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DAMAGE AND FRACTURE OF VISCOUS-PLASTIC COMPRESSIBLE MATERIALS

A.R. Arutyunyan*, R.A. Arutyunyan

St.-Petersburg State University, Universitetsky pr., 28, St.-Petersburg, Petrodvoretz, 198504, Russian Federation

*e-mail: a.arutyunyan@spbu.ru

Abstract. Experimental creep curves and long-term strength curves for viscoelastic compressible materials have been obtained at room temperature for a wide range of stresses. The residual density change (loosening) of the material is considered as the main damage factor. A modified creep equation for the loosening medium is proposed, which can describe the second and third regions of the creep curve. Based on proposed equation the criterion of long-term strength is formulated. It is shown that in the region of relatively high stresses and under the assumption of incompressibility of the material, this criterion coincides with the known Hoff law of viscous fracture.

Keywords: polymer materials, poly methyl methacrylate, pores, cracks, crazing, loosening, damage, creep, density changes, creep curve, fracture, long-term strength criterion

1. Introduction

Investigations of the hidden stage of fracture under creep conditions [1] are shown that structural materials, in particular polymer materials, are damaged due to the pores and cracks accumulation using the crazing mechanism [2,3]. In works [4-8] the theoretical investigations of craze problem of polymer materials are performed. Different crazing initiation and damage models are proposed. The ability of these models applying to describe the crazing mechanism are analyzed. Papers [9-12] are devoted to experimental investigation of crazing in polycarbonate and poly methyl methacrylate specimens subjected to uniaxial tensile stress and tensile creep experiments at different stress and temperature levels. The different possibilities of cracks healing and crazing reduction are discussed. The pores and cracks, which are appeared during creep conditions in polymer materials lead to irreversible changes in the density [13,14] of the material. A correlation between creep and damage processes [14] is occurred. Taking into account these conditions, experimental and theoretical studies of these processes are considered. The experimental results on creep and long-term strength of poly methyl methacrylate specimens at room temperature for a wide range of stress changes (62-25 MPa) and times to fracture (2-620000 minutes) are presented. The residual density change (loosening) of the material is considered as the main damage factor. A modified creep equation for the loosening medium is proposed, which can describe the second and third regions of the creep curve. Based on this equation the criterion of long-term strength is formulated. It is shown, that in the region of relatively high stresses and under the assumption of incompressibility of the material, the criterion coincides with the known Hoff law of viscous fracture [15]. It is well known, that Hoff's criterion, describes only the initial region of the experimental long-term strength curve. With a reduction of stress and transition in the region of brittle fractures this criterion deviates from the Hoff condition to smaller durability's.

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2. Creep law for a compressible medium

Let's consider the creep problem of a specimen stretched by a given load P. Creep law for a medium with hardening is given by the ratio [16,17]

$$\varepsilon^{\beta}\dot{\varepsilon} = B\sigma^{m}, \tag{1}$$

where σ is true stress, $\dot{\varepsilon} = \frac{1}{l}\frac{dl}{dt}$ is creep rate, $\varepsilon = ln\, l / l_0$ is strain, l_0 is initial and l is current specimen length, B, m, β are constants.

Considered, that $\sigma = P/F = \sigma_0(F_0/F)$ and taking into account the mass conservation law, the equation (1) can be written as follows

$$\varepsilon^{\beta}e^{-m\varepsilon}\dot{\varepsilon} = B\sigma_0^{m}\left(1-\frac{\rho_0-\rho}{\rho_0}\right)^{m}, \tag{2}$$

where $\sigma_0 = P/F_0$ is nominal stress, ρ_0, F_0 are initial and ρ, F are current density and cross section area of specimen.

To solve equation (2) it is necessary to have experimental relations of material loosening changes during creep. Experiments shown that power or exponential laws can be used to describe loosening changes of structural materials. To describe processes of loosening of poly methyl methacrylate the following law for the function of loosening is accepted

$$\frac{\rho}{\rho_0} = \frac{\rho_*}{\rho_0} + \frac{\rho_0-\rho_*}{\rho_0}e^{-\alpha t}, \tag{3}$$

where ρ_* is value of density at fracture, α is constant.

