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Viorica Marina
ORCID ID: 0000-0001-6210-935X
associate professor, Doctor of Physic and Math Sciences,
Machine Design Fundamentals Department
Technical University of Moldova,
Republic of Moldova

ABOUT THE BOUNDARY BETWEEN THERMOVISCOELASTIC AND THERMOVISCOELASTOPLASTIC DEFORMATION PROCESSES

Abstract. *The concept of the loading surface, which is fundamental in flow theories, is at the same time the most vulnerable point of these theories. Within the framework of the representation of microheterogeneous materials in the form of an infinite number of kinematically interconnected subelements with different properties, the boundary between reversible and irreversible behavior becomes conditional. It is shown that the duration of the reversible state with respect to deformation is determined not by the thermoviscoelastic, but by the thermoviscoplastic properties of the material.*
Keywords*: stress, strain, subelement, thermoviscoelastic, structure.*

Introduction

The unevenness of reversible and irreversible strains due to both the graininess of the polycrystal structure and the uneven distribution of defects in the atomic lattices of crystallites is taken into account by representing the body element in the form of an infinite number of kinematically interconnected subelements having different properties [1–6]. Unlike various versions of the flow theory, for a model with an infinite number of subelements, the boundary between reversible and irreversible strain becomes conditional, determined only on the basis of an artificially introduced tolerance for a change in irreversible strain, i.e., exactly as it follows from the experimental data [2-3]. According to structural models, when a body element is loaded, a continuous transition from a reversible state to an irreversible state is observed. The reversible and irreversible behavior of the model differs only in the number of subelements involved in the irreversible strain region.

1. Constitutive Equations for Thermoviscoelastic Deformation Processes

In the reversible strain region, the tensor and scalar properties of the material are determined based on the expression

$$t_{ij} = C_{ijnm} d_{nm},\ C_{ijnm} = C_{ijnn}(\gamma, T), \tag{1}$$

where t_{ij}, d_{nm} *- macroscopic stress and strain tensors, respectively,* C_{ijnm}*- material elasticity constants depending on temperature T and strain rate parameter.*

For elastically isotropic materials, relation (1) decomposes into two types of equations

$$\sigma_{ij} = 2G(\gamma, T)\varepsilon_{ij},\ \sigma_{ij} = t_{ij} - \frac{1}{3} t_{kk}\delta_{ij},\ \varepsilon_{ij} = d_{ij} - \frac{1}{3} d_{kk}\delta_{ij},\ \sqrt{\varepsilon_{ij}\varepsilon_{ij}} \le \varepsilon_{nn}(\gamma, T) \tag{2}$$

$$\sigma_0 = K(T)(\varepsilon_0 - \varepsilon_T),\ \sigma_0 = \frac{1}{3} t_{kk},\ \varepsilon_0 = \frac{1}{3} d_{kk}. \tag{3}$$

Here through σ_{ij}, ε_{ij} *- deviators of stress and strain tensors are indicated,* G *- shear modulus,* K *- volume modules of elasticity,* σ_0, ε_0 *- spherical stress and strain tensors,* ε_{nn} *- microscopic elastic limit,* ε_T *- non-mechanical volume change.*

The equations of thermoviscoelastic processes "Eq.(2), (3)" have all the characteristic features of the material in the reversible region. Considering that the volume modules of elasticity is not sensitive to the loading rate, rheological effects can be studied based on expression "Eq.(2)", which can be represented as a single scalar equation

$$\sigma = 2G(\gamma, \upsilon)\varepsilon, \tag{4}$$

where $\sigma = \sqrt{\sigma_{ij}\sigma_{ij}}$ *- stress tensor deviator module,* $\varepsilon = \sqrt{\varepsilon_{ij}\varepsilon_{ij}}$ *- strain tensor deviator module. Under loading at a constant rate of strain change* $\dot{\varepsilon} = const.$*, it follows from (4) that* $\dot{\sigma} = const.$ *and vice versa, which leads to a linear relationship between stresses and strains in such tests. In experiments with* $\sigma = const.$ *on the basis of*

"Eq.(4)" it is possible to describe creep, and with the $\varepsilon = const.$ *stress relaxation of a body element. In experiments with* $\sigma = const.$ *on the basis of "Eq.(4)" it is possible to describe the creep, and with* $\varepsilon = const.$ *the relaxation of the stress of an element of the body. Note that each value of stress corresponds to a single equilibrium value of strain, and vice versa* $G(0,\upsilon) = G_0(\upsilon)$, $\sigma = G_0\varepsilon$. *The equilibrium value of the response is reached only after sufficient time has elapsed. Depending on the type of function* $G(\gamma,\upsilon)$, *it may take from microseconds to very long periods of time to reach equilibrium.*

2. Estimation of the duration of the reversible loading section

To specify the duration of the reversible state, it is necessary to consider the kinematic scheme of the connectivity of the system of subelements. For this purpose, we use the equations of connection between macro and microstates proposed in [4,5,9]

$$(\tilde{\sigma}_{ij} - \sigma_{ij})(\varepsilon_{ij} - \tilde{\varepsilon}_{ij}) = 3(\tilde{\sigma}_0 - \sigma_0)(\tilde{\varepsilon}_0 - \varepsilon_0), \quad (5)$$

$$\tilde{\sigma}_{ij} - \sigma_{ij} = B(\varepsilon_{ij} - \tilde{\varepsilon}_{ij}), \quad (6)$$

where parameter B characterizes the inhomogeneities of the deformation and loading processes in the system of subelements.

