strain on the triaxiality by exponential functions:

$$\overline{\varepsilon}_f^{ax} = C_1 e^{-C_2\eta} \quad for \;\; \xi = \pm 1 \tag{7}$$

$$\overline{\varepsilon}_f^{ps} = C_3 e^{-C_4\eta} \quad for \;\; \xi = 0 \tag{8}$$

describing two extreme cases – axisymmetry, when the ductility of material is the highest, and plane strain, when it is the lowest. Transition between these two states is made by the elliptic function:

$$\left(\frac{\overline{\varepsilon}_f^{ax} - \overline{\varepsilon}_f}{\overline{\varepsilon}_f^{ax} - \overline{\varepsilon}_f^{ps}} \right)^n + |\xi|^n = 1 \tag{9}$$

where *n* is hardening exponent. Resolving equation (9) for $\overline{\varepsilon_f}$ and substituting equation (7) and (8), the final expression is:

$$\overline{\varepsilon}_f = F(\eta, \xi) = C_1 e^{-C_2\eta} - \left(C_1 e^{-C_2\eta} + C_3 e^{-C_4\eta} \right) \left(1 - |\xi|^n \right)^{\frac{1}{n}} \tag{10}$$

5. CALIBRATION

There was one material test available, which is enough for the complete calibration of constant strain criterion, where the fracture strain was calculated from principal strains:

$$\bar{\varepsilon}_f = \sqrt{\frac{2}{3}\left(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2\right)} \tag{11}$$

Material constants for Oh fracture criterion was calibrated by comparison of the compression test results and the parallel numerical simulation. Stress-strain history was found from which the material constant C_{Oh} was calculated.

Calibration of the EWK model was made with the help of the automatic constant calibrator, which is provided with the material model in PamCrash, as mentioned by eq. (3). This calibrator needs only one test data element as well. For the exact calibration, four tests should be done, but the automatic calibration works well and the results are reliable.

Xue-Wierzbicki criterion was calibrated by comparing the test results and their digital simulation. Constants C_2 and C_4 were taken from Bao and Wierzbicki [5].

Table 1. Calibration of constant values
Tabela 1. Kalibracja wartości stałych

Fracture Criterion	Calibration constants
Constant strain	$\bar{\varepsilon}_f$ =0.598
Xue-Wierzbicki	C_1 = 1.31, C_2 = 1.77, C_3 = 0.31, C_4 = 0.01, n = 0.2
Oh	C_{Oh} = 0.31
EWK	Dc = 1.0, a = 1.92, α = 1.22, β = -0.263

6. USER MATERIAL IN PAMCRASH

PamCrash version 2005.1 provides several material models to simulate material rupture – constant plastic strain, Gurson, EWK and Kolmogorov-Dell. Although these options give wide flexibility in choice of failure criteria, there are some promising criteria to be tested, which have to be implemented by means of user material.

It is not possible to include only the failure criteria, the user material has to deal with constitutive model as well. In this work the von Mises yield surface with isotropic hardening was used. The results were compared with the identical model already existing in PamCrash. Single element tests of uniaxial tension, compression and shear as well as the complex 3D case of tension test give almost identical results with the order of differences as small as 10^{-5}%.

7. PRESENTATION AND DISCUSSION OF THE RESULTS

The easiest way to judge the results is by appearance and number of eroded elements. They should form lines, representing thin cracks, and there should be as few as possible.

The progress of the trimming process can be seen in Figs. 6÷9 (all pictures show the isolines of a damage parameter, which initially has zero value and value of one when the element is about to be eliminated) which shows the behaviour of all fracture models at times 1ms, 2ms, 3ms and 4ms. Geometry of the chip can be compared with the experimental results (Fig. 3).

