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COMBINED FRACTURE MODELS OF PLASTIC MATERIALS

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Abstract *This paper discusses the influence of the type of stress-strain state on the fracture prediction accuracy of AA7108-T6 aluminum alloy in numerical simulation. The plasticity curve of the extruded profile, approximated using the plasticity condition of Barlatt et al. demonstrates that plane deformation in the direction of maximum stress produces a stress state with a principal stress ratio close to nearly uniform biaxial tension. Nevertheless, the experimental tests showed significant differences in the fracture strain values. This indicates the necessity to take into account not only the nature of the stress state, but also the peculiarities of the deformed state when predicting the fracture of materials. The obtained results emphasize the importance of an integrated approach in the development of fracture criteria and the construction of combined models.*

In order to improve the accuracy of prediction, a combined model of tear-off fracture was developed, in which the character of the stress-strain state is described by a certain parameter. In this case, the fracture plane is oriented perpendicular to the direction of maximum normal stress. A combined model of shear fracture is also presented, in which fracture occurs along the plane of action of maximum tangential stresses, taking into account the corresponding parameter of the stress-strain state.

The dynamic fracture diagrams obtained by the developed models were compared with the test results of various specimens.

The models demonstrate a high degree of correspondence with experimental data, confirming their applicability for the description of complex loading modes. The results emphasize the effectiveness of the combined approach to fracture modeling and its prospects for further research and engineering applications.

Keywords: plastic materials, fracture, aluminum alloy AA7108-T6, combined model of fracture, stress-strain state, plasticity curve, Barlatt's condition, numerical simulation, finite elements, dynamic diagram.

Fracture of plastic materials under complex loading conditions is one of the most important problems of modern deformable solid mechanics. The safety and durability of critical engineering structures in the aerospace, transport, energy and construction industries directly depend on the reliability of predicting the behavior of structural materials under ultimate loads. Aluminum alloys, having high specific strength and good machinability, are widely used in structures subjected to intensive operational loads. However, even for such materials, failure can occur by various mechanisms - from breakaway to shear - depending on the local stress-strain state.

Classical fracture criteria, as a rule, are based on either stress or strain states and often do not provide an adequate description of real fracture processes, especially for complex loading paths. This requires the development of more universal models capable of taking into account the complex interaction of various factors. One of the effective approaches is the use of combined fracture models, which allow integrating the influence of several material characteristics and loading conditions.

This work is aimed at investigating the fracture characteristics of AA7108-T6 aluminum alloy using a combined approach that includes both breakaway and shear simulations, taking into account the relevant stress-strain state parameters.

Fig. 1 shows the plasticity curve of a pressed profile made of aluminum alloy AA7108-T6 from [1], approximated by the plasticity condition of Barlat et al. [2]. If in finite element modeling the plasticity surface is used as a plastic potential, then at plane deformation in the x direction, which corresponds to the maximum stress σ_x, a stress state with the ratio of principal stresses σ_y / σ_x, approximately equal to 0,9 is established, i.e. very close to biaxial uniform tension. Meanwhile, in corresponding bending tests of wide specimens, i.e., under plane deformation, a fracture strain of about 0,2 was measured, and in drawing tests with a spherical punch under approximately uniform biaxial tension, a fracture strain of 0,44 was obtained.

It follows that in such cases, in addition to the type of stress state, the type of deformed state should be taken into account when calculating the fracture strain.

