Growth and Closure of Voids in Metals at Negative Stress Triaxialities

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Abstract. Damage of metals subjected to large plastic deformations typical for forming processes is mainly governed by void nucleation, growth and coalescence. An opposite process may occur in deformation processes with negative stress triaxialities: the closure of strain-induced defects under large hydrostatic pressure. Understanding the mechanisms of damage growth and healing under plastic deformation of metals is still an urgent problem. In order to solve it a theoretical framework for anisotropic ductile damage based on a physically motivated concept for changes in the void volume and shape was recently developed [6]. Strain-induced damage was experimentally determined during uniaxial compression of cylindrical metallic specimens with artificial voids represented by fully-trough drilled holes. It was revealed that the governing physical mechanism of failure is a change in void shapes due to compressive stresses at low negative stress triaxialities in contrast to the growth of voids volume due to high positive stress triaxialities in the processes with dominating tensile stresses. The tensorial model presented in [6] proved to be able to describe kinetics of ductile damage, failure as the ultimate damage, and the closure of voids at negative stress triaxialities.

Introduction

The scheme of ductile material compression has been successfully implemented in many metal forming processes and can be characterized by negative values of stress triaxiality. Damage mechanics considers ductile failure as a kinetic deterioration of the deformed material. The difficulties of the analysis of damage kinetics are related to the determination of the material functions which appear in the constitutive equations. Stress triaxiality under plastic compression varies considerably both over the specimen volume (in the meridian section) and over the strain path. The averaged values of stress triaxiality are commonly used for the analysis of plastic compression.

The recent studies [1, 5] show that the known ductile damage criteria have had only limited success in predicting the fracture in upsetting/forging processes. Different experimental setups seem to give different values of the critical material parameters required in various ductile damage criteria. There have been little efforts to predict defects in upsetting/forging using continuum damage mechanics models [2-4]. In the present work, an attempt is made to predict failure occurrence using a recently developed tensorial framework for ductile damage [6] along with the large deformation elasto-plastic FEM analysis.

Theoretical background

In order to determine strain components for the formulation of a tensorial model for ductile damage as well as for processing of experimental data we made use of the typical geometric models for a macroscopic representative volume element (RVE) and a mesoscopic volume element with a single void (ME) shown in Fig. 1 and Fig. 2 [6].

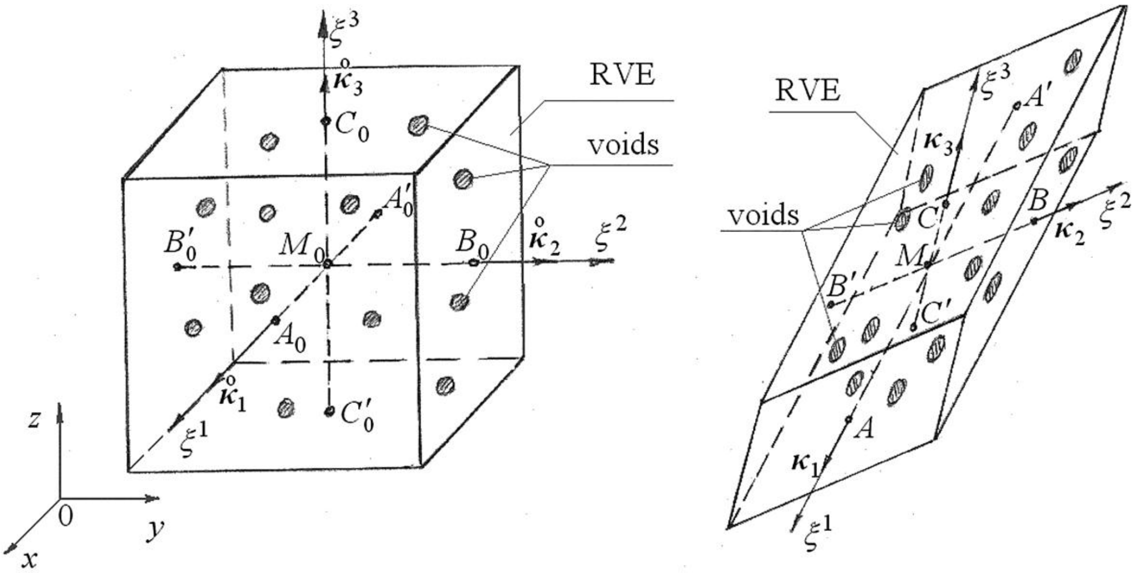


Fig. 1: Representative volume element (RVE) under arbitrarily complex deformation; *left:* initial moment, *right:* current moment

