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Relationship between elongation and porosity for high porosity metal materials[①]

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Abstract: A simplified model was proposed targeting at the isotropic high porosity metal materials with well-distributed structure. From the model the mathematical relationship between elongation and porosity was deduced for those materials, and the relationship formula was derived generally for actual high porosity metals at last, whose validity is supported by the representative experiment on a nickel foam prepared by electrodeposition.

Key words: high porosity metal material; elongation; porosity **Document code**: A

1 INTRODUCTION

High porosity metal materials are widely applied daily for their specific characteristic[1~5]. As engineering materials, the mechanical properties are basic for them[1,3,5]. Porous bodies need be tensioned, pressed, bent or shaped in some cases, so high porosity metal materials are demanded certain capacity of plastic deformability at room temperature. For other instance, in acting as high porosity aviation constructural materials, the mechanical property is more important for them[2,6,7]. Elongation of porous materials depends on porosity greatly[8], and works in this aspect were once thought highly of by some people. The relationship between elongation and porosity for porous metals was studied not much at all before, just for the powder sintered materials with low porosity the conversion formulas were put forward[8~10]. While, high porosity metals have been manufactured by metal-deposition on organic porous bodies[2,11~15] and some other ways in recent years, with their porosity being higher than 90 % generally, exceeding the range studied on former experimental materials very much, and their structure feature is relatively well-distributed with void continuous. Aiming at these high porosity bodies with three-dimensional reticulated structure, in present work, a simplified model has been established, the relation formula between elongation and porosity has been established, the relation formula between elongation and porosity has been deduced and derived, whose calculation has been proved to be in agreement with the test result by relative experiment.

2 ESTABLISHMENT OF ANALYSIS MODEL AND DEDUCTION OF RELATIONSHIP FORMULA

2.1 Fundamental hypothesis of analysis model

Three-dimensional isotropic well-distributed high porosity materials may be simply thought as bodies composed of mass wires interlinking in the light of diagonal lines of cubes, and the wires act as the edges constituting mass octahedron void unit like body-centered cubic lattices (see Fig. 1). This structure way can make the porous body have equality in three representative interperpendicular directions, and the centrosymmetrical axis of that unit octahedron is in the tensile direction (see the arrow direction in Fig. 1). As for the high porosity metals prepared by the above-mentioned methods of metal deposition on

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organism foam, the joint position (simply called "node") has bigger effective area than the wire body, so the capacity bearing load is higher for the node, and the fracture generally occurs in the wire bodies during tension course. Meanwhile, the plastic deformation of total porous body taking place through tension course is mainly the plastic deflection of mass wire along the tensile direction, from which the percentage of relative extension is the elongation (δ) of this porous material.

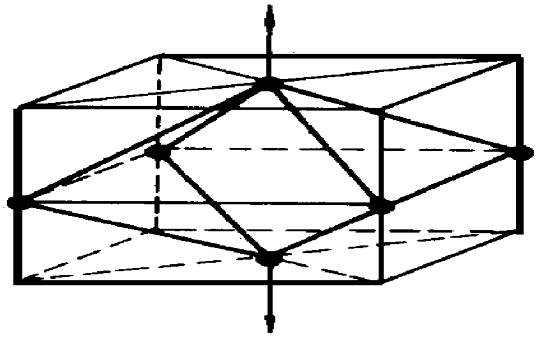

Fig.1 Schematic diagram of unit octahedron model

2.2 Deduction and result of relationship formula between elongation and porosity

2.2.1 Simplified treatment of model and relative dimensions

For convenience of calculation, the edges of the unit octahedron may be considered as the cylinders, and the internal vacancies of the edges themselves do the cylinder hollows. Let the porosity of continuous voids outside the metal wires, i.e., main voids, be θ', and the porosity of the internal vacancies within the metal wires θ'', so the total porosity is $\theta = \theta' + \theta''$, meanwhile, $\theta' \gg \theta''$. Besides, let the edge length of cubes containing the unite octahedron be a, then the following relations may be obtained according to the solid geometry and relationships between volume proportions coordinating Fig.1.