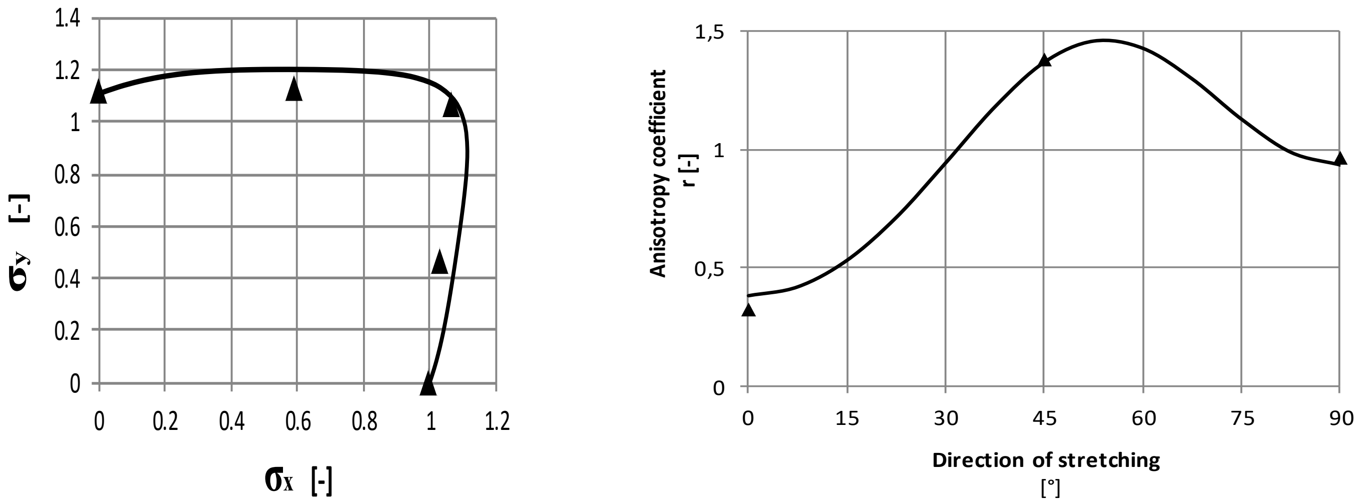


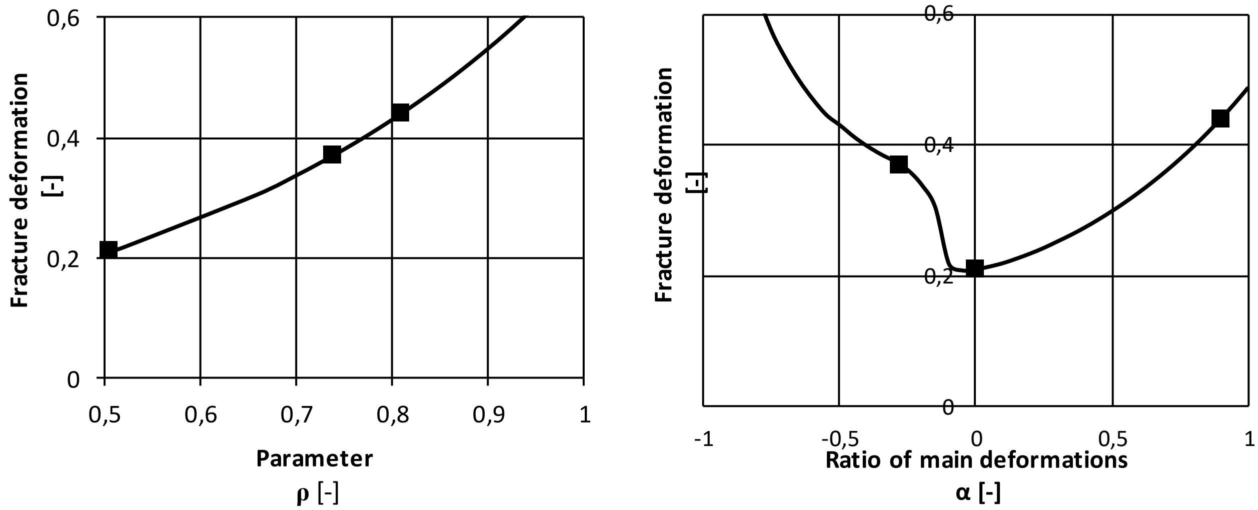
Fig. 1. Plasticity surface and dependence of the anisotropy coefficient of the aluminum profile on the tensile direction from [1]. Stresses are referred to the tensile strain resistance in the direction of pressing

In accordance with this, a model of break-off fracture was developed (in break-off fracture, the fracture plane is close to the plane where the maximum normal stress acts), in which the type of stress-strain state is characterized by the parameter

$$\rho = \frac{1 - s\eta}{\dot{\varepsilon}_{\max} / \dot{\varepsilon}_g}.$$

Here $\eta = \sigma_{ii} / \sigma_M$ is the stiffness of the stress state, where σ_M is the stress intensity, $\dot{\varepsilon}_{\max} > 0$ is the maximum strain rate, $\dot{\varepsilon}_g = \sqrt{2\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}/3}$ is the geometric equivalent strain rate, and s is a material parameter.

The breakaway diagram is approximated by the equation $\varepsilon_{nf}^{**} = d\exp(q\rho)$, with two material parameters d and q.