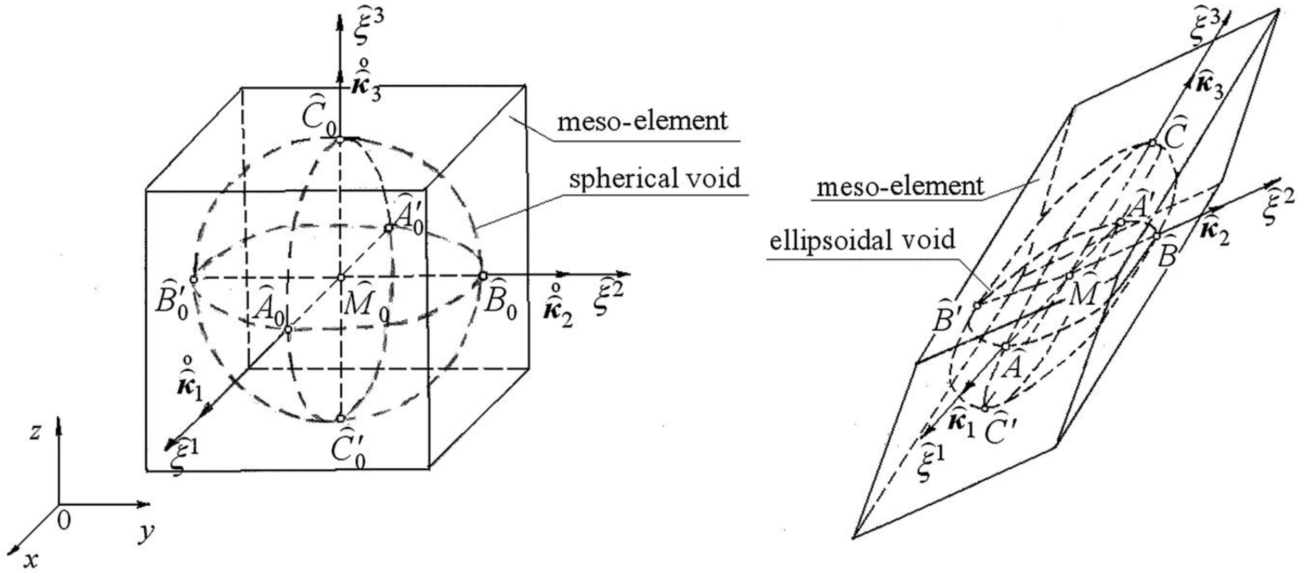


Fig. 2: Meso-element with an ellipsoidal void under arbitrarily complex deformation, *left:* initial moment, *right:* current moment

The following notation is used: Since the strains are defined at the macroscale (for the RVE) and at the mesoscale (for the ME) the tensors of strain increments and strain rates are also introduced at the macroscale, $\mathrm{d}\boldsymbol{\varepsilon}$ and $\dot{\boldsymbol{\varepsilon}}$, and at the mesoscale, $\mathrm{d}\bar{\boldsymbol{\varepsilon}}$ and $\dot{\bar{\boldsymbol{\varepsilon}}}$, respectively. The corresponding tensorial components are denoted by $\mathrm{d}\varepsilon_{ij}$, $\dot{\varepsilon}_{ij}$, $\mathrm{d}\bar{\varepsilon}_{ij}$, $\dot{\bar{\varepsilon}}_{ij}$, including volumetric parts, $\mathrm{d}\varepsilon^{k\cdot}_{\cdot k}$, $\dot{\varepsilon}^{k\cdot}_{\cdot k}$, $\mathrm{d}\bar{\varepsilon}^{k\cdot}_{\cdot k}$, $\dot{\bar{\varepsilon}}^{k\cdot}_{\cdot k}$, and deviatoric components, $\mathrm{d}e_{ij}$, $\dot{e}_{ij}$, $\mathrm{d}\bar{e}_{ij}$, $\dot{\bar{e}}_{ij}$, as well as the equivalent von Mises measures, $\mathrm{d}\varepsilon_{\mathrm{eq}}$, $\dot{\varepsilon}_{\mathrm{eq}}$, $\varepsilon_{\mathrm{eq}}$, $\mathrm{d}\bar{\varepsilon}_{\mathrm{eq}}$, $\dot{\bar{\varepsilon}}_{\mathrm{eq}}$, $\bar{\varepsilon}_{\mathrm{eq}}$. Covariant tensor components are useful when formulating the constitutive equations for strain-induced damage. Covariant components of both the strain increment tensor and the strain rate tensor are geometrically meaningful and can be defined in terms of the metric tensor components. In order to determine these components established kinematic equations are used [6].