Edge length of the octahedrons:

$$L = \frac{\sqrt{3}}{2} a \tag{1}$$

Edge diameter of the octahedrons:

$$r = \sqrt{\frac{1 - \theta'}{4\sqrt{3}\pi}}\, a \tag{2}$$

Hollow diameter of the edges:

$$r' = \sqrt{\frac{\theta''}{4\sqrt{3}\pi}}\, a \tag{3}$$

Cross-sectional area available for edge prisms:

$$S_0 = \pi r^2 - \pi r'^2 = \frac{\sqrt{3}}{12}(1 - \theta) a^2 \tag{4}$$

2.2.2 Deduction of relationship formula between elongation and porosity

When the unit octahedron is tensioned along the axis, the included angle between the edges and the centrosymmetrical axis tends to decrease, so the edge (AB) might as well be thought as the cantilever whose side node (A) is stable and top node (B) suffers the external load (see Fig.2, which is the plane figure consisting of four opposite edges within the unit octahedron (referring to Fig.1), where α_0 expresses the original included angle between the edges and the centrosymmetrical axis of the unit octahedron ($\alpha_0 = \arcsin \sqrt{3}/3$), p' means the external load on the edge top (B) of the unit octahedron, and p_1 and p_2 do two components of force p' in the edge axis and vertical direction with the edge axis on B point of the edge, respectively).

Drawing lessons from the relation between the maximum stress (σ_{max}) created by a cantilever and the bearing bending moment (M) in material mechanics:

$$M = \sigma_{max} Z$$

(where Z is the bending sectional modulus of the edge), the following corresponding analysis is performed.

As a cantilever, the bigger the bending

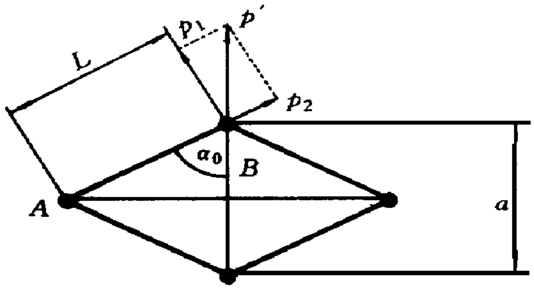

Fig.2 Analytical schematic for elongation of unit octahedron

moment borne by the prism, the bigger the degree tendency of the possible bend and deflection; while the higher its bending sectional modulus, the stronger its ability to resist bend and deflection. Therefore, the deflection angle at the prism fracture, $(\alpha_0 - \alpha)$ (where α is an included angle between the prism and the axis of octahedron, and $0 < \alpha < \alpha_0$), may increase with the increase of the limit bending moment that it is capable of bearing, $M_{max} = \sigma_0 Z$ (where σ_0 means the tensile strength of the corresponding compact material), and decrease with the increase of its bending sectional modulus Z. Thus, it can be thought for computation convenience that the amount of $(\alpha_0 - \alpha)$ is proportional directly to the limit bending moment M_{max} and inversely to the bending sectional modulus Z, namely

$$(\alpha_0 - \alpha) = \gamma\left(\frac{\sigma_0 Z}{Z}\right) = \gamma\sigma_0 \quad (5)$$

where γ is a proportion factor determined by material, i.e., by the same material made by the same production technique. It can be seen from the above that α is an included angle of feature deflection limit determined by material.

Observing the tension of porous bodies with certain plasticity, it can be found that the actual tensile force borne by the porous body increases gradually from zero with the process starting and proceeding, and the internal wire body deflects to result in an included angle with tensile direction decreasing gradually, namely the unit octahedron is elongated gradually. When the tensile force reaches a certain value, the maximum stress created in the inside of the prism gets the tensile strength of the corresponding compact body, the edge will deflect to a corresponding limit position and then break.

Referring Fig.2 and the cross section diagram of the note (see Fig.3, which is made by cutting the node through the plane lying on two opposite edge axes), relative sizes are computed by means of geometric methods.

