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Deformation aspects of anisotropic-porous bodies sintering

E. OLEVSKY and V. SKOROHOD*

Max-Planck-Institute f. Metallforschung, Stuttgart, Germany

** Institute for Problems of Materials Sciences, Kiev, Ukraine*

INTRODUCTION

In the present work an attempt to bring the data of the shape (and its evolution) of the pores morphologically oriented in definite direction into the phenomenological model of sintering was undertaken. Such peculiarities of microstructure must be a reason of the phenomenon of shrinkage anisotropy often having a place in sintering practice.

THEORY

The present theory is based on the principles of the thermodynamics of the irreversible processes and contains as one of the main the notion of dissipative potential. Being a function of a configuration change rate (in this case - of the strain rates), the dissipative potential determines the concrete energy dissipation mechanism. In view of [1] :

$$D = D_0 + P_L e \quad (1)$$

where D - dissipative potential for sintering process; D_0 - dissipative potential initiated by stresses arising in the solid phase, $P_L e$ - dissipative potential of capillary stresses being equal, correspondingly, to the multiplication of effective Laplace stress P_L and volume change rate e .

The constitutive relations can be found from (1) on the base of Onsager principle [2] :

$$\sigma_{ij} = \frac{\partial D_0}{\partial W} \frac{\partial W}{\partial e_{ij}} + P_L \delta_{ij} \quad (2)$$

where σ_{ij} - stress tensor, e_{ij} - strain rates tensor, δ_{ij} - Kronecker's symbol; W - equivalent strain rate [1].

Laplace stresses, whose main directions coincide with ellipsoid's axes, have the form :

$$P_{L0ij} = \frac{\alpha}{r_i} \delta_{ij} \quad (3)$$

where α is a surface tension coefficient; r_i - curvature radius.

For curvature radii in main semi-axes directions (fig.1) :

Fig.1 Pore in the form of an ellipsoid of rotation

$$r_1 = \frac{a^2}{c}, \quad r_2 = r_3 = \frac{c^2}{a} \quad (4)$$

From (1) it follows that sintering as the process of diminishing of free surface energy is being accompanied by pores' volume decrease. Here the generalization is in the ascertain that free surface energy has to be diminished both on account of voids' volume decrease and on account of their shape change. Herewith (1) is written :

$$D = D_0 + e_{ij} P_{Lij} \quad (5)$$

Here $e_{ij} P_{Lij}$ is a convolution of a strain rate tensor with an effective tensor of Laplace stresses P_{Lij} .

In present investigation the authors used Eshelby's results [3], which were obtained for the relationship between effective and local strains, taking place around the ellipsoidal inclusion in elastic medium. Herewith, using the hydrodynamic analogy of theory of elasticity, we can operate by the equations [3], replacing the strains by the corresponding strain rates, and elasticity moduli - by corresponding viscosity coefficients.

Considering a model of anisotropic-porous body with texture of ellipsoidal pores, one should take into account not only the said nonuniform action of capillary stresses in different directions but anisotropy of porous body viscous properties also. We have a medium with a symmetry of properties in the plane being perpendicular to the direction of pores' orientation. The media of such a type are called transverse-isotropic [4]. We apply the results of [21] to obtain the values of effective moduli, being the properties of equivalent homogeneous medium.

RESULTS AND DISCUSSION

The results of calculations in the form of relationships of porosity θ and pores' semi-axes ratio $\frac{c}{a}$ via specific time of sintering τ are shown in fig.2.

$$\tau = \int_0^t \frac{\alpha}{r_0 \eta_0} dt \quad (6)$$

Fig.2 Evolution of porosity and semi-axes ratio

for the various initial values of θ and $\frac{c}{a}$. As it follows from the traditional ideas of sintering micro-kinetics [5] the shape of the pores undergoes spheroidization during thermotreatment. Nevertheless, H. Exner and E. Giess in the work [6] pointed out and made an attempt to ground theoretically the phenomenon of self-similar "tightening" of the voids at the intermediate stages of sintering. The work [7] contains the analogous information about the pores just of the ellipsoidal form. The results presented in fig.3 in full measure confirm the given fact. The results of calculations show also the smaller shrinkage value for the smaller initial values of $\frac{c}{a}$ during the same specific time of sintering.

From the above-mentioned an important conclusion follows :

- the bodies, having more spherical initial shape of pores get the larger volume shrinkage (under the same initial porosity). It should also be born in mind that under higher initial porosities the higher valuer of $\frac{c}{a}$ can be reached. Besides, the lower initial semi-axes ratio, the higher degree of spheroidization.

The fact is pointed out [7] that when the semi-axes ratio $\frac{c}{a} \geq 0.2$ the porous system changes the pores' form intensively, diminishing by doing so their volume. The given result is obtained by means of the analysis of the dependence of the value of ratio of ellipsoid's surface area and an area of the surface of the ball with the same volume on the correspondent $\frac{c}{a}$. Herewith, as it follows from fig.3, the boundary between the bands of moderate and intensive increasing of $(\frac{c}{a})_{\max}$ corresponds to $(\frac{c}{a})_{\max} = 0.2 \div 0.3$ (!). Thus, we have a definite correlation between the pure geometric approach [7] and an approach proposed in the present work, based on the methods of continuum mechanics. It's also interesting to research the macroparameters evolution. There is an information of the radial and axial strain rates evolution under various initial values of θ and $\frac{c}{a}$ in fig.3. As it

Fig.3 Radial and axial strain rates evolution

follows from the data being presented the positive values of axial strain rate can correspond to the process of sintering of the

anisotropic-porous cylindrical body, that is the spheroidization of the ellipsoidal pores can be accompanied by the swelling of the body in the direction of smaller semi-axis.

CONCLUSIONS

1. The continuum-structural model of sintering has been elaborated, based on the rheological conception and taking into consideration the ellipsoidal pores' form evolution during the process of thermotreatment.

2. The calculations of micro-kinetics of sintering, performed in conformity to the proposed model, indicate an effect of self-similar "tightening" of the voids, being initiated at some definite stage of sintering. The initial moment of the said effect depends on the initial values of porosity and semi-axes ratio, which in main must correspond to the interval $\frac{c}{a} = 0.2 \div 0.3$.

The analysis of the calculation data indicates the larger volume shrinkage of the bodies with more close to spherical initial form of the pores under the same initial porosity.

3. The calculations of macro-kinetics of sintering indicate a possibility of swelling for anisotropic-porous bodies, containing the oriented ellipsoidal voids, under sintering in the direction of the smaller semi-axes of ellipsoids.

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