The analysis of ductile damage is based on the damage rate tensor: $\dot{\omega}_{ij} = \dot{\bar{\varepsilon}}_{ij} / \bar{\varepsilon}_{\mathrm{f}}$ ($\bar{\varepsilon}_{\mathrm{f}}$ denotes a normalizing factor related to the material failure). A decomposition of the increments of the damage tensor $\mathrm{d}\boldsymbol{\omega}$ into a volumetric and a deviatoric part, $\mathrm{d}\omega_{ij} = (1/3)\delta_{ij}\,\mathrm{d}\omega^{k\cdot}_{\cdot k} + \mathrm{d}\widetilde{\omega}_{ij}$ (where $\mathrm{d}\omega^{k\cdot}_{\cdot k}$ denotes the first invariant of the tensor $\mathrm{d}\boldsymbol{\omega}$ and δ_{ij} is the Kronecker delta), is physically meaningful. The volumetric part, $(1/3)\delta_{ij}\,\mathrm{d}\omega^{k\cdot}_{\cdot k}$, describes the damage increment caused by a change in void volume. The deviatoric increment, $\mathrm{d}\widetilde{\omega}_{ij}$, accounts for the increase in damage caused by a change in void shape. Such a view on damage kinetics enables us to introduce two damage measures, ω_1 and ω_2, for damage assessment:

$$\mathrm{d}\omega_1 = \mathrm{d}\omega^{k\cdot}_{\cdot k} = \frac{\dot{\bar{\varepsilon}}^{k\cdot}_{\cdot k}}{\bar{\varepsilon}_{\mathrm{f}}}\mathrm{d}t\,,\quad \mathrm{d}\omega_2 = \sqrt{3\dot{\widetilde{\omega}}^{i\cdot}_{\cdot j}\dot{\widetilde{\omega}}^{j\cdot}_{\cdot i}}\,\mathrm{d}t = \frac{\sqrt{3\dot{\bar{e}}^{i\cdot}_{\cdot j}\dot{\bar{e}}^{j\cdot}_{\cdot i}}}{\bar{\varepsilon}_{\mathrm{f}}}\mathrm{d}t = \tfrac{3}{\sqrt{2}}\frac{\dot{\bar{\varepsilon}}_{\mathrm{eq}}}{\bar{\varepsilon}_{\mathrm{f}}}\mathrm{d}t\,. \tag{1}$$

For an experimental study and modeling of ductile damage in terms of ω_1 and ω_2 it is convenient to define $\bar{\varepsilon}^{k\cdot}_{\cdot k}$ and $\bar{\varepsilon}_{\mathrm{eq}}$ and their derivatives as material functions of the equivalent deviatoric strain $\varepsilon_{\mathrm{eq}}$ of the RVE. The differential measures of damage can be finally represented as the integral normalized measures of damage, $\omega_1, \omega_2, \omega_{\mathrm{eq}} \in [0;1]$:

$$\omega_1 = \int_0^{\varepsilon_{\mathrm{eq}}} \frac{\left[\bar{\varepsilon}^{k\cdot}_{\cdot k}(\varepsilon_{\mathrm{eq}})\right]'}{\bar{\varepsilon}_{\mathrm{f}}(\varepsilon_{\mathrm{eq\,f}})}\mathrm{d}\varepsilon_{\mathrm{eq}}\,,\quad \omega_2 = \frac{3}{\sqrt{2}}\int_0^{\varepsilon_{\mathrm{eq}}} \frac{\left[\bar{\varepsilon}_{\mathrm{eq}}(\varepsilon_{\mathrm{eq}})\right]'}{\bar{\varepsilon}_{\mathrm{f}}(\varepsilon_{\mathrm{eq\,f}})}\mathrm{d}\varepsilon_{\mathrm{eq}}\,,\quad \omega_{\mathrm{eq}} = \int_0^t \sqrt{\left(\frac{\mathrm{d}\omega_1}{\mathrm{d}t}\right)^2 + \left(\frac{\mathrm{d}\omega_2}{\mathrm{d}t}\right)^2}\,\mathrm{d}t\,, \tag{2}$$

where ω_{eq} denotes the equivalent measure of damage, and the dash refers to differentiation with respect to $\varepsilon_{\mathrm{eq}}$. The damage tensor $\boldsymbol{\omega}$ and two normalized measures ω_1 and ω_2 associated with its invariants describe both the possibility of macroscopic failure in the danger zone of deformed materials and the possibility of the onset of active void coalescence and formation of large cavities. These measures are applied for the assessment of a quality of the meso-structure of metallic components produced by forming procedures (for details see [6]).