In previous unit octahedron, connecting the geometric relationship in Fig.3 with two Formulas (1) and (2), the edge length can be obtained deducting the node loss:

$$L_1 \approx L - 2 \cdot \overline{OO_1}$$

$$\approx \sqrt{3}\left[\frac{1}{2} - \sqrt{\frac{\sqrt{3}(1 - \theta')}{8\pi}}\right] a \quad (6)$$

so the height of the original void involved by the unit octahedron (Fig.4(a)) is as

$$h_1 \approx 2 L_1 \cos \alpha_0$$

$$\approx \left[1 - \sqrt{\frac{\sqrt{3}}{2\pi}}(1 - \theta')^{1/2}\right] a \quad (7)$$

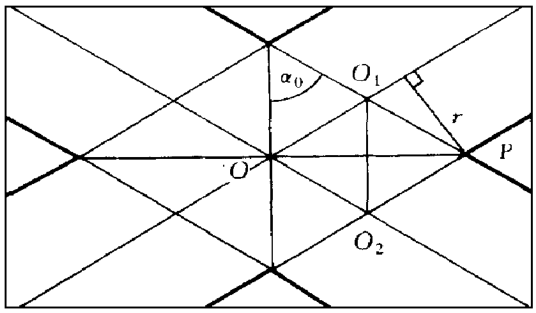

Fig.3 Node sectional diagram of unit octahedron for analyzing elongation from Fig.1

Referring to the relative computational method in Ref.[16], the absolute plastic elongation after the prism breakdown comprises the plastic deformations both of the even and the shrink necking, namely the length of the prism after deflection fracture can be expressed approximately by the following formula:

$$L_2 \approx (1 + k_1) L_1 + k_2 \sqrt{S_0} \quad (8)$$

where k_1 and k_2 are constants for the same material, and $k_1 = k_2 = 0$ when the material is pure brittle. Under the mechanism that the maximum tensile stress results in breakdown which is mainly caused by the bending moment, borne by the wire body, the crackle will immediately expand once a side of the wire body is broken, both of the plastic elongation and necking-down of the wire body itself are relatively small, and the elongation of the porous body mainly depends on the plastic deflection of the wire body. Thereby, in the above formula, both k_1 and k_2 are small, especially for k_2.

Connecting Formula (8) with Formulas (4) and (6), the height of the void contained by the unit octahedron after the edge deflection fracture can be obtained as following:

$$h_2 \approx \left[2 L_2 - k_2 \sqrt{S_0}\right] \cos \alpha$$

Fig.4 Schematic diagram of void height within unit octahedron before porous body tensioning (a) and after porous body fracturing (b)

$$\approx \left\{ \sqrt{3}(1 + k_1)\left[1 - \frac{\sqrt{3}}{\sqrt{2\pi}}(1 - \theta')^{1/2} \right] + \frac{\sqrt{3}}{12} k_2 (1 - \theta')^{1/2} \right\} a \cos \alpha \qquad (9)$$

In the above formula a $k_2 \sqrt{S_0}$ should be deducted because only one of each pair of prisms of the unit octahedron is generally under necking-down and another is just under even plastic elongation (Fig. 4 (b)). The force deflection state of each unit octahedron with the even porous body should be almost the same, only the even plastic deformation elongation is also produced for mass unit octahedron edge at the site without breakdown, along the total height direction (i.e., the elongation direction) of the porous body, so the height of the voids contained within them after the prows body breakdown will be

$$h_3 \approx h_2 - k_2 \sqrt{S_0} \cos \alpha \approx \sqrt{3}(1 + k_1)\left[1 - \frac{\sqrt{3}}{\sqrt{2\pi}}(1 - \theta')^{1/2} \right] \cdot a \cos \alpha \qquad (10)$$

The cross-section area available to load at the node is larger than that at the wire body, and its bearing capability is relatively higher than that of the wire body, so the node plastic deformation at the edge tensile breakdown is generally small, and can be omitted roughly in comparison with the size change along the tensile direction caused by the edge deflection. Supposing the considered porous body includes m ($m \gg 1$) unit octahedrons in tensile direction (see Fig.4), and combining Formulas (7), (9) and (10), the elongation of the whole porous body can be derived as

$$\delta \approx \frac{[h_2 + (m - 1) h_3] - m h_1}{m a} \approx [\sqrt{3}(1 + k_1)\cos \alpha - 1] \cdot \left[1 - \frac{\sqrt{3}}{\sqrt{2\pi}}(1 - \theta')^{1/2} \right] + \frac{\sqrt{3} k_2}{12 m}(1 - \theta')^{1/2} \cos \alpha \qquad (11)$$

If the considered initial scale distance is long enough (actually it needn't be long for the void size is relatively very small generally), namely the amount m of the included unit octahedrons along the tensile direction is large enough (actually it needn't be very large for k_2 is very small), the weight of the second term can be omitted in the above formula, so the total elongation of the porous body after breakdown has little relation with the initial scale distance, then

$$\delta \approx [\sqrt{3}(1 + k_1)\cos \alpha - 1] \cdot$$

$$\left[1 - \sqrt{\frac{\sqrt{3}}{2\pi}}(1 - \theta')^{1/2}\right] \quad (12)$$

When the material is brittle and brittle fracture takes place, $k_1 = 0$ and $\cos\alpha = \cos\alpha_0 = \sqrt{3}/3$, then substituting the values of k_1 and $\cos\alpha$ into the above formula and $\delta = 0$ can be gotten. That is, the elongation is zero under brittle fracture of the porous body.

