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ELASTIC MODULUS OF HIGHLY POROUS NICKEL-BASED MATERIALS

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The results of experimental and theoretical investigations of the structural sensitivity of the elastic modulus of powders biporous nickel are reported. The previously proposed theoretical dependence of the elastic modulus of a biporous system on structural parameters has been verified. It is shown that the elastic characteristics of biporous materials can be varied over a wide range if the parameters θ_{micr}, θ_{macr}, and λ (the particle size ratio of the pore-forming agent and the powder) are varied. The values of those parameters to some degree also affect the mechanical behavior of biporous nickel near the porosity limit θ_c. If λ and $\theta_{macr}/\theta_{micr}$ increase while the integrated porosity remains constant the elastic modulus and the porosity limit rise.

In [1] we proposed an expression relating the elastic modulus of a biporous body to the parameters of porous space,

$$E = E_{\Theta}^{\text{micr p}}\left[1 - \left(\Theta - \Theta_{\text{micr p}}\right) / \left(\Theta_c - \Theta_{\text{micr p}}\right)\right]^{\beta},$$

where Θ is the total porosity of the material, Θ_{micr} is the porosity of the powder subsystem, Θ_c is the total porosity limit, $\beta = 2/(1 + g)$ (g is the matrix coefficient of the material, which, according to [2], is sensitive to the pore-forming agent/powder size ratio λ), and $E_{\Theta}^{micr} = E_0(1 - \Theta_{micr}/\Theta_c^{micr})^2$ is the elastic modulus of the powder subsystem. The porosity limit Θ_c^{micr} of the powder system has been found experimentally to be 0.65.

Unlike most approaches to the analysis of how porosity affects the elastic modulus [3-6], the expression proposed in [1] has made it possible to analyze the mechanical behavior of a porous material near the limiting point Θ_c and also to take the structural sensitivity of β into account. A series of experiments using specimens of highly porous nickel was conducted to validate the given approximation.

Specimens of highly porous nickel were prepared by cold pressing and subsequent sintering in hydrogen at 700°C. To PNK-48S carbonyl nickel with an average particle size of 6 μm we introduced fine (40 μm) and coarse (300 μm) PNK-OP6 pore-forming agent. Three batches of specimens were made. The first batch consisted of specimens of porous nickel with 15-45% porosity without a filler (the porosity was varied by varying the pressing force) To ensure a porosity of 4-15% the powders were recompacted after low-temperature annealing at 600°C. The second batch consisted of biporous specimens with a total porosity of 35-70%. The porosity in the given case was varied by introducing various amounts of the pore-forming agent (coarse or fine) while the porosity of the powder subsystem remained constant $\Theta_{micr} = 15 \pm 5\%$. The third batch consisted of specimens with a constant total porosity $\Theta = 70 \pm 2\%$. The structure of the pore space of the materials of that batch was varied either by varying the ratio $\Theta_{macr}/\Theta_{micr}$ or by varying the pore-forming agent/powder size ratio λ. The total porosity Θ of each specimen was determined by hydrostatic weighing. The macroposity Θ_{macr} was calculated on the assumption that the volume of the macropores formed is equal to the volume of the pore-forming agent and Θ_{micr} was determined from the formula $\Theta = \Theta_{macr} + \Theta_{micr} - \Theta_{macr} \cdot \Theta_{micr}$. The respective values of the porosity for each specimen are shown in Table 1.

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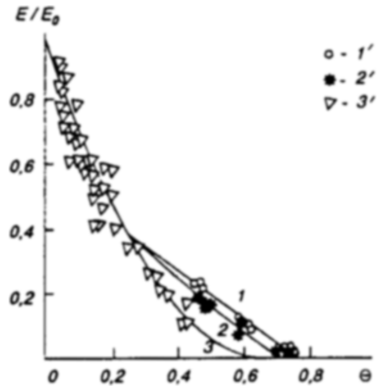

Fig. 1

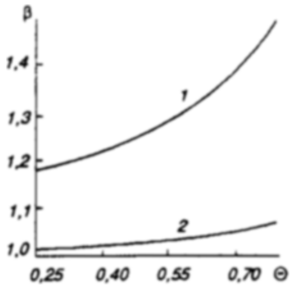

Fig. 2

Fig. 1. Experimental data (1'-3') and calculated curves (1-3) of the normalized elastic modulus as a function of the total porosity of biporous nickel with $\Theta_{macr} = 0.25$: 1, 1' and 2, 2') material with pore-forming agent ($\lambda = 50$ and 6, respectively); 3, 3') specimens without filler.