Experiments and simulations

The sought material functions which appear in Eq. (2) were experimentally determined for three ductile structural metals, *viz*., low-carbon steel (C 0.10-0.16%), aluminum alloy AlMg3, and pure copper (Cu 99.97 %). Upsetting tests for cylindrical specimens were performed. The design matrix for compression tests involved five types of specimens shown in Fig. 3. While type *A* had no any artificial voids the remaining four types had various arrangements of three fully-through drilled cylindrical holes. Type *B* had vertical holes in the meridian cross-section. Types *C*, *D*, and *E* had horizontal holes arranged at different angles to the axis of compressive load, *i.e.*, 90° (*C*), 45° (*D*), and 0° (*E*). The set of "void" arrangements were chosen based on the following rationale: Types *B* and *C* represented various orientations of the axis of holes w.r.t. the axial compressive load direction. The deformation of these specimens allowed us to reveal and to compare a contrasting effect of the hydrostatic pressure (negative stress triaxialities) on the dilatation within a zone with artificial voids.

The plan of experiments provided a variation of two more factors in compression tests, namely the ratio of the initial diameter to the initial height ($d_0/h_0 = 0.75;\ 1.00;\ 1.25$), and the relative distance between centers of holes ($l_h/d_h = 1.5;\ 2.5$). These factors affect strongly both the evolution of damage and the strain to fracture. The chosen range of d_0/h_0 corresponds to initial sizes of cylindrical bar-shaped billets which are widely applied in extrusion processes.

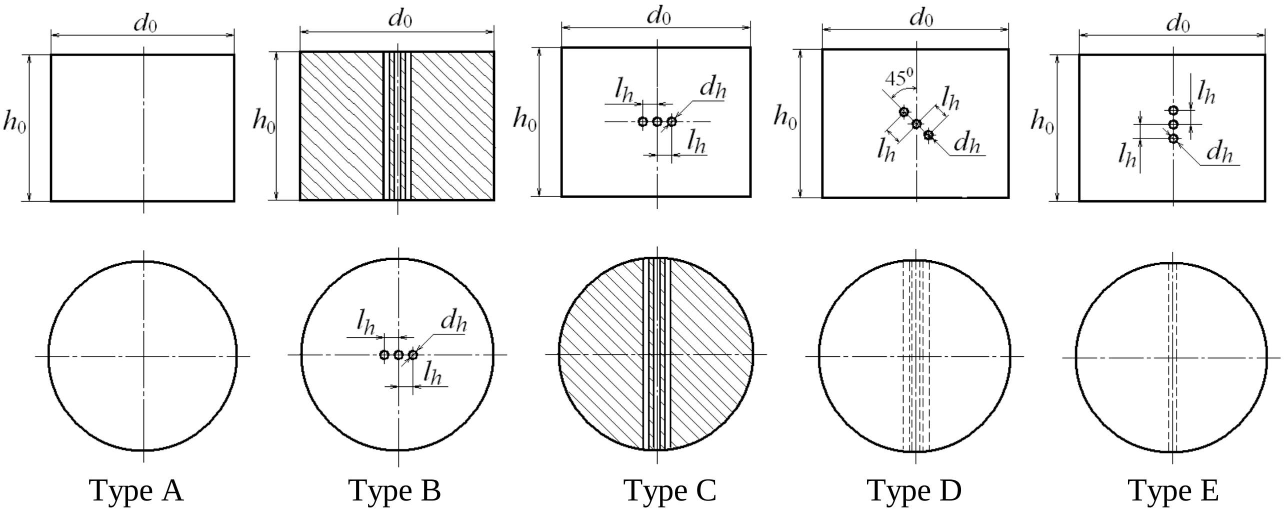
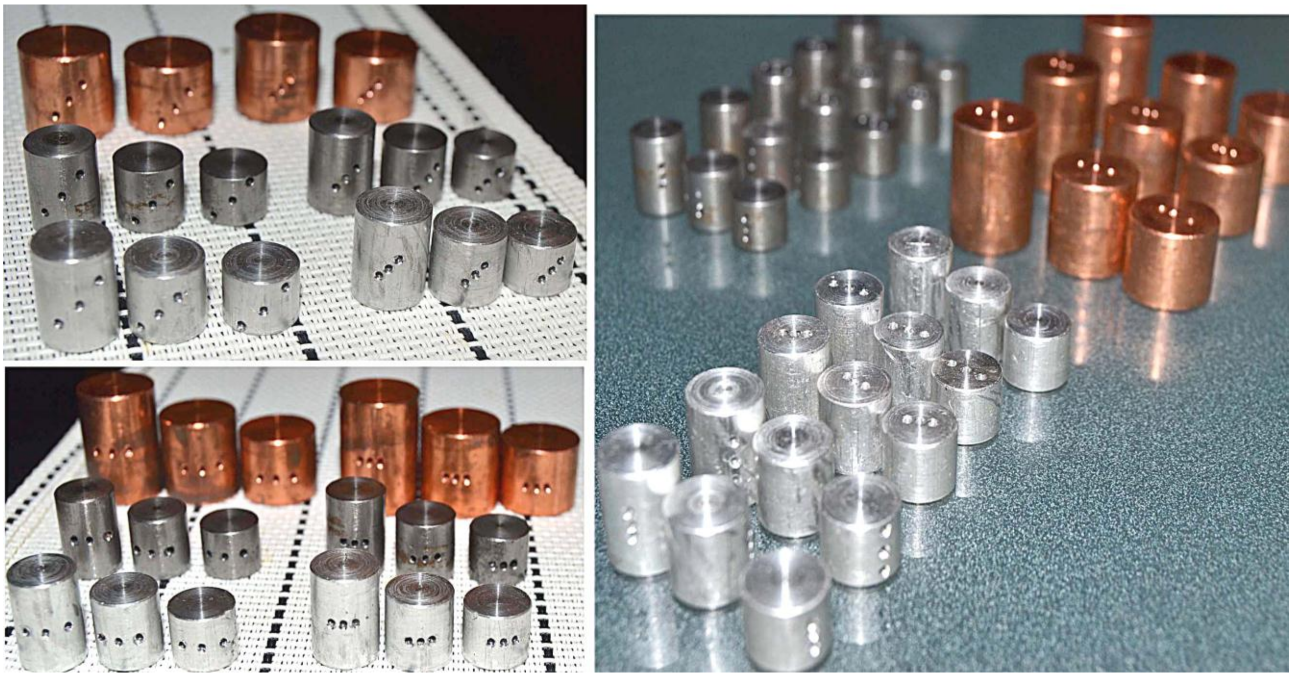


