COMBINED EFFECT OF DIFFERENT FLOW MECHANISMS OF A POROUS CRYSTALLINE BODY IN HOT COMPACTING.

III. SUCCESSIVE CONNECTION MODEL

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In [1] it was reported that certain mechanisms connected in parallel cannot be combined. Therefore, to draw a final conclusion regarding the possibility of the simultaneous action of two mechanisms of flow of porous polycrystalline bodies during hot compacting we shall examine a model of their successive connection retaining the sequence accepted in [2].

In parallel connection the same mean quadratic stress in the examined elements corresponds to different mean quadratic strains. Therefore, for a convalent polycrystal in which the main flow mechanism is creep according to Haazen, the total mean quadratic strain rate $\dot{\bar{\varepsilon}}$ is represented by the sum of Eqs. (1) and (5) and is expressed by Eq. (22) from [1]. The mean quadratic creep rate according to Haazen, present in Eq. (22), can be written in the form

$$\frac{1}{\varepsilon_H}\frac{d\bar{\varepsilon}_H}{dt} = \frac{1}{2}Ba\bar{\sigma}^{m+1} \tag{1}$$

or after integration

$$\ln\frac{\bar{\varepsilon}_H}{\varepsilon_0} = \frac{1}{2}Ba\int_0^t \bar{\sigma}^{m+1}dt. \tag{2}$$

Thus, the mean quadratic strain $\bar{\varepsilon}_H$ of the covalent polycrystal, forming a porous body, depends exponentially on the kinetic parameter Ba, the rms stress $\bar{\sigma}$, and time t:

$$\bar{\varepsilon}_H = \varepsilon_0\exp\left[\frac{1}{2}Ba\int_0^t \bar{\sigma}^{m+1}dt\right]. \tag{3}$$

The integral in the right-hand part of this equation represents the product of pressure (if P = const) by the value $2^{(m+1)2}D(m, \rho, t)$, determined by the integral (28) in [1]. As reported in [1], in successive bonding not only the strain rates but also strains are additive. Therefore, Eq. (22) from [1] will be written in the integral form

$$\bar{\varepsilon} = \frac{1}{2}A\int_0^t \bar{\sigma}^n dt + \varepsilon_0\exp\left[\frac{1}{2}Ba\int_0^t \bar{\sigma}^{m+1}dt\right]. \tag{4}$$

The first term will be transferred from the right to the left-hand part of Eq. (4):

$$\bar{\varepsilon} - \frac{1}{2}A\int_0^t \bar{\sigma}^n dt = \varepsilon_0\exp\left[\frac{1}{2}Ba\int_0^t \bar{\sigma}^{m+1}dt\right]. \tag{5}$$

The resultant equation is identical to Eq. (3) in which part from the total strain, relating to the operation of the Haazen mechanism, is separated. Therefore,

$$\ln\frac{\bar{\varepsilon} - \frac{1}{2}A\int_0^t \bar{\sigma}^n dt}{\varepsilon_0} = \frac{1}{2}Ba\int_0^t \bar{\sigma}^{m+1}dt. \tag{6}$$

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Differentiation Eq. (6)

$$\frac{\dot{\bar{\varepsilon}} - \frac{1}{2} A \bar{\sigma}^n}{\bar{\varepsilon} - \frac{1}{2} A \int\limits_0^t \bar{\sigma}^n dt} = \frac{1}{2} Ba \bar{\sigma}^{m+1}, \tag{7}$$

we obtain the equation

$$\dot{\bar{\varepsilon}} = \frac{1}{2}\left[A\bar{\sigma}^n + Ba\left(\bar{\varepsilon} - \frac{1}{2} A \int\limits_0^t \bar{\sigma}^n dt\right)\bar{\sigma}^{m+1}\right], \tag{8}$$

in which the quantity ε_H, which remains unknown in Eq. (21) from [1], is fully determined

$$\bar{\varepsilon}_H = \bar{\varepsilon} - \frac{1}{2} A \int\limits_0^t \bar{\sigma}^n dt = \bar{\varepsilon} - 2^{\frac{n-2}{2}} A \int\limits_0^t \frac{P^n dt}{(\rho\chi)^{\frac{n}{2}}}. \tag{9}$$

