Damage criterion comparison at unidirectional and alternating torsion of samples

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Abstract. The paper presents the results of the analysis of computer simulation of unidirectional and alternating torsion of cylindrical samples in the software complex Deform 3D. The accumulated deformation degree and damage criterion were taken as compared parameters. Damage was calculated by two existing methods: Cockroft-Latham and Bogatov methods. The results of the analysis show that the proposed method for determining the damage criterion is more accurate when testing samples for alternating twisting than the most currently used method since it takes into account the number of loading stages and the plastic deformation amplitude.

1 Introduction

With the development of machine-building and metallurgical industries more high requirements for quality and performance are demanded from the metal products. One of the most important indicators of the quality of steel products is the ability to withstand high loads without destruction for long periods of time and often in adverse environmental conditions. Therefore, it is very important to accurately determine strain degree and tensile stresses value that the finished metal can withstand before the formation of macrofracture, which further leads to cracks, internal continuity failure of the metal and as a consequence its destruction. Damage criterion is an indicator to determine the critical strain degree and the magnitude of tensile stresses.

The aim of this work is to conduct the comparative analysis of damage criterion on the basis of computer simulation in the software complex Deform 3D in one of the mechanical tests types: torsion (unidirectional and alternating).

Currently in metal forming there is a variety of methods which allows to assess the damage degree of the materials. The most popular and frequently used method is the Cockroft -Latham damage criterion [1]. According to which the initiation of a macrofracture is occurring when the value of the plastic strain in the direction of the maximal principal tensile stress achieves critical value peculiar to each material and determined by the curves of hardening under tension or torsion of cylindrical samples:

$$\int_0^{\varepsilon_f} \sigma_{\max} d\varepsilon = C , \tag{1}$$

and the normalized Cockroft -Latham criterion in a dimensionless form:

$$\int_0^{\varepsilon_f}\left(\frac{\sigma_{\max}}{\sigma_s}\right)d\varepsilon = C, \tag{2}$$

where ε_f –maximum strain at failure,

$\sigma_{\max}$ –maximal principal tensile stress,

σ_s – strain resistance,

C – material constant.

However, the Cockroft -Latham criterion does not take into account the material loading history and the deformation behavior. Therefore, in this paper, to achieve set aim, it is proposed to use the method considered in the work [2, 3], which has an advantage over the Cockroft -Latham criterion, since it considers the material loading history and the deformation behavior, whether monotonic or alternating. It is assumed that metal has no damage before deformation. The moment of the microfracture appearance or sample separation during testing is associated with the achievement the value of damage ω = 1 (microfracture criterion). According to the proposed method, the influence of the deformation behavior of the samples on the plasticity is estimated using the indexes a and Λ_p, which are included in the metal damage accumulation model under monotonic (3) deformation.

$$\omega = \int_0^{\Lambda_i}\frac{a\Lambda^{a-1}}{\Lambda_p^a}d\Lambda\ . \tag{3}$$

where $\Lambda = \tan\gamma$ – shear strain degree,

Λ_i – plastic strain amplitude,

$a = a_0^{1+0,238\frac{\sigma}{T}}$ and $\Lambda_p = \Lambda_{p_0}\exp^{\left(\lambda\frac{\sigma}{T}\right)}$ – determining relations of the ductile failure mechanics known from the approximation of experimental data,

$\frac{\sigma}{T}$ – relative mean normal stress,

a_0, Λ_{p_0}, λ – coefficients, which depend on the steel or alloy grade, determined with the use of experimental data by the least-squares method.

The model of metal fracture under alternating plastic deformation is based on the idea that the intensity of metal damage accumulation at the beginning of each stage is zero and depends on the amplitude of alternating deformation Λ_i. During alternating deformation damage has the property of additivity, and for n deformation stages is determined by summation (4):

$$\omega = \sum_{i=0}^{n}\int_0^{\Lambda_i}\frac{a\Lambda^{a-1}}{\Lambda_p^a}d\Lambda\ , \tag{4}$$

It is assumed that the proposed method for determining the fracture of metals will allow to more accurately determine the value of the damage criterion for unidirectional or alternating torsion of cylindrical samples in comparison with existing methods.

2 Research methodology

Computer simulation of unidirectional and alternating torsion of cylindrical samples was carried out in the software complex Deform 3D. Steel 20 was selected as a material for the test samples (object type elastoplastic), for which the coefficients are equal to $a_0 = 2{,}8$, $\Lambda_{p_0} = 2{,}85$ and λ = -0,669. During the samples torsion the relative mean normal stress $\frac{\sigma}{T}$ and Lode coefficient μ_σ (used to estimate the stress state, characterizing the stress deviator and type of sample testing) are equal to zero, thus the indexes $a = a_0$, $\Lambda_p = \Lambda_{p_0}$ and λ coefficient is irrelevant. The samples were tested at constant values of thermomechanical parameters: σ/T = const; μ_σ = const; temperature Θ = const and shear-strain rate H = const.