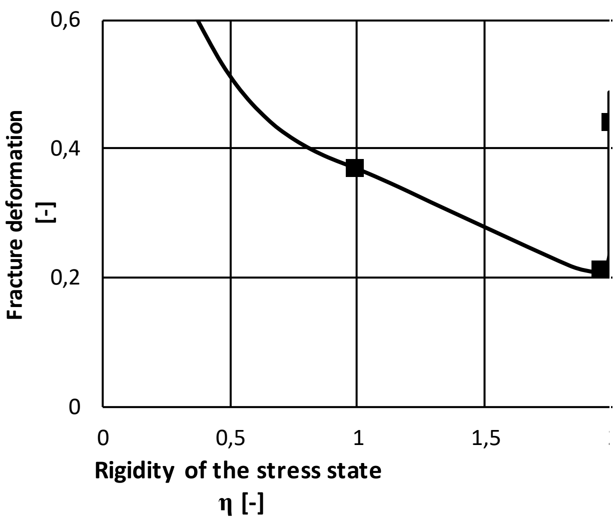


Fig. 2. Dynamic breakaway diagram of the aluminum profile according to the combined model versus test results (bottom left to right: tensile and bending in pressing, drawing with a hemispherical punch).

Fig. 2 shows in different coordinates the dynamic (100 1/s) breakaway diagram of the aluminum profile, whose ductility curve is shown in Fig. 1. The results of uniaxial tensile, bending and drawing tests with a hemispherical punch are compared with the calculation according to the given breakaway model with the following parameters $s = 0.287$, $d = 0.062$, $q = 2.4264$.

In the combined shear model (in shear fracture, the fracture plane is close to the plane on which the maximum tangential stress acts), the parameter of the stress-strain state type is written as

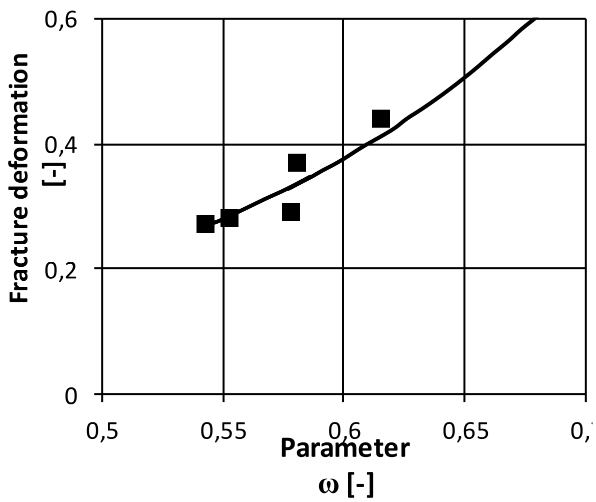
$$\omega = \frac{1 - k\eta}{g}$$

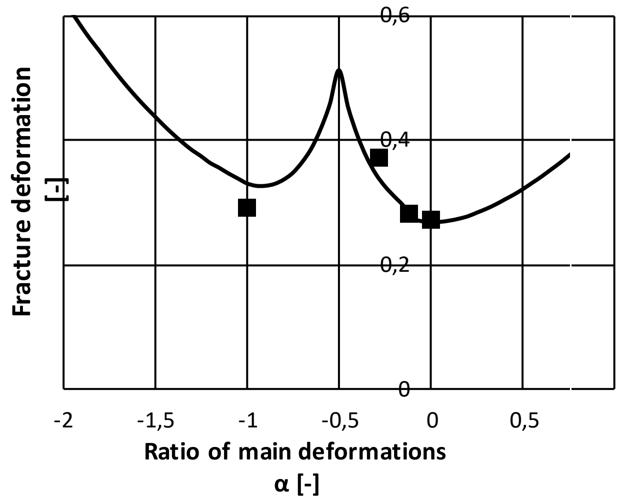
Here $g = \dot{\gamma}_{\max} / \dot{\varepsilon}_g$, where $\dot{\gamma}_{\max}$ is the maximum plastic shear rate, k is the material parameter.

The shear diagram is approximated by the equation

$$\varepsilon_{sf}^{**} = b_1 \exp(-f\theta) + b_2 \exp(f\theta),$$

with the three material parameters b_1, b_2 and f.