Equation (7) shows that the positive value of the kinetic parameter Ba in consecutive connection of the examined mechanisms is ensured if the following conditions are fulfilled

$$\dot{\bar{\varepsilon}} > \frac{2^{\frac{n-2}{2}} A P^n}{(\rho\chi)^{\frac{n}{2}}}, \tag{10}$$

$$\bar{\varepsilon} > 2^{\frac{n-2}{2}} A \int\limits_0^t \frac{P^n dt}{(\rho\chi)^{\frac{n}{2}}}. \tag{11}$$

At constant temperature and pressure, from Eq. (10), we obtain

$$\frac{\dot{\bar{\varepsilon}}(\rho_1)}{\dot{\bar{\varepsilon}}(\rho_2)} > \left[\frac{\rho_2 \chi(\rho_2)}{\rho_1 \chi(\rho_1)}\right]^{\frac{n}{2}} > 1, \tag{12}$$

$$\dot{\bar{\varepsilon}}(\rho_1) > \dot{\bar{\varepsilon}}(\rho_2). \tag{13}$$

Condition (13) fully coincides with the condition (11) from the report [2] for parallel connection of two flow mechanisms. We examine additional conditions resulting from the requirement from the positive value of A. We shall assume that Ba = const, and we shall equate the expressions for Ba, obtained from Eq. (7), corresponding to two values of relative density ρ_1 and ρ_2:

$$\frac{\dot{\bar{\varepsilon}}(\rho_1) - \frac{1}{2} A \bar{\sigma}^n(\rho_1)}{\bar{\sigma}^{m+1}(\rho_1)\cdot \bar{\varepsilon}_H(\rho_1)} = \frac{\dot{\bar{\varepsilon}}(\rho_2) - \frac{1}{2} A \bar{\sigma}^n(\rho_2)}{\bar{\sigma}^{m+1}(\rho_2)\cdot \bar{\varepsilon}_H(\rho_2)}. \tag{14}$$

denoting

$$q_s := \left[\frac{\bar{\sigma}(\rho_1)}{\bar{\sigma}(\rho_2)}\right]^{m+1} \frac{\bar{\varepsilon}_H(\rho_1)}{\bar{\varepsilon}_H(\rho_2)} = \left[\frac{\rho_2 \chi(\rho_2)}{\rho_1 \chi(\rho_1)}\right]^{\frac{m+1}{2}} \frac{\bar{\varepsilon}_H(\rho_1)}{\bar{\varepsilon}_H(\rho_2)}, \tag{15}$$

where $\bar{\varepsilon}_H$ is determined by Eq. (9), we obtain

$$A=\frac{\bar{\dot{\varepsilon}}(\rho_1)-q_s\bar{\dot{\varepsilon}}(\rho_2)}{2^{\frac{n-2}{2}}\left\{\frac{1}{[\rho_1\chi(\rho_1)]^{\frac{n}{2}}}-\frac{q_s}{[\rho_2\chi(\rho_2)]^{\frac{n}{2}}}\right\}}. \tag{16}$$

from Eq. (16) we have that A > 0, if

$$\frac{\bar{\dot{\varepsilon}}(\rho_1)}{\bar{\dot{\varepsilon}}(\rho_2)}>q_s, \tag{17}$$

$$\left[\frac{\rho_2\chi(\rho_2)}{\rho_1\chi(\rho_1)}\right]^{\frac{n}{2}}>q_s>1. \tag{18}$$

Since the quotients obtained from dividing the quantities ($\rho\chi^{m+1/2}$) and $\bar{\varepsilon}_H$, which determine q_s, in the opposite direction, the condition (19) limits the increase of m. According to the conditions (8) and (13) from the report [2], for parallel connection this limitation does not occur. The condition (12) for consecutive connection requires that the exponent n should be lower. On the whole, the conditions permit m + 1 > n with the restriction of the upper values. Consequently, the physical mechanisms where one of these mechanisms is characterized by a high exponent m and the other one by a low of value of n, cannot be connected consecutively,