During unidirectional or alternating torsion testing, it is more rational to use the samples with a neck in the central zone with a radius of *R*. In the work [4] it is shown that the optimal ratio of the neck radius *R* and the diameter of the sample in the smallest section *d* is 1,25. The use of such samples (Figure 1) allows not only to localize the strain, but also to more accurately determine the strain degree before the fracture occurs. For computer simulation, a solid model of the sample with the following dimensions was made: *D* = 10 mm, *R* = 10 mm, *d* = 8 mm, length of the working part of the sample *l* = 20 mm.

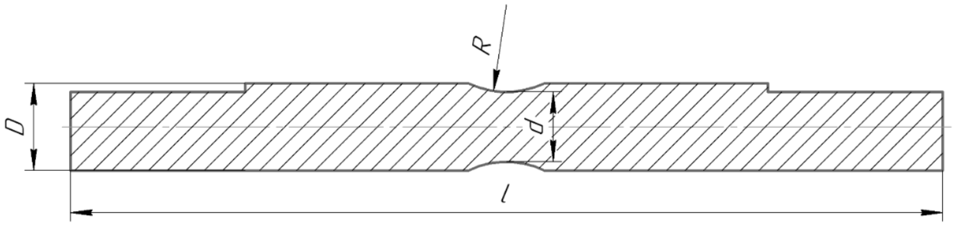
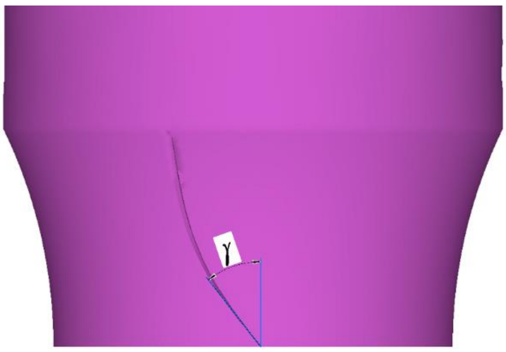


Figure 1. Torsion testing sample

For a more accurate determination of the indicators of the stress-strain state and the damage criterion on the solid-state model, a fine-mesh density window was created (Figure 2a). In both cases of unidirectional and alternating torsion of the samples, the total torsion angle was 180° (π rad). The amplitude of plastic deformation at alternating torsion was 45° (π/4 rad). The torsion speed was 10 RPM. To measure the angle γ the stripe on the sample was made (Figure 2b).

a)



b)

Figure 2. Solid model of the sample: a – general view, b – γ angle measurement.

To determine the stress-strain state and the damage criterion in the sample cross section 21 points were plotted across the diameter in the central part (point 1 at the sample surface and point 21 at the sample axis) at a distance of 0.2 mm from each other (Figure 3). Point tracking allowed to record and import the values of the required parameters at any moment of time in a table form in order simplify the processing of the obtained after computer simulation data.

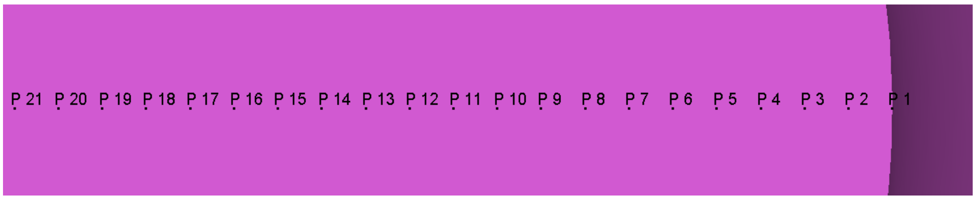


Figure 3. Point tracking

In order to simplify the calculations, the influence of temperature on the damage value and the accumulated strain degree was not taken into account.

3 Results and discussion

The values of all parameters are specified for the sample surface (tracking point 1).

The unidirectional torsion computer simulation results are presented in Table 1.

Table 1. The unidirectional torsion computer simulation results

Torsional angle	π/4	π/2	3π/4	π
γ	38,3	55,3	64,3	69,57
$\mathbf{\Lambda_c}$	0,7898	1,4442	2,0778	2,6846
$\mathbf{\Lambda_D}$	0,8081	1,4523	2,1129	2,7496
$\mathbf{\omega_c}$	0,0275	0,1491	0,4128	0,8459
$\mathbf{\omega_{C\text{-}L}}$	0,2691	0,4962	0,7199	0,9163

where Λ_c – calculated shear strain degree depending on the γ angle;

Λ_D – shear strain degree according to Deform 3D;

ω_c – damage criterion, calculated by the method [2];

$\omega_{C\text{-}L}$ – Cockroft-Latham damage criterion.

