APPROXIMATE MEANS FOR EVALUATING TENSILE STRENGTH OF HIGH POROSITY MATERIALS①

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ABSTRACT Based on the simplified structure model of high porosity materials, the formulas for approximately evaluating the tensile strength of these materials have been derived from the corresponding deductions taken by means of the relative theories about geometry and mechanics. The results show that, the tensile strength of these materials not only associates with the material sort and production method, but do further have a direct value relationship with the porosity, θ. This value relationship can be specifically expressed by the power of the item $(1 - \theta)$, and it makes the tensile strength variation display a complicated nonlinear law with the porosity. In addition, the application of those formulas has been investigated with the corresponding experiment on a nickel foam.

Key words high porosity material tensile strength evaluation

1 INTRODUCTION

The tensile strength is an important property for engineering materials, and the same for the porous ones, so people have been thinking highly of the theoretical evaluation of the tensile strength for pore-containing bodies. More than 20 corresponding calculation formulas are introduced just in Ref.[1], some of which have similar types, others are very different, but all of their calculations are by means of porosity which is the specific index for porous bodies.

The high porosity metals, which have been developed rapidly in recent years, may be regarded as the new porous materials, and their production methods are generally different from the traditional powder sintering technology, but the electrodeposition on organic porous bodies[2-5], the metal gas phase deposition on organic porous bodies[6,7] and the metal fibre concentration[8], etc. They possess a three-dimensional reticulated structure consisting of continuous voids, and their porosities are ranging from 80s to 90s percent. These high porosity materials may be applied to battery electrode matrixes, filters, catalyst carriers[2,4,5], electrochemical process cathodes such as in electric composition[3], fluid mixers[4], heat exchangers[3,8], silencer materials, electromagnetic shielders[4,8], composite metal materials and some other fillers[5,8]. As the functional and constructional materials are utilized widely, the acoustic, thermal, damping and electromagnetic shielding properties of porous metals have been systematically studied by Prof. He Deping in Southeast University of China and his students, and their tensile strength is a basic mechanical property, so its explicit value range will be demanded in excellent designs for high quality materials and many