In consecutive connection of the mechanism of uphill creep according to Van Buren and conventional exponential creep, determined by Eqs. (6) and (1) in [1], the Eq. (23) is fulfilled, together with that given in [1]. Solving this equation with respect to B_V, we have

$$B_V=\frac{2\bar{\dot{\varepsilon}}-A\bar{\sigma}^n}{\bar{\sigma}^{2m}t^2}, \tag{19}$$

which gives for $B_V > 0$ the conditions (10), (12), and (13). At B_V = const the kinetic parameter A is described by the expression

$$A=\frac{2\,[\bar{\dot{\varepsilon}}(\rho_1)-q_V\bar{\dot{\varepsilon}}(\rho_2)]}{[\bar{\sigma}(\rho_1)]^n-q_V\,[\bar{\sigma}(\rho_2)]^n}, \tag{20}$$

where

$$q_V:=\frac{[\bar{\sigma}(\rho_1)]^{2m}t_1^2}{[\bar{\sigma}(\rho_2)]^{2m}t_2^2}=\left[\frac{\rho_2\chi(\rho_2)}{\rho_1\chi(\rho_1)}\right]^m\frac{t_1^2}{t_2^2} \tag{21}$$

at P = const. From Eq. (2) we obtain the conditions for the positive value of A in consecutive connection of the examined mechanism:

$$\frac{\bar{\dot{\varepsilon}}(\rho_1)}{\bar{\dot{\varepsilon}}(\rho_2)}>q_V, \tag{22}$$

$$\left[\frac{\rho_2\chi(\rho_2)}{\rho_1\chi(\rho_1)}\right]^{\frac{n}{2}}>q_V>1. \tag{23}$$

They are identical with the conditions (17) and (18). However, the ratios of the squares of time for q_V in Eq. (21) restrict the value of m at the top to a lesser degree than if Eq. (15) is fulfilled, i.e., in the case of consecutive connection of Haazen mechanism with the mechanism of climb or grain boundary creep.

In consecutive connection of two creep mechanisms, determined by the exponential laws with different kinetic parameters A_1, A_2 and exponents n_1 and n_2 the following ratio is fulfilled

$$2\bar{\dot{\varepsilon}} = A_1\bar{\sigma}^{n_1} + A_2\bar{\sigma}^{n_2}. \tag{24}$$

Determining by this method the quantities A_1 and A_2, we obtain

$$A_1 = \frac{2\bar{\dot{\varepsilon}} - A_2\bar{\sigma}^{n_2}}{\bar{\sigma}^{n_1}}, \tag{25}$$

$$A_2 = \frac{\bar{\dot{\varepsilon}}(\rho_1) - r_s\bar{\dot{\varepsilon}}(\rho_2)}{2^{\frac{n_2-2}{2}} P^{n_2}\left\{\frac{1}{[\rho_1\chi(\rho_1)]^{\frac{n_2}{2}}} - \frac{r_s}{[\rho_2\chi(\rho_2)]^{\frac{n_2}{2}}}\right\}}, \tag{26}$$

where

$$r_s := \frac{[\bar{\sigma}(\rho_1)]^{n_1}}{[\bar{\sigma}(\rho_2)]^{n_1}} = \left[\frac{\rho_2\chi(\rho_2)}{\rho_1\chi(\rho_1)}\right]^{\frac{n_1}{2}} > 1. \tag{27}$$

The equations (25) and (26) give the conditions for simultaneous actions of two examined mechanisms which are consecutively connected

$$\frac{\bar{\dot{\varepsilon}}(\rho_1)}{\bar{\dot{\varepsilon}}(\rho_2)} > \left[\frac{\rho_2\chi(\rho_2)}{\rho_1\chi(\rho_1)}\right]^{\frac{n_2}{2}} > \left[\frac{\rho_2\chi(\rho_2)}{\rho_1\chi(\rho_1)}\right]^{\frac{n_1}{2}}, \tag{28}$$

$$n_2 > n_1. \tag{29}$$

As in the case of parallel connection of the mechanism, to evaluate the Laplace pressure P_L we shall use the ratio of the strain rate at different external pressure and the same relative density ρ = const using Eq. (8) at $m + 1 > n$. After tranformations, we obtain

$$A(s\bar{\sigma}_1^n - \bar{\sigma}_2^n) = Ba\left\{\left[\bar{\varepsilon}_2 - 2^{\frac{n-2}{2}}AP_2^n\int_0^t(\rho\chi)^{-n/2}dt\right]\bar{\sigma}_2^{m+1} - s\left[\bar{\varepsilon}_1 - 2^{\frac{n-2}{2}}AP_1^n\int_0^t(\rho\chi)^{-n/2}dt\right]\bar{\sigma}_1^{m+1}\right\}, \tag{30}$$

where

$$s := \frac{\bar{\dot{\varepsilon}}_{P=P_2+P_L}}{\bar{\dot{\varepsilon}}_{P=P_1+P_L}}, \tag{31}$$