As can be seen from Table 1, the difference between the values of calculated shear strain degree and shear strain according to the program data is not more than 2.5%, which makes it possible to judge that the convergence of theoretical calculations and computer simulation results is good.

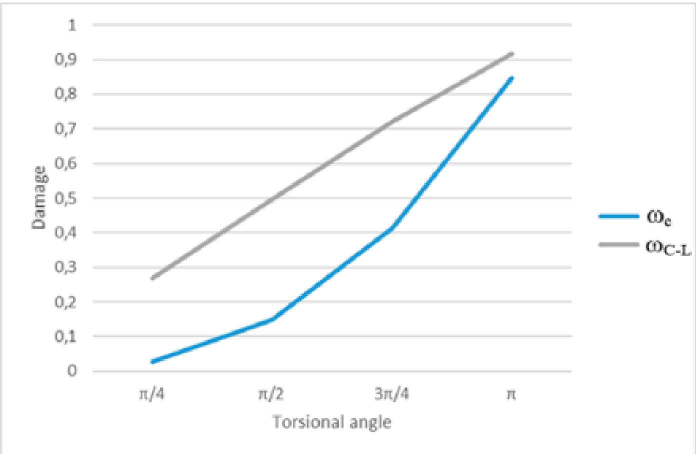


Figure 4. Damage criterion comparison during unidirectional torsion

Figure 4 shows a comparison graph of the damage values at unidirectional torsion. As can be seen from the figure, the damage curve according to the Cockroft -Latham criterion is linear and at the angle of twisting π/4 rad already has a higher value than by the calculated method. The convergence appears only at large torsional angles. From this it could be concluded that the proposed method allows more accurately determine the damage value at small torsional angles.

The alternating torsion computer simulation results are shown in Table 2.

Table 2. The alternating torsion computer simulation results

Torsional angle	π/4	π/2	3π/4	π
γ	38,27	33,4	30,1	29,07
Λ_c	0,7889	1,4483	2,0279	2,5839
Λ_D	0,8025	1,4755	2,1059	2,7163
ω_c	0,0274	0,0440	0,0556	0,0659
$\omega_{C\text{-}L}$	0,2673	0,4920	0,7021	0,9059

During alternating torsion (Table 2), the difference between the values of calculated shear strain degree and shear strain according to the program data is not more than 5%, which also indicates a good convergence of theoretical calculations and computer simulation results.

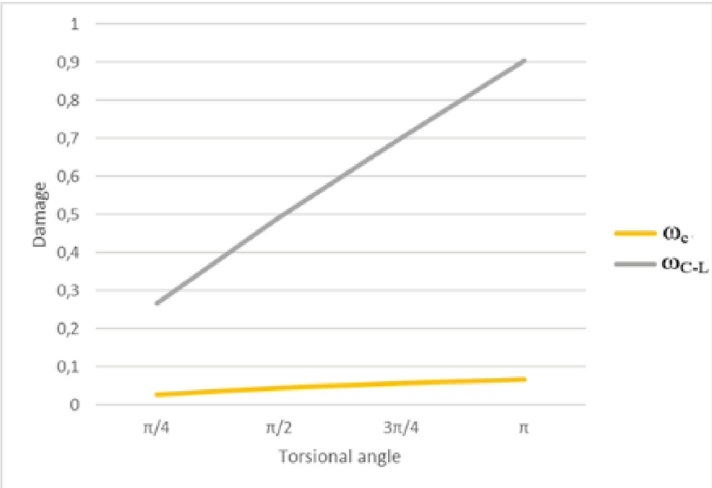


Figure 5. Damage criterion comparison during alternating torsion

Damage criterion comparison results at alternating torsion are presented in Figure 5. During calculating the damage at alternating torsion, it is assumed that the intensity of the accumulation of damage at the beginning of the *i-th* stage is zero and does not depend on the accumulated damage in the previous stages. Due to this, the sample could be subjected to alternating deformation by a greater number of deformation stages before the fracture than during monotonic deformation.

Conclusion

Computer simulation of the samples testing at unidirectional and alternating torsion was performed. The degree of shear deformation and damage criterion were chosen as the comparable parameters. The damage criterion was calculated using two existing methods. By comparative analysis results, it was determined, that the values of shear deformation degree according to computer simulation and theoretical calculation, in both cases of unidirectional and alternating torsion have good convergence. Comparison of damage calculation methods has shown that the use of the proposed in this paper method is more appropriate than the use of the existing method of Cockroft-Latham, because it considers the loading stages number and the plastic deformation amplitude and provides more accurate results at small torsional angles.

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