Fig. 3: Five types of cylindrical specimens

Upsetting tests were performed in a deformation-controlled manner by using a universal compressive testing machine with measurement instrumentation. Identical specimens were compressed to different stages in order to capture the fracture initiation (in each test). The moment of fracture will be detected by the onset of the macroscopic crack propagation on the side surface of specimens (shear fracture). Because of the friction between the specimens and the platens, a barreling effect occurs during the experiment near the equator of the specimens. Lubrication as well as chafing-plates was used in order to reduce the contact friction between the specimen and the platens. The dimensions of artificial voids and of the specimen were measured after each stage by means of a general-purpose optical microscope.



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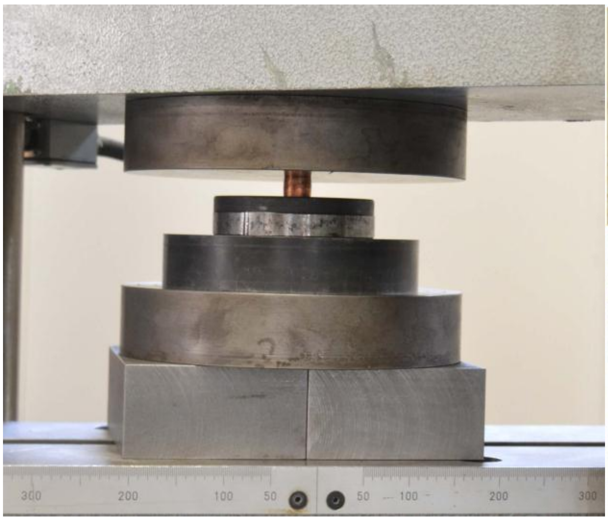


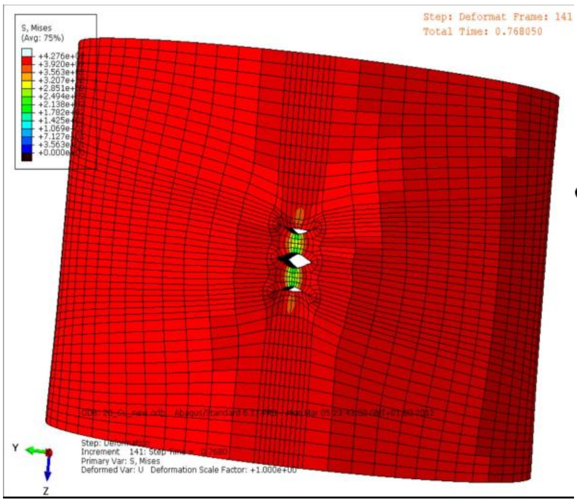
b

c

Fig. 4: Upsetting tests: (a) cylindrical specimens before compression; (b) a specimen in the testing machine; (c) different specimens after compression

This stepwise deformation of the specimens coupled with measurements of changing defects allowed us to determine the parameters of the evolution of damage during plastic deformation. As a result of the tests the material functions $\bar{\varepsilon}^{k\cdot}_{\cdot k}$ and $\bar{\varepsilon}_{\mathrm{eq}}$ incorporated into Eqs. (2) were determined for each investigated material that allowed us to find the sought damage functions ω_1, ω_2 and ω_{eq}.