According to (3) we will have: $t=0$, $\rho=\rho_0$, $t\to\infty$, $\rho=\rho_*$.

Introducing (3) into (2), taking approximately that $\beta=0$ and solving equation (2) under the initial conditions $t=0$, $\varepsilon=0$, the following relation for creep deformation is obtained

$$\varepsilon = \frac{1}{m}ln\left\{1-mB\sigma_0^{m}\left[\left(1-m+m\frac{\rho_*}{\rho_0}\right)t+\frac{m}{\alpha}\left(1-\frac{\rho_*}{\rho_0}\right)\left(1-e^{-\alpha t}\right)\right]\right\}^{-1}. \tag{4}$$

3. Formulation of the creep fracture criterion

The relation (4) is further used to formulate the long-term strength criterion. Let's assume that the creep deformation reaches the limit value $\varepsilon=\varepsilon_p$ in the fracture time $t=t_p$. By introducing these conditions into the equation (4), we can obtain the following fracture criterion

$$\frac{1-e^{-m\varepsilon_p}}{mB\sigma_0^{m}} = \left[\left(1-m+m\frac{\rho_*}{\rho_0}\right)t_p+\frac{m}{\alpha}\left(1-\frac{\rho_*}{\rho_0}\right)\left(1-e^{-\alpha t_p}\right)\right]. \tag{5}$$

For compressible material it is considered that $\rho_0=\rho_*$ and under the condition $\varepsilon_p\to\infty$ the formula (5) coincides with the Hoff criterion

$$t_p = \frac{1}{mB\sigma_0^{m}}. \tag{6}$$

It is well known, that Hoff's criterion (6) describes well only the initial part of the long-term strength curve, which corresponds to the relatively large values of deformations and small durability's. On Figure 1 in the $ln\sigma_0 - lnt_p$ coordinates the Hoff criterion shown by line 1. The general fracture criterion (5) has the form of a curve 2, which deviates from straight line 1 in the direction of shorter durability's. As can be seen from Fig. 1, the experimental points are close to curve 2. In the calculations according to the formulas (5) and (6) the following coefficients values are used: $m = 17.2$, $B = 3.6 \cdot 10^{-33} [MPa]^{-17,2} [min]^{-1}$, $\alpha = 3.66 \cdot 10^{-3} [min]^{-1}$, $\rho_* / \rho_0 = 0.3$, $\varepsilon_p = 0.04$.

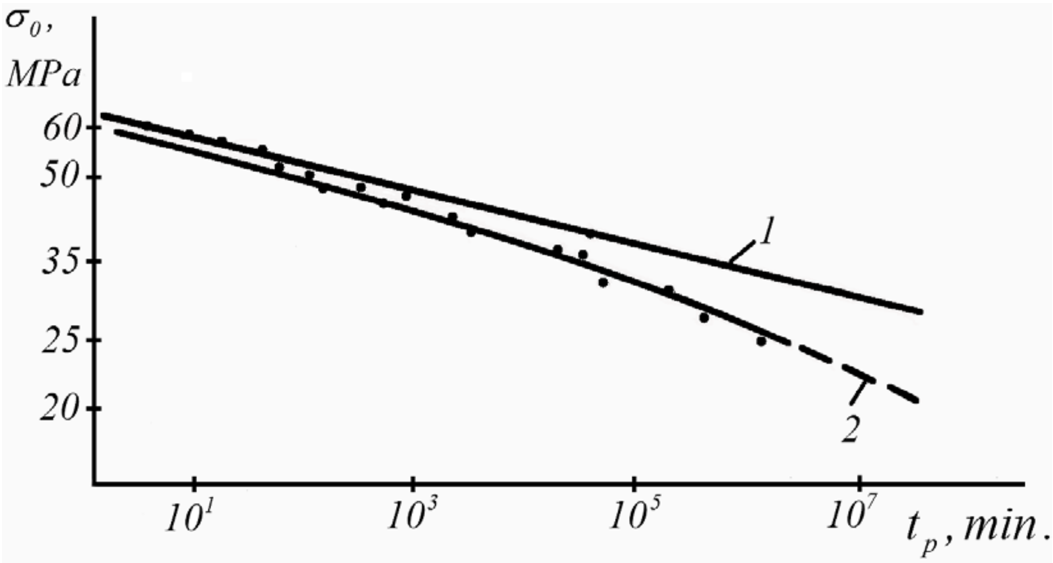

Fig. 1. Long-term strength curves: 1 – according to Hoff's criterion (6), 2 – according to criterion (5), ● – experimental points)