Fig. 2. Calculated sensitivity β as a function of the total porosity of material with a microporosity of 0.25. Here and in Figs. 3 and 4: $\lambda = 6$ (1), 50 (2).

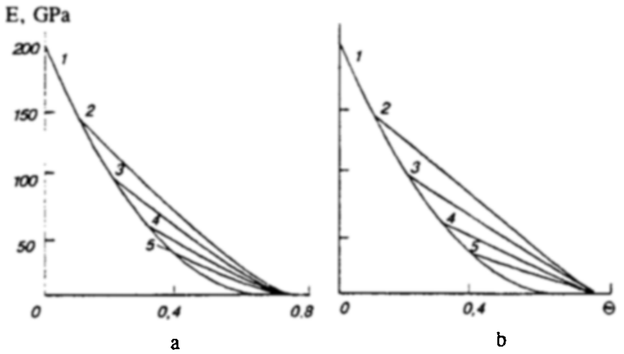

Fig. 3. Calculated curves of the elastic modulus of biporous materials as a function of the total porosity: 1) material without filler; $\Theta_{micr} = 0.1$ (1, 2), 0.2 (3), 0.3 (4), and 0.4 (5).

The elastic modulus of the materials studied was measured by the static method under the conditions of four-point bending tests on a CERAM testing machine, fitted with a high sensitivity displacement transducer. The strain sensitivity of $3 \cdot 10^{-5}$, which allowed the elastic modulus to be measured to within $\pm 5\%$, ensured a displacement sensitivity of 1 μm for the $3.5 \times 5.0 \times 50$-mm specimens.

Comparison of the experimental and calculated curves of the normalized elastic modulus as a function of the specimens of batches 1 and 2 on their total porosity (Fig. 1) allowed us to make the following conclusions. Curve 3, which describes the experimental data for nickel powder without filler, corresponds to calculation from Eq. (1) for a powder system for $\Theta_c = 65\%$, $\beta = 2$ and coincides with the analogous curve given in [1] for iron powder. This indicates that powder materials based on ductile metals obtained by cold pressing under various forces and subsequent sintering have a pore space with the same structure.

Experimental data for biporous materials with a constant microporosity of 25% and a variable macroporosity $\lambda_1 = 6$, $\lambda_2 = 50$ are described well by curves 1 and 2, which were calculated from Eq. (1) for $\Theta_{c_1} = 74\%$ and $\Theta_{c_2} = 76\%$ (the porosity limit was determined by extrapolating the experimental results to the zero value of the elastic modulus) and the sensitivity coefficient

TABLE 1. Characteristics of Nickel-Based Biporous Materials

Θ	Θ_{macr}	Θ_{micr}	E, MPa	
			Experiment	Calculation
		$\lambda=50$		
0,463	0,302	0,269	42073	49698
0,465	0,305	0,230	42164	46611
0,587	0,402	0,301	23133	21444
0,592	0,368	0,354	21400	17021
0,607	0,494	0,223	24945	23868
0,612	0,488	0,242	18840	21867
0,618	0,461	0,282	13897	18557
0,684	0,402	0,471	4096	3890
0,714	0,492	0,412	6564	3327
0,706	0,542	0,356	6102	5067
0,705	0,595	0,245	6639	7548
0,723	0,650	0,166	5148	5972
		$\lambda=6$		
0,455	0,321	0,197	57200	44100
0,478	0,305	0,248	29238	35542
0,483	0,305	0,254	33076	34182
0,487	0,299	0,269	32164	32397
0,578	0,405	0,281	12418	15619
0,584	0,407	0,288	24444	16106
0,695	0,498	0,394	2008	1829
0,699	0,572	0,269	1938	2239
0,702	0,572	0,303	2892	2239
0,707	0,621	0,195	1639	1907
0,708	0,639	0,218	2107	1786

$$\beta = \frac{2}{1 + \left[\frac{(1-\Theta)(\lambda-1)}{\lambda(1-\Theta)+\Theta-\Theta_{micr}}\right]^2}. \tag{2}$$

In this article a correction based on a more accurate analysis of the experimental and calculated data given in [1], $\beta = 2/(1 + g^2)$, is introduced into the dependence of β on the matrix coefficient. The calculated curves of $\beta(\Theta)$ for materials with a microporosity of 25% are given in Fig. 2 for $\lambda_1 = 6$ and $\lambda_2 = 50$.