The model of growth and closure of artificial defects under compression was also implemented into the commercial FEM-code ABAQUS in terms of a user-defined subroutine. The fine mesh (as compared to the size of an artificial void) allowed modeling of the stress-strain state at the mesoscale. The comparison between numerical and experimental results showed that a model provides a good fit (Fig. 5).



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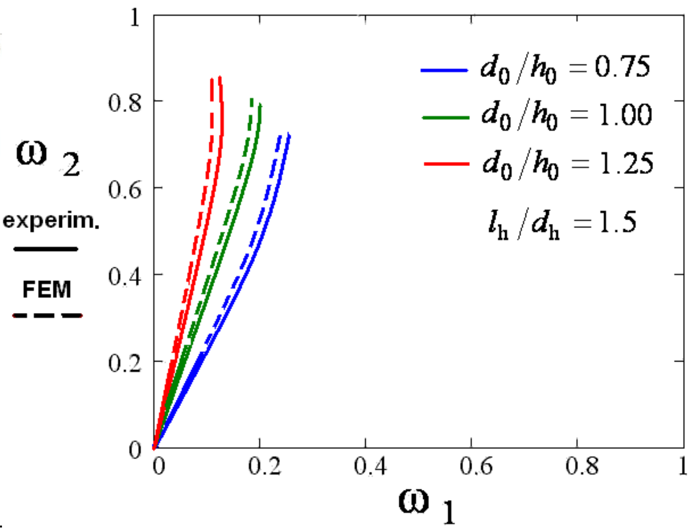


b

Fig. 5: Compression tests: (a) FE simulation of the copper specimen E; (b) damage evolution

Results and discussion

It was found how the equivalent von Mises strain to failure, $\varepsilon_{\mathrm{eq\,f}}$, depends on void arrangement that appeared to be a significant factor for the evolution of strain-induced damage. All steel specimens revealed failure. However, the aluminum and copper specimens without holes as well as those with vertical holes if compressed to higher strains, $\varepsilon_{\mathrm{eq}}$ = 1.56…1.63, did not reveal any signs of failure. Tests made involving specimens with vertical holes agreed with those given in [2] and [3], where it was revealed that failure occurred on the meridian surface but not in the specimen's core. Significant hydrostatic pressure in the core healed artificial defects and prevented failure.

The hypothesis that there can be such a stress triaxiality that failure does not occur even on the meridian surface [1, 5] was confirmed (Fig. 6). Large hydrostatic pressure led to the closure of defects and formed chemical bonds between the joined surfaces of defects (that corresponds to pressure welding at the mesoscale). In our experiments the strains $\varepsilon_{\mathrm{eq}}$ = 1.04…1.67 were obtained at the dimension ratios d/h = 5.0…7.0. These values correspond to those in extrusion processes.

The equivalent damage vs. the equivalent strain curves reveal the "equilibrium" point for the kinetic process of growth and closure of defects (Fig. 6). Material failure can occur only before this equilibrium point. Moreover, the governing physical mechanism of failure is a change in void shapes due to compressive stresses at low negative stress triaxialities in contrast to the growth of voids volume due to high positive stress triaxialities in the processes with dominating tensile stresses. Ellipsoidal voids oriented in the direction of shear bands initiate macroscopic cracks on a specimen's lateral surface. If the strain does not attain the ultimate value before the point of kinetic equilibrium the further plastic deformation of a material is accompanied by a growing influence of negative stress triaxiality on the closure of defects, and the failure (macroscopic crack) does not occur. The stage of the active closure corresponds to a rapid growth of the equivalent strain to fracture on the fracture loci given in [1] (Fig. 7).

