Prediction of fracture based on an assessment of "damage" of a metal by plastic deformation

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Abstract. Using the hypothesis of damage summation and the linear law the accumulation of such a method is proposed for predicting the fracture with large plastic deformation.

Modern views on the mechanism of failure during plastic deformation are based on the experimentally established fact "loosening" of the material associated with the origin, development and merging of damage (pores) with the growth of the strain with the subsequent formation of microtrain, ultimately leading to destruction[1,2].

In the framework of a phenomenological approach, considering the damage without specifying its physical form, in categories in continuum mechanics, we will create a model of the fracture of materials by cold plastic deformation.

The damage will be characterized by a certain scalar quantity \( \Psi \), which displays the degree of exhaustion of ductility with increasing strain. The value of \( \Psi \) in the initial (undeformed) state \( \Psi=0 \), \( \Lambda=0 \) (\( \Lambda \) is the degree of shear deformation of the considered material particle of a deformable body) \( \Psi_p=1, \Lambda=\Lambda_p \) at the moment of fracture, when the ductility of the metal material in the particle is exhausted, \( \Psi<1 \) in the range of \( 0<\Lambda<\Lambda_p \). The function \( \Psi=\Psi(\Lambda) \) displays the pattern of accumulation of \( \Psi \) as the exhaustion of ductility due to the growth of the indicator strain \( \Lambda \). \( K=K(\Lambda) \) – dependence, showing the evolution of stress-strain state in a neighbourhood of the considered material particle (path deformation).

Such a representation of the history of deformation and possibilities of plastic deformable material in a single system of coordinates \( \Lambda=\Lambda(K) \) allows to estimate the damage of \( \Psi \) as a function of the form

\[
\Psi = [K(\Lambda), \Lambda_p(K)]
\]

and admits a geometric interpretation (Fig. 1) development of fracture process.
Fig. 1 Diagram to determine the patterns of damage accumulation is \( \Psi = \Psi[K_\lambda(\Lambda), \Lambda_p(K)] \) when the deformation by compression, torsion, stretching for \( K = \text{const} \).

In the right part of Fig. 1 is shown conventionally the diagram of plasticity of the material of \( \Lambda_p=\Lambda_p(K) \) in the representation of Bridgman. In the right part of the picture – according to \( \Psi = [K(\Lambda), \Lambda_p(K)] \) – reflecting a pattern of damage accumulation for a linear law.

During construction of chart plasticity of \( \Lambda_p=\Lambda_p(K) \) are chosen such kinds of tests in which the score, if possible, should not change during the test, i.e., \( K = \text{const} \). In Fig. 1 are schematically presented data on the tensile, compression, torsion, tension, in which the index schema of the stress state are respectively equal to \( K_\lambda = -1, K_p = 0, K_p \approx 1 \), and the limit degree of deformation at the time of destruction is marked as \( \Lambda_p > \Lambda_p > \Lambda_p \). Line \( \Lambda_p > \Lambda_p > \Lambda_p \) (right part of Fig. 1) characterizes the pattern of change \( \Psi \) in compression, torsion, respectively, when taking into account the hypothesis of linear damage accumulation.

The definition accumulated in the process of deformation distortion, such as twisting to the value of the degree of deformation of \( \Lambda_\kappa \) can be carried out graphically, as the intersection of a line \( 0\Lambda_p \) with a line drawn parallel to the abscissa of the point \( \Lambda_\kappa \). From the similarity \( \Delta 0\Lambda_p \) and \( \Delta 0\Psi_C \) (left part of Fig. 1) results that

\[
\Psi_\Lambda_\kappa = \Lambda_\kappa / \Lambda_p
\]  

(1)

the amount of potential to fracture damage, which means the residual resource of plasticity is equal.

\[
\Psi_\phi_c = 1 - \Psi_\Lambda_\kappa^t
\]  

(2)

In Fig. 2 a, b presents a calculation scheme of determination of damage and limit the degree of deformation \( \Lambda_\kappa \) for the set of monotonic deformation:

a) \( \Lambda_\kappa (K_\lambda = \text{const}) + \Lambda_p (K_p = \text{const}) \), torsion + tension to failure

b) \( \Lambda_\phi (K_p = \text{const}) + \Lambda_p (K_\lambda = \text{const}) \), tension + torsion to failure

In the case of a) deformation at the beginning is performed by torsion under a "softer" scheme of the stress state \( K_\lambda = 0 = \text{const} \), the definition \( \Psi_\Lambda_\kappa \) and \( \Psi_\phi_c \) shown earlier in figure 2 and are calculated with relations (1), (2).