In the irreversible region of deformation, we represent the components of the deviators of the strain tensors of the body element and subelements as sums of reversible - $e_{ij}, \tilde{e}_{ij}$ and irreversible components - $p_{ij}, \tilde{p}_{ij}$

$$\varepsilon_{ij} = e_{ij} + p_{ij}, \; \tilde{\varepsilon}_{ij} = \tilde{e}_{ij} + \tilde{p}_{ij} \quad . (7)$$

Taking into account "Eq.(7)" and the assumption of elastic isotropy of subelements and body element

$$\tilde{\sigma}_{ij} = 2G\tilde{e}_{ij}, \; \sigma_{ij} = 2Ge_{ij}, \quad (8)$$

expression "Eq.(6)" can be represented as [4]

$$\tilde{e}_{ij} - e_{ij} = m(p_{ij} - \tilde{p}_{ij}), \; m = \frac{B}{B + 2G}. \quad (9)$$

With proportional loading

$$\frac{\sigma_{ij}}{\sigma}=\frac{\tilde{\sigma}_{ij}}{\tilde{\sigma}}=\frac{\varepsilon_{ij}}{\varepsilon}=\frac{p_{ij}}{p},$$

relations "Eq.(9)" are reduced to one equation [4]

$$\tilde{e}-e=m(p-\tilde{p}),\ \tilde{p}=\sqrt{\tilde{p}_{ij}\tilde{p}_{ij}},$$

$$p=\sqrt{p_{ij}p_{ij}},\tilde{e}=\sqrt{\tilde{e}_{ij}\tilde{e}_{ij}},\ e=\sqrt{e_{ij}e_{ij}}. \quad (10)$$

Under the assumption of linear strengthening of subelements $\tilde{e}=\tau+a\tilde{p}$ from "Eq.(10)", we find

$$\tilde{p}(\tau,\tau',\gamma,T)=\begin{cases}\dfrac{\tau'-\tau}{m+a},\tau\le\tau'\\ 0,\tau\ge\tau'\end{cases}. \quad (11)$$

Macroscopic irreversible deformation is determined based on the formula

$$p=\int_{\tau_0}^{\tau'}\tilde{p}(\tau,\tau',\gamma,T)y(\tau)d\tau, \quad (12)$$

where $y(\tau)$ - distribution density function of yield strengths of subelements.

The speed parameter is determined by the expression

$$\gamma=\frac{1}{\psi'}\int_0^{\psi'}\tilde{p}d\psi\ ,\ \psi'=\int_{\tau_0}^{\tau'}y(\tau)d\tau. \quad (13)$$

here ψ' - current weight of irreversibly deformed subelements. Based on (11) - (13), one can obtain a general expression for the speed parameter γ. According to [7], at the initial moment of the onset of yield

$$\gamma(t_1)=\frac{\dot{\varepsilon}(t_1)-\varepsilon_{nn,\upsilon}\dot{\upsilon}}{a+m}. \quad (14)$$

From "Eq.(2)" and "Eq.(14)" it follows that thermoviscoelastic processes are determined by two factors: the dependence of the shear modulus on the state parameters γ,T and the extent of the thermoviscoelastic state of the body element $\varepsilon_{nn}(\gamma,T)$. The duration of the reversible state with respect to deformation is determined by non-thermoviscoelastic properties given by the function $G=G(\gamma,\upsilon)$, and thermoviscoplastic $\varepsilon_{nn}=\varepsilon_{nn}(\gamma,\upsilon)$.

Substituting "Eq.(14)" into "Eq.(2)", we obtain an equation that determines the time of onset of yield

$$\varepsilon_{nn}\left[\frac{\dot{\varepsilon}(t_1)-\varepsilon_{nn,\upsilon}\dot{\upsilon}}{a+m},\upsilon(t_1)\right]=\varepsilon(t_1). \qquad (15)$$

Based on "Eq.(15)", it is possible to describe the phenomenon of fluid retention. This phenomenon follows from the equation of the continuity of the transition of a material from a reversible state to an irreversible one. It turned out that on the basis of the concept of the continuity of the transition, it is possible to describe from a unified position a wide variety of thermoviscoelastic and thermoviscoelastoplastic processes, endowing the subelements with only the simplest properties.

Conclusion

1. It is shown that the thermoviscoelastic properties of a polycrystal are described on the basis of the dependence of the shear modulus on temperature and strain rate. The modulus of elasticity, Poisson's ratio and other elastic characteristics can only be expressed in terms of one universal function of thermoviscoplasticity.

2. The duration of the reversible state with respect to deformation is determined not by the thermoviscoelastic properties given by the function of the shear modulus versus temperature and velocity parameter, but by the thermoviscoplastic properties of the subelement with the lowest yield strength.

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