The true structure status of the porous body is far more complicated than that of the simplified treatment in the deduction. All factors, including the wire body shape, the void shape, the distribution and evens of the void diameter, the specific mode of the structure and defect, and so on, can affect elongation. Factors deciding this specific structure principally depend on the production technique and the material sort to be used, so the above formula ought to be revised by the factor indicating the technique effect and the material sort, and it can be achieved by the simple mode of coefficient multiplication:

$$\delta \approx k_3[\sqrt{3}(1 + k_1)\cos\alpha - 1] \cdot \left[1 - \sqrt{\frac{\sqrt{3}}{2\pi}}(1 - \theta')^{1/2}\right] \quad (13)$$

Owing to all α, k_1 and k_2 being constants depending on the porous body material, it can be assumed:

$$K \approx k_3[\sqrt{3}(1 + k_1)\cos\alpha - 1] \quad (14)$$

and introduced into Formula (13), then

$$\delta \approx K[1 - 0.53(1 - \theta')^{1/2}] \quad (15)$$

where K is a constant depending on the material sort and the specific technique producing porous bodies.

For the actual common high porosity metals, it can be thought that $\theta' \gg \theta''$ and , $\theta' \approx \theta$, so Formula (15) can be further approximately written as

$$\delta \approx K[1 - 0.53(1 - \theta')^{1/2}] \quad (16)$$

It can be seen from the above formulas deduction:

(1) If only the porous body size in tensile direction is large enough, or say that the included void amount is large enough, elongation only relates to porosity for the same material made by the same product technique.

(2) The deduction of the above formulas is based on the isotropic porous body with even structure, while the porous body is anisotropic, previous unit octahedron in analysis model is elongated or pressed, namely original included angle α_0 between the octahedron edge and centrosymmetrical axis makes change. According to Formula (5), the feature limit included angle will change accordingly. According to Formula (14), the effect of this change is finally brought into the factor K in Formulas (15) and (16). Therefore, when the porous body is anisotropic, the factors in the above formulas depend on not only production technique and material sort to be used, but also tensile direction.

3 EXPERIMENTAL VERIFICATION OF RELATION FORMULAS

3.1 Preparation of experimental material and sample and test

The nickel foam prepared by metal nickel electroplating on the polyurethane sponge sheet about 2 mm thick was employed as the experimental materials. Referring to Ref.[11], the samples for the tensile strength test were dumbbell shaped having a total length of 12 cm and a variable thickness which varied with the samples. The samples were 1 cm wide in the neck (4.6 cm in length) and tapered at each end over a length of 1.6 cm to 2.0 cm in width.

XLL-50 type tensile strength tester was used to measure the tensile strength, all tests were done at the room temperature of 25 ℃, and the samples were pulled at a constant rate of 8.2 mm/min. Elongation was calculated referring to GB228-87. Each four samples were tested for the same porosity, the mean value of the tensile strength was taken, and the results are shown in Fig.5.

3.2 Application of formulas and discussion

3.2.1 Introduction of other computation formulas

Ref. [8] has introduced the following relation formula between elongation and porosity for porous bodies from a fracture theoretical model for plastic metals by Joel S:

$$\delta = K_1 - K_2 \ln\theta \quad (17)$$

as well as other two empirical relation formulas between elongation and porosity for sintered irons established on basis of a great deal of experimental data:

$$\delta = \delta_0 (1 - \theta)^n \qquad (18)$$

and

$$\delta = \delta_0 \theta^{-K_1} \exp(-K_2 \theta) \qquad (19)$$

where δ_0 is the elongation of corresponding compact material; n, K_1 and K_2 are all material constants related to production technique.