Further, in the present case, the deformation by stretching, is performed with more "rigid" scheme of the stress state of \( K_p = 1 = \text{const} \) at a higher rate of damage accumulation is described by the line \( 0\Lambda_p \). Allowed to destruction, deformation stretching \( \Lambda_p \) taking into account the relations (1), (2) and the similarity of triangles \( 0\Lambda_p 1 \) and \( \Lambda_p^tPKC' \) will be equal to
Fig. 2 Calculation scheme for the definition of the parameter "damage" ($\Psi$) of a steel and limit the degree of deformation ($\Lambda_S$) depending on the way of deformation $K=K(\Lambda)$; a) the path of deformation – torsion to $\Lambda_K=\text{const}$ + elongation till fracture: $\Lambda_{\Sigma}=\Lambda_K+\Lambda_p>\Lambda_{\Psi}$; b) the way of deformation – stretching to $\Lambda_{PK}=\text{const}$ + torsion till deformation $\Lambda_K=\text{const}$; $\Lambda_{\Sigma}=\Lambda_p+\Lambda_K<\Lambda_{PK}$. 1- chart of plasticity

$$\Lambda_p = (1 - \frac{\Lambda_K}{\Lambda_{PK}})\Lambda_{pp},$$ (3)

Before the final destruction of the degree of deformation $\Lambda_{\Sigma(\Lambda_p,\Lambda_K)}$ for path deformation for case a) is equal to

$$\Delta\Lambda_{\Sigma(\Lambda_p,\Lambda_K)} = \Lambda_p + \Lambda_{pp} > \Lambda_{pp},$$ (4)

Thus, despite the fact that the completion of deformation in this case is stretching, where the ultimate degree of deformation of equals the $\Lambda_{pp} \Delta\Lambda_p$ the total degree of deformation $\Lambda_S$ the destruction will be more $\Lambda_{pp}$ than $\Delta\Lambda_p$ as pre-deformation was carried out with a "softer" scheme of the stress state.

The destruction in Fig. 2 is marked with *, which is located above the curve plasticity of $\Lambda_p=\Lambda_p(K)$.

Similarly, Fig. 2 b) was determined by accumulated damage $\Psi_p$, the total plastic deformation up to fracture $\Lambda_{\Sigma(\Psi_p,\Lambda_K)}$, and $\Lambda_K$ in a different way of deformation (scheme b) (at the beginning of tension on the $\Lambda_p$ and subsequent deformation by torsion to failure). From the obtained results it follows the following pattern: when the paths of deformation $K=K(\Lambda)$ emerging from a "soft" $K_h$ schemes of the stress state in the direction of "hard" schemes accumulated by the time of the destruction of the limiting degree of deformation $\Lambda_S$ is greater than the limiting degree of deformation on the plasticity.
chart in $K_K$ corresponding to the moment of destruction. The reverse pattern is observed when deformation paths developing from the "hard" $K_H$ schemes of the stress state in the direction of "soft" one.

\[ \Delta \varepsilon > \Delta \varepsilon_{PK} \text{ where } K_H < K_K \]
\[ \Delta \varepsilon < \Delta \varepsilon_{PK} \text{ where } K_H > K_K \]  \hspace{1cm} (5)

where $K_H$ and $K_K$ are the indicators of the scheme of stress state for the beginning and end of deformation.

Experimental evaluation of limit deformations of destruction on the routes of deformation showed the similarity in the range of 10-15% from the calculated values.

References:
[1] Migachev B A 1994  Features of damage accumulation during the hot deformation of metals. – Metals, No. 4, pp. 135-140.
[2] V G Shibakov, D L Pankratov, R V Shibakov 2014 Connection between machines durability during operation and the complex of physic-mechanical properties, formed during the production of critical parts IOP Conference Series: Materials Science and Engineering 69 012040