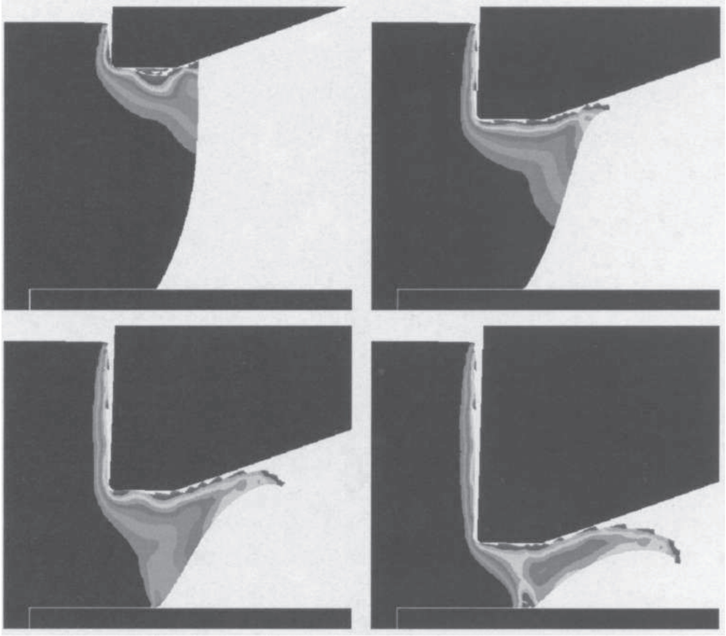

Fig. 6. Constant strain criterion
Rys. 6. Kryterium stałego odkształcenia

The constant strain criterion was tested first. The evolution of the process in Fig. 6 clearly shows that the performance of this criterion is very low. Its weakness is that it works only in situations where stress and strain conditions (especially stress triaxiality) are the same or very similar to those used in calibration tests. This drawback is manifested most when the loading conditions are compressive. The slope of the fracture strain-triaxiality curve is very steep in this region and besides there is a discontinuity at the triaxiality value of -0.33. This state corresponds to the uniaxial compression and Bao and Wierzbicki [1] proved that no fracture occurs below this value. Constant strain criterion does not respect these facts, which results in unrealistic elimination of too many elements. Missing finite elements do not constitute a narrow crack, but a large bulk of "evaporated" material.

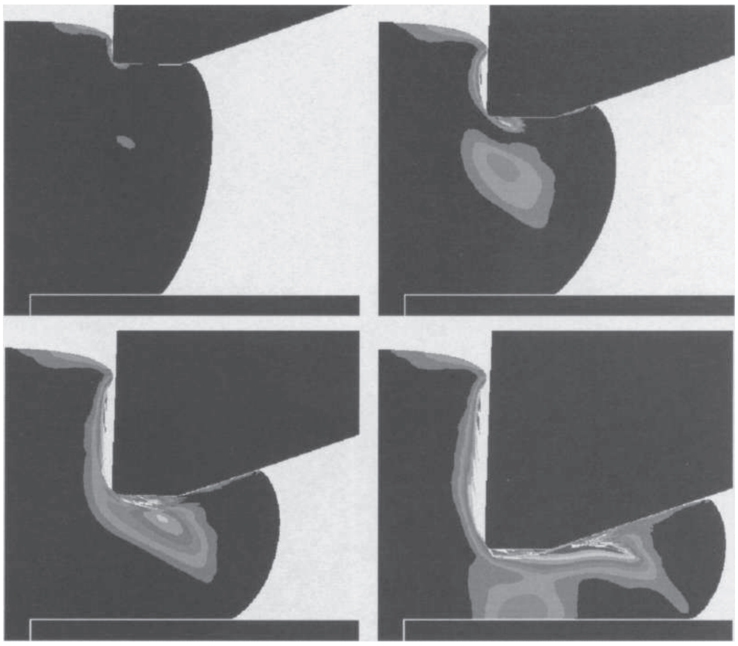

Fig. 7. Xue-Wierzbicki criterion
Rys. 7. Kryterium Xue-Wierzbickiego

Xue-Wierzbicki criterion (Fig. 7) suffered the opposite problem. Here, the fracture limit could not be reached during almost the entire trimming process simulation even at the end, when the deformation of the material was excessive.

With an application of criterion Oh (Fig. 8) the chip was formed by shear separation in the plane of maximum shear stress (45° to the tool movement). This can be interpreted as a creation of a slip band, which can be found in the metallographic analysis pictures.

The EWK material model (Fig. 9) produced very satisfactory results. Material damage was localized in the same areas where the slip bands can be found in the experimental data. The difference is that the fractures stopped in the chip, while in reality the slip bands run through the material to the surface, creating a stepped shape of the chip.