P_1 and P_2 are the axial pressures: $P_2 > P_1$, $\bar{\varepsilon}_2 > \bar{\varepsilon}_1$, $\bar{\sigma}_2 > \bar{\sigma}_1$. The right-hand part of Eq. (30) is known to be positive, and the validity is determined by its left-hand part at

$$s > \left(\frac{\bar{\sigma}_2}{\bar{\sigma}_1}\right)^n = \left(\frac{P_2 + P_L}{P_1 + P_L}\right)^n \tag{32}$$

or

$$s^{\frac{1}{n}} > \frac{P_2 + P_L}{P_1 + P_L}, \tag{33}$$

which shows that

$$P_L > \frac{P_2 - s^{\frac{1}{n}}P_1}{s^{\frac{1}{n}} - 1}, \tag{34}$$

which differs only by the exponent s from Eq. (17) in [2] for parallel connection of similar mechanisms. In describing metallic polycrystals, in Eq. (33) we should use n_1.

LITERATURE CITED

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RELATIONSHIPS GOVERNING EXTRUSION OF POWDER BIMETALLIC MATERIALS.

I. STRESS—STRAIN STATE IN EXTRUSION OF DISSIMILAR MATERIALS

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Synthesis of dissimilar powder materials by extrusion is an important problem of technology of powder metallurgy. These materials include mainly the bimetals whose deformation and relations have been studied insufficiently.

Examination of the extrusion process is used mainly to examine the stress—strain state of the technological shell of monometallic materials [1-3], and also to determining the true values of the components of the stress—strain state of bimetallic blank by calculating the permissible ratio of the properties [4]. At a specific relation of the strength characteristics of dissimilar materials the equality of their discharge rates is disrupted and this leads to periodic thinning and thickening of the parent metal or the failure of external layer, i.e., the sleeve [4]. The application of protective shells made of a steel creates additional technological problems (consumption of metal, removal of the shell by pickling or machining). It can be justified in individual cases, for example, in extrusion of low-deformability alloys and active metals (titanium, aluminum, etc.).

To facilitate description, the deformation process of a porous body in extrusion is conventionally divided into two stages: compacting (upsetting and discharge) [5]. We shall examine only the second stage, i.e., discharge of a cylindrical powder bimetal (sleeve—rod design) through a conical die (Fig. 1).

In extrusion of dissimilar materials with greatly different properties (σ_B, σ_T), the geometrical parameters, i.e., the angle of the die funnel and the radius of the rod prior to shaping, should be such as to ensure that the slip line of the bimetal during extrusion shows no discontinuities in the components (Fig. 2).

Evaluation of the radius of the rod of the bimetallic component after shaping was based on the equality of the drawing coefficients λ of the sleeve and the rod. Consequently,

$$R_r = (R_i/R_f)\cdot R, \tag{1}$$

where R_i and R_f are respectively the initial and final radius of the bimetal, and R is the radius of the rod after extrusion, mm.

To determine the optimum radius of the rod at which the required bonding strength of the layers of the bimetal with the different yield limits is obtained, it is necessary to satisfy the following condition: during discharge the radial travel speed of the particles V_r, and the normal radial σ_r and tangential $\tau_{(r,\alpha)}$ stresses of the contact surfaces of dissimilar components should be equal:

$$V_{r_1} = V_{r_2}, \quad \sigma_{r_1} = \sigma_{r_2}, \quad \tau_{(r,\alpha)_1} = \tau_{(r,\alpha)_2}, \tag{2}$$

if the materials do not harden during extrusion. In this case, we can accept the yielding condition in which the intensity of the stress deviator is a constant quantity [6]:

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