The creep, long-term strength and loosening curves was received in experiments at room temperature on samples made by poly methyl methacrylate for a wide range of stress changes (62-25 MPa) and times to fracture (from 2 min to 620000 min). The flat specimens of poly methyl methacrylate with following dimensions were used: working length 60 mm, width 10 mm, thickness 5 mm. At the specified stress range 220 specimens has been tested.

When poly methyl methacrylate was chosen as a model material, the following conditions [18] were used. Due to the features of the transition to a glassy state in poly methyl methacrylate, a supramolecular structure with rather loose packing of macromolecules is formed. Therefore, in creep experiments at room temperature, not only large elastic deformations occurred, but also irreversible deformations associated with the destruction of the microstructure of the glassy-like body.

The limiting strains vary between 4-7%, when specimens testing for creep at room temperature. After unloading, the reversible part of the deformation is restored, and the remaining deformation is irreversible and corresponds to the loosening of the material. It is possible to obtain the rules of loosening changes during creep using multiple process of unloading and rest (reclining) of specimens. These curves for two stress levels and a half-hour rest are marked correspondingly by 1 and 2 on Fig. 2 and Fig. 3. Numbers 3 indicate creep curves for these stress levels: 34 MPa (Fig. 2) and 40 MPa (Fig. 3).

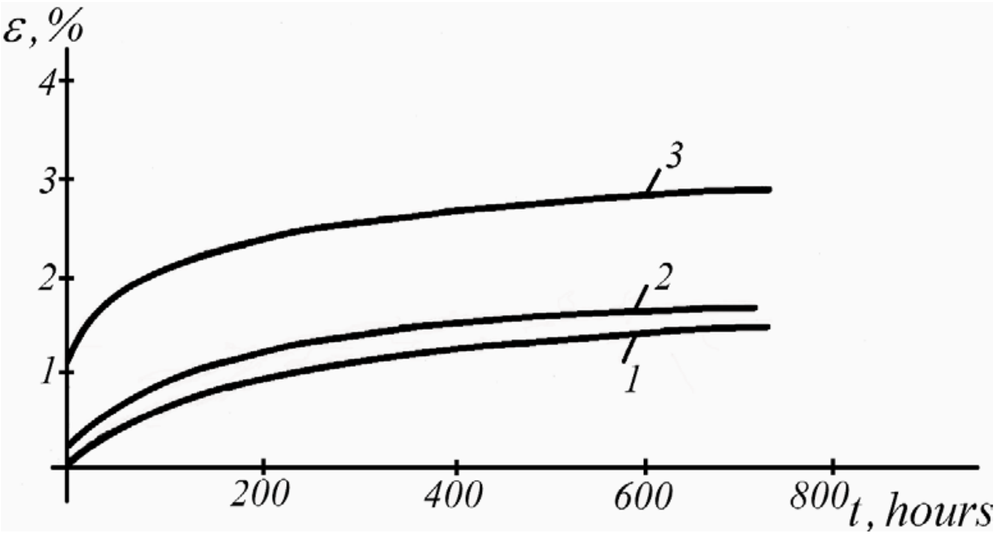

Fig. 2. Loosening curves 1, 2 and creep curve 3 for stress level 34 MPa

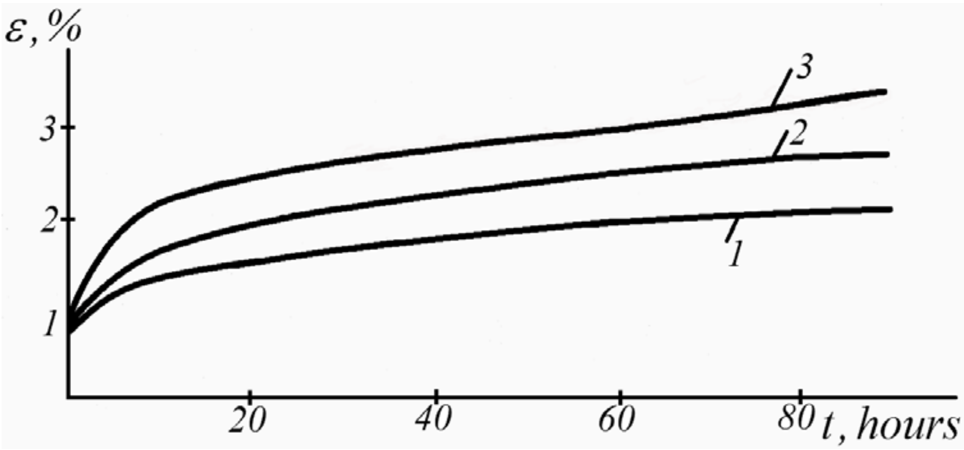

Fig. 3. Loosening curves 1, 2 and creep curve 3 for stress level 40 MPa

Formula (3) is used to describe the loosening curves. In this case, it is taken into account that the studied material is quite brittle, so it can be considered approximately $F = F_0$, then from the mass conservation law follows $\rho / \rho_0 = e^{-\varepsilon_*}$, $\rho_* / \rho_0 = e^{-\varepsilon_{**}}$. Taking into account these relations, the formula (3) can be written in the following form