The relation formulas of theoretical analysis about sintered porous bodies introduced by Ref. [10] are respectively:

$$\delta = \left[1 - 1.21\,\theta^{\frac{2}{3}}\right]^{\frac{3}{2}} \qquad (20)$$

$$\delta = \left[1 - \theta\right]^{\frac{3}{2}} \cdot n^{-\frac{1}{2}} \qquad (21)$$

$$\delta = \left[1 - \theta\right]^{\frac{3}{2}} \cdot \left[1 + C^2\right]^{-\frac{1}{2}} \qquad (22)$$

where n is the branching amount per unit cross-section (it's a constant for the present experimental material), and C is sensitivity of ductility to the void amount.

There are two constants needing to be determined in Formulas (17) and (19) so that they are inconvenient to use, and the present experimental data are so disperse that they are not abundant for multi-coefficient formulas. While, the application of Formula (20) must meet the condition of $(1 - 1.21\,\theta^{2/3}) > 0$, namely θ is under range of 0.75, so this formula can not be applied because porosity considered in this experiment is over 0.8. In addition, it can be known by the expression that the application effects of Formulas (21) and (22) are the same. Thus, in following context, only two Formulas (18) and (21) with singular coefficient will be used for comparison with Formula (16), derived from this paper.

3.2.2 Computation results using different formulas

With compact nickel elongation datum $\delta_0 = 0.3$ offered by Ref.[17] in Formula (18), the average constants in the three Formulas (16), (18) and (21) for the experimental material can be computed out respectively using the experimental data, introduced back into the original formulas, and the following relations can be gotten successively:

$$\delta = 0.44\left[1 - 0.53(1 - \theta)^{\frac{1}{2}}\right] \qquad (16')$$

$$\delta = 0.3(1 - \theta)^{0.313} \qquad (18')$$

$$\delta = 26.1(1 - \theta)^{\frac{3}{2}} \qquad (21')$$

Computations are done using Formulas (16′), (18′) and (21′), and the results are displayed in the relation figure between elongation and porosity (Fig.5) together.

Fig.5 Relationship between elongation after fracture and porosity for porous nickel produced by electrodeposition

3.2.3 Suitability of present theoretical formulas to high porosity materials

The experimental data in Fig.5 are relatively despersive owing to the effect of measurement errors, but except Sample 9# (its jointed press is relatively severe), the other samples manifest a tendency of elongation raising with porosity enlarging. The theoretical curve of Formula (16′) is coincided with the above tendency but two other ones deviate significantly. It can be obtained that elongation is decreasing with the enlargement of porosity from Formula (17) to (22), which is also verified by practice of porous materials with porosity not too high. So it can be seen that for the same metals containing voids prepared by the same technique, their elongation change with porosity divides into two situations:

(1) When porosity is low, voids included in the porous material are mainly the isolated closed ones, voids can be thought as "impurity", breakdown principally depends on the decrease of effective bearing area of materials, stress concentration created by voids, and so on, elongation is

mainly the plastic one along the tensile direction, and elongation decreases with porosity raising, so does the material plasticity.

(2) After porosity is larger than a certain value, voids in the porous material will turn continuous gradually and occupy main space of the porous body, the metal body turns the three-dimensional net structure with wire bodies jointing one another, the maximum stress created by the bending moment on the metal wire body exerted by load becomes the decisive factor of breakdown, and elongation is mainly the plastic deflection of the wire body along the tensile direction. The structure feature of porous materials and the breakdown elongation mechanism have transformed, which makes elongation become slightly high with the enlargement of porosity. But generally speaking, the porosity range in the first case is much wider, and the last case only happens in the range of quite high porosity, so the present theoretical formulas adapt to high porosity and the formulas put forward by seniors do only lower porosity.

4 CONCLUSIONS

(1) Elongation of high porosity metal materials slightly enlarges with enlargement of porosity and shows the opposite rule in comparison with porous metals in range of low porosity, which is mainly made by difference of elongation mechanism for the two.

(2) The relation formula about elongation of high porosity materials and porosity can be expressed as

$$\delta \approx K[1 - 0.53(1 - \theta)^{1/2}]$$

where K is a constant depending on the production technique of porous bodies and the material sort, and is relative to tensile direction when the porous body is anisotropic; θ is total porosity. Deduction of the above formula bases on the structure feature of materials with high porosity and the formula only suits high porosity range, such as 80 % or higher.

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