Since the real microporosity of the materials of batch 2 ranged from 20 to 3%, it is of interest to analyze the calculated elastic modulus of biporous nickel as a function of the total porosity for various values of Θ_{micr} (Fig. 3). Note that the effect of the microporosity decreases as λ increases. The exact calculated values of the elastic modulus of specific specimens with the actual values of Θ_{micr} and the corresponding experimental data are given in Table 1. They agree to within $\pm 10-15\%$ over w wide range of porosity for a large part of the specimens.

The curves in Fig. 4 of the elastic modulus of biporous materials as a function of the macroporosity were calculated from (1), with allowance for the fact that $\Theta_{micr} = (\Theta - \Theta_{macr})/(1 - \Theta_{macr})$, for cases when $\Theta = 68$, 70, and 72%, $\lambda_1 = 6$ and $\lambda_2 = 50$. Since the model proposed in [1] for describing the porosity limit of biporous materials works satisfactorily only for small microporosities (up to 10%), calculated values of Θ_c could not be obtained for the materials studied in our work. Taking into account the weak experimental dependence of Θ_c on the microporosity in the range 20-50%, when calculating the elastic modulus of highly porous materials we assumed the porosity limit to be constant, 74 and 76% for $\lambda_1 = 6$ and $\lambda_2 = 50$, respectively. The theoretical relations predict that the elastic modulus increases considerably as the microporosity increases in the neighborhood of the limiting point. The absolute value of the elastic modulus in this case depends strongly on the level of total porosity. For example, the elastic modulus drops by more than half when Θ of a material with a fine filler rises from 70 to 72%. That must be taken into account in an analysis of the experimental data obtained in studies of specimens from the third batch.

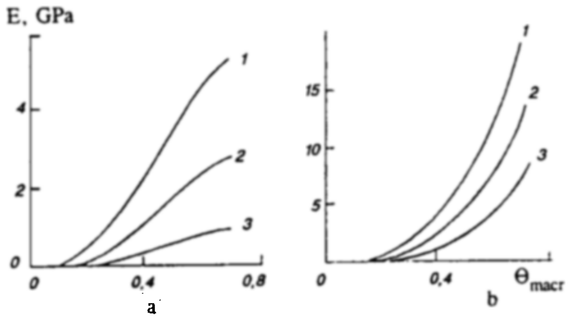

Fig. 4. Calculated curves of the elastic modulus of biporous materials as a function of the total macroporosity: 0.68 (1), 0.70 (2), 0.72 (3).

When preparing specimens of more highly porous materials with a fixed total porosity we assumed that shrinkage had not occurred during the high-temperature sintering. In practice, however, slight shrinkage is observed in materials with high porosity; this facilitates a change in the total porosity, that change being larger when the microporosity is higher (Table 1).

The experimental values of the elastic modulus of highly porosity nickel depend weakly on the macroporosity for a constant λ. In our view, that effect is due to the simultaneous action of two factors: a structural-geometric factor, which is responsible for the increase in the elastic modulus with increasing macroporosity, and a technological factor, which causes the total porosity to rise as the macroporosity increases and the elastic modulus decreases (Fig. 4a). The calculated values of the elastic modulus for specific values of Θ, Θ_{macr}, and Θ_{micr} of highly porous materials are in good agreement with experiment (Table 1) and support the proposed scheme.

In summary, Eq. (1) that we proposed satisfactorily describes the experimental relations of the elastic modulus over a wide range of porosities, including highly porous states; since it involves many parameters the equation makes possible a detailed analysis of the structural sensitivity of the elastic modulus of systems with a complex structure of pore space.

On the basis of experimental investigations and theoretical analysis the elastic modulus of biporous materials we have established the following laws: the nature of the dependence of the relative elastic modulus on the porosity is determined by the structural and geometric features of the porous system and is independent of the properties of the metallic base of the material; the elastic characteristics of biporous materials can be changed over a wide range by varying Θ, Θ_{micr}, Θ_{macr}, and λ; the increase in the elastic modulus of a biporous material is determined by the increase in the size ratio of the pore-forming agent and the powder as well as by the growth of the ratio $\Theta_{macr}/\Theta_{micr}$ for a given total porosity.

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