Fig. 8 represents the closure of artificial voids The stages *b* and *c* in Fig. 8 correspond to the growth of damage mainly due to changes in void shape (damage parameter ω_2). At high compression ratios the hydrostatic pressure increases extremely and leads to the active closure of voids. At stage *d* the ligament occurs in the middle of the void. As a result we have two smaller voids separated by the ligament. This process is opposite to void coalescence and was termed "anti-coalescence." Anti-coalescence can lead to the complete closure (stage *e*). The transformation of spherical voids into elongated voids and the location of the major axis of the ellipsoid in the specimen's cross-section contribute to the closure as well. The major axis of an elongated void is orthogonal to the compressive force. Therefore, the conditions for the void closure (*i.e.*, for "anti-coalescence") are favorable. The developed tensorial framework proved to be able to describe kinetics of ductile damage, failure (as ultimate damage), and the void closure under hydrostatic pressure. To this end the use of our second damage parameter, ω_2, which is associated with the deviatoric tensor of damage, is very important.

One of the urgent problems that will be addressed in our future studies is the accurate determination of the variable negative stress triaxiality both in upsetting tests and non-steady-state metal forming processes. Stress triaxiality, ST, and Lode angle, ϕ_σ, are extremely changing in such processes both over the volume of the plastic zone and over the time, *i.e.*, they are the functions of coordinates and time: $ST = ST(x_i, t)$ and $\phi_\sigma = \phi_\sigma(x_i, t)$. Accordingly, the material particles move along flow trajectories in a variable field of parameters ST and ϕ_σ. The strain to failure, $\varepsilon_{\mathrm{eq\,f}}$, can not be considered as the constant when predicting ductile damage and failure in non-steady-state processes. The use of its values, $\left(\varepsilon_{\mathrm{eq\,f}}\right)_{\mathrm{m}}$, averaged w.r.t. the material volume and, moreover, w.r.t. the process time, can introduce an uncertain error in the calculations. With the use of experimental data (both own and published by other authors) the dependences of the limit strain to failure on stress triaxiality and Lode angle will be analyzed. 3D fracture loci will be determined for the chosen materials, *viz.*, low carbon steel, aluminum alloy and pure copper, at variable values of stress triaxialities and Lode angles. The interval on which the function $\varepsilon_{\mathrm{eq\,f}} = \varepsilon_{\mathrm{eq\,f}}(ST, \phi_\sigma)$ will be defined includes the following ranges of stress triaxiality and Lode angle: $ST \subset [-1.5;0]$ and $\phi_\sigma \subset [0;\pi/6]$, respectively. This interval corresponds to the stress state which occurs in the material processed by extrusion.

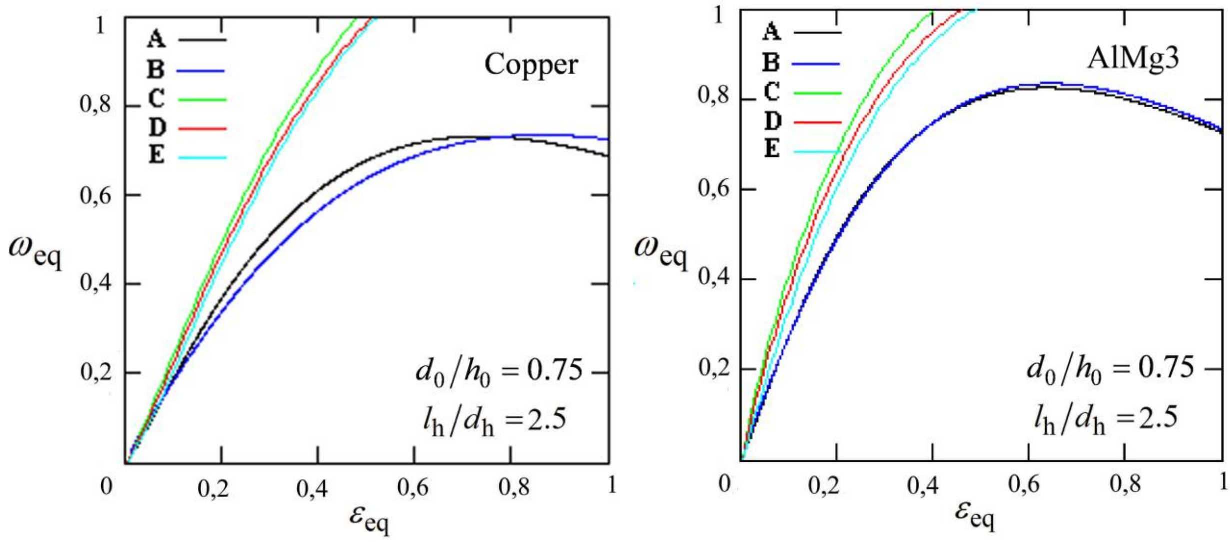


Fig. 6: Equivalent damage *vs.* equivalent strain for copper (*left*) and aluminum specimens (*right*)

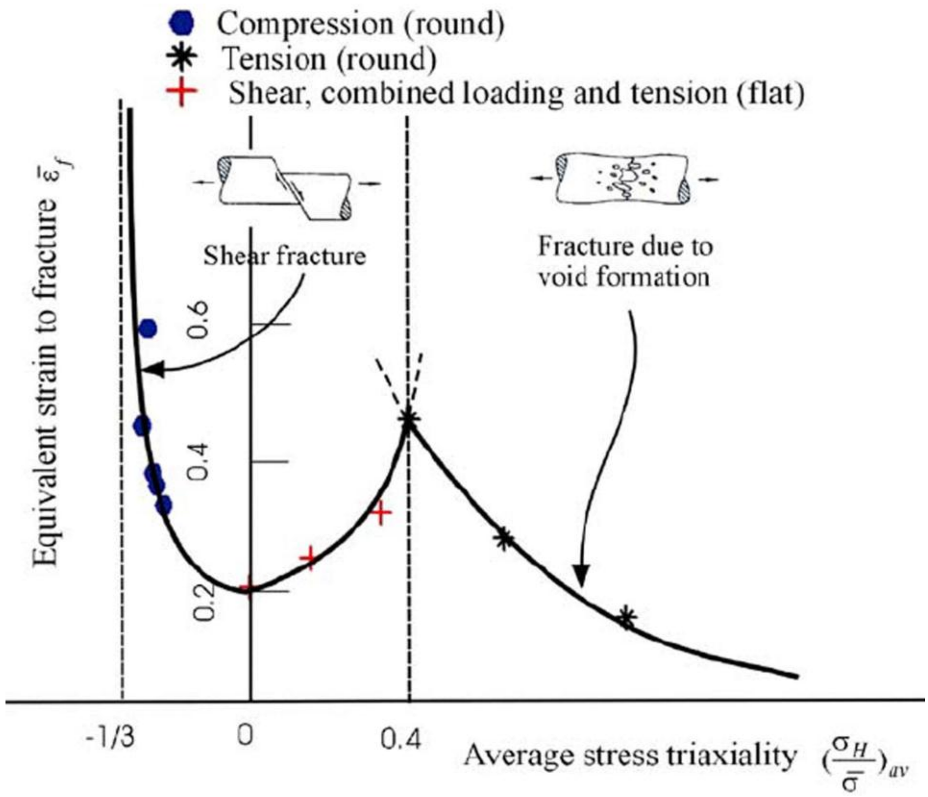
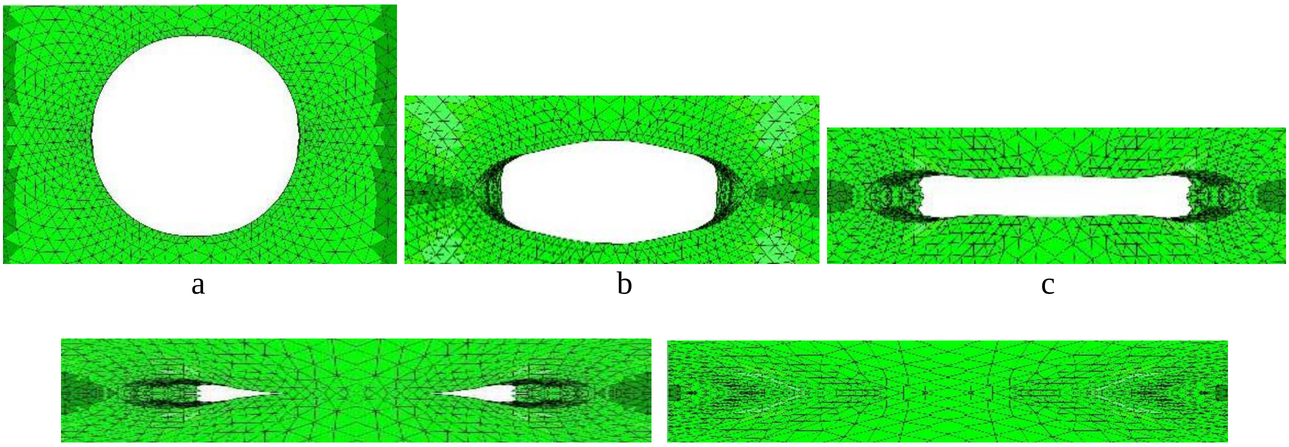


Fig. 7: Dependence of the equivalent strain to fracture on the stress triaxiality [1, 5]



a b c d e

Fig. 8: FE simulation of the closure of an artificial void: *a* initial state; *b*, *c* change in a void shape; *d*, *e* closure of a void

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