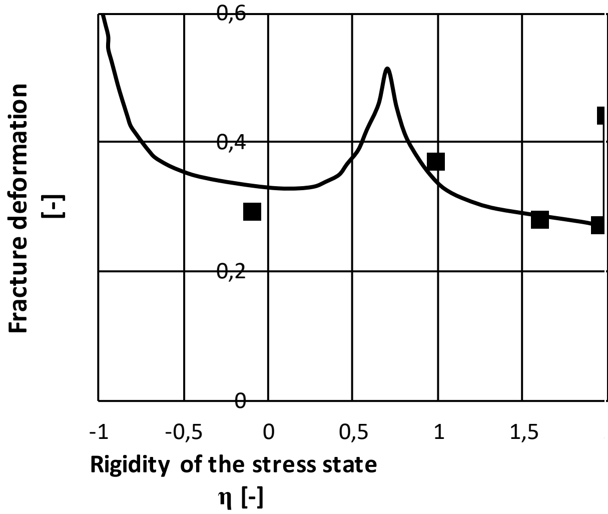


Figure 3. Dynamic shear diagram of an aluminum alloy profile: model in comparison with test results (bottom from left to right: shear, tensile of flat specimens with a hole and with grooves in the transverse direction and at an angle of 45° to the axis, according to Erickson).

Fig. 3 shows in different coordinates the dynamic shear diagram of the aluminum profile, the plasticity curve of which is shown in Fig. 1. The test results are compared with the shear model calculation with the following parameters $k = 0.03$, $b_1 = 0.032$, $b_2 = 0.0107$, $f = 5.931$.

Conclusions

1. The character of the deformed state has a significant influence on the failure of plastic materials, and it must be taken into account along with the stress state in numerical simulation.

2 The use of plasticity curve approximated by Barlatt's condition allows to adequately describe the behavior of aluminum alloy AA7108-T6 under complex loading paths, especially under conditions of plane deformation.

3. The developed combined models of fracture – by detachment and shear – provide a more accurate description of the fracture mechanism, reflecting the influence of both normal and tangential stresses, and their corresponding parameters of the stress-strain state.

4. The example of aluminum alloy AA7108-T6 shows that at close stress states (e.g., uniform biaxial tension), but different deformation paths, significant differences in ultimate strains are observed, up to more than twofold increase. This confirms the necessity to take into account the influence of the deformation path when building fracture models, especially in numerical simulations using finite element analysis.

5. The presented models have high predictive ability and can be used for fracture analysis of aluminum and other ductile alloys in engineering practice.
6. The combined approach to fracture modeling is a promising direction in the field of fracture mechanics and can be adapted for different types of materials and loading conditions.

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КОМБІНОВАНІ МОДЕЛІ РУЙНУВАННЯ ПЛАСТИЧНИХ МАТЕРІАЛІВ

Анотація. В даній роботі розглядається вплив виду напружено-деформованого стану на точність прогнозу руйнування алюмінієвого сплаву AA7108-T6 під час чисельного моделювання. Крива пластичності пресованого профілю, апроксимована з використанням умови пластичності Барлата та ін., демонструє, що в разі плоского деформування в напрямі максимального напруження формується напружений стан із відношенням головних напружень, близьких практично до рівномірного двовісного розтягу. Проте експериментальні випробування показали істотні відмінності в значеннях деформації руйнування. Це вказує на необхідність враховувати не тільки характер напруженого стану, а й особливості деформованого стану при прогнозуванні руйнування матеріалів. Отримані результати підкреслюють важливість комплексного підходу під час формування критеріїв руйнування та побудови комбінованих моделей.

З метою підвищення точності прогнозу було розроблено комбіновану модель руйнування відривом, у якій характер напружено-деформованого стану описується певним параметром. При цьому площину руйнування орієнтовано перпендикулярно до напрямку максимального нормального напруження. Також представлено комбіновану модель руйнування зрізом, у якій руйнування відбувається за площиною дії максимальних дотичних напружень, з урахуванням відповідного параметра напружено-деформованого стану.

Проведено зіставлення динамічних діаграм руйнування, отриманих за розробленими моделями, з результатами випробувань різних зразків.

Моделі демонструють високий ступінь відповідності експериментальним даним, підтверджуючи їхню застосовність для опису складних режимів навантаження. Результати підкреслюють ефективність комбінованого підходу до моделювання руйнування і його перспективність для подальших досліджень та інженерного застосування.

Ключові слова: пластичні матеріали, руйнування, алюмінієвий сплав AA7108-T6, комбінована модель руйнування, напружено-деформований стан, крива пластичності, умова Барлата, чисельне моделювання, скінченні елементи, динамічна діаграма.

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