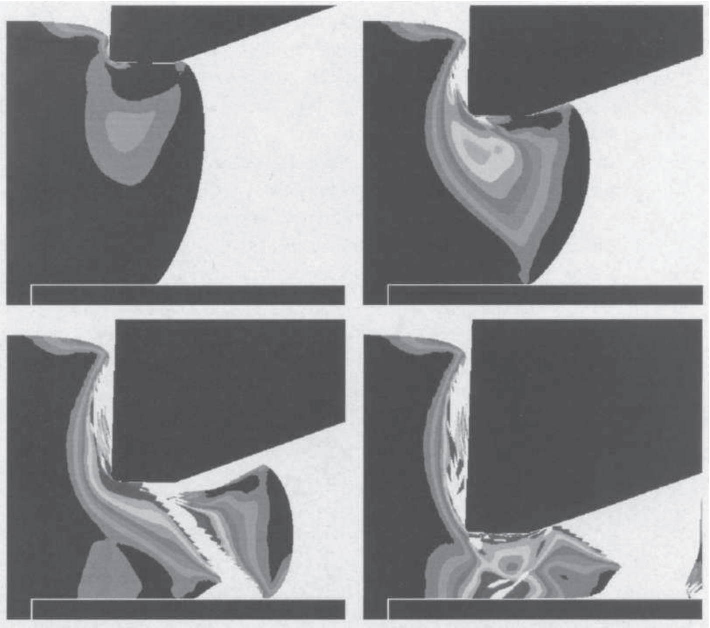

Fig. 8. Oh criterion
Rys. 8. Kryterium Oh

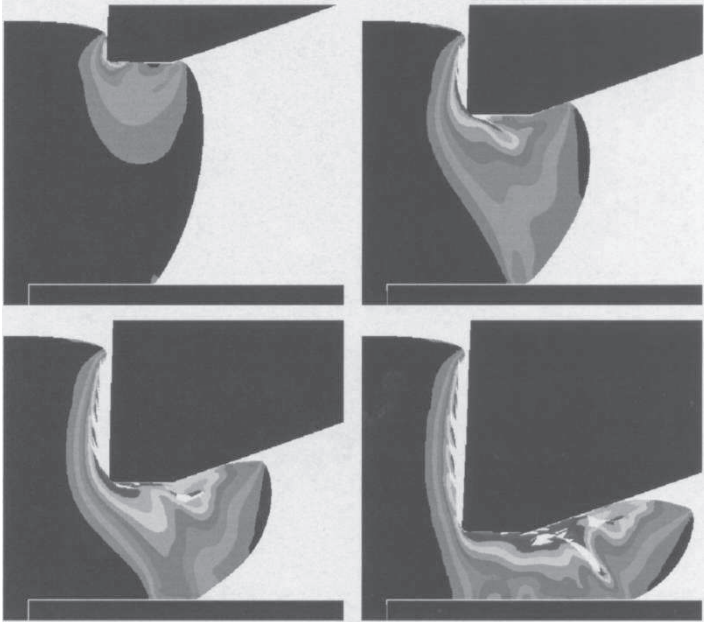

Fig. 9. EWK criterion
Rys. 9. Kryterium EWK

CONCLUSIONS

Four ductile fracture criteria (constant strain, Oh, EWK and Xue-Wierzbicki) were tested to prove their ability to simulate material fracture under compressive loading conditions. Computer modeling was compared with the experimental testing. The results indicated that the EWK and Oh criteria are suitable for compression loading, while Xue-Wiezbicky and constant strain criteria did not seem to give reliable results in this specific loading type.

Future research will be focused on the material testing and more precise calibration of material model parameters. Application of meshless methods is another direction of our interest. The latest yersions of LS-Dyna, SPH method and Element Free Galerkin method were programmed and their performance in ductile fracture is promising. A brief summary of what has been done in meshless simulation together with proposed future steps can be found in [2].

ACKNOWLEDGEMENTS

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WYZNACZENIE CZTERECH KRYTERIÓW PĘKANIA W WARUNKACH OBCIĄŻEŃ ŚCISKAJĄCYCH

Streszczenie: W pracy przedstawiono przydatność różnych kryteriów pękania w warunkach obciążeń ściskających. Badano cztery kryteria: stałych odkształceń, EWK, Oh oraz Xue-Wierzbickiego. Pierwsze dwa są zaimplementowane w programie PamCrash v.2005.1, natomiast dwa pozostałe należało zaprogramować. Stwierdzono, że kryterium stałych odkształceń daje niewystarczające rezultaty a kryterium Xue-Wierzbickiego, chociaż uniwersalne jest nieprzydatne dla warunków obciążeń ściskających. Dobrą zgodność uzyskano dla kryteriów EWK i Oh.

Słowa kluczowe: przełom plastyczny, usuwanie częściowe, symulacja F