$$\varepsilon_* = ln\left[e^{-\varepsilon_{**}} + \left(1 - e^{-\varepsilon_{**}}\right)e^{-\alpha t}\right]^{-1}. \qquad (7)$$

It is shown that the processes of damage accumulation have non-monotonic character, which is depend on the stress value. At relatively high stresses, the value of the accumulated loosening is insignificant, and the character of its changes can be non-monotonic.

The experimental curve of loosening accumulation depending on the stress is shown on Fig. 4. The curve has a bell-shaped character, the maximum of which corresponds to the stress at the level of the elastic limit, which is equal to 25-30 MPa.

On the long-term strength curve, this point corresponds to the transition to brittle fracture. This statement corresponds for two fracture mechanisms under creep conditions: viscous (deformation) and brittle fracture using the mechanism of crazing [3] and irreversible density changes. This fracture pattern is observed in the optical study of cracks. Specimens tested under conditions of high stresses are fractured with a small number of cracks. After unloading the strain is almost completely restored. In the conditions of long-term experiments at low stresses, the whole sample is covered by a well-observed system of cracks, which are normal to the direction of tensile stresses action.

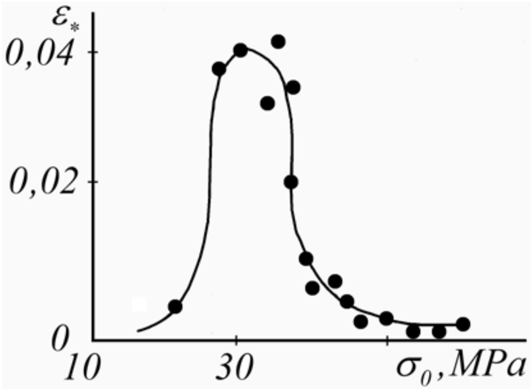

Fig. 4. Experimental curve of loosening accumulation depending on the stress

4. Conclusions

A modified creep equation for the loosening medium is proposed. The residual density change (loosening) of the material is considered as the main damage factor. Based on creep equation the criterion of long-term strength is formulated. Experimental creep curves and long-term strength curves for poly methyl methacrylate have been obtained at room temperature for a wide range of stresses and times to fracture. It is shown that the processes of damage accumulation have non-monotonic character depending on the stress value. The obtained experimental curve of loosening accumulation depending on the stress has a bell-shaped character, the maximum of which corresponds to the stress at the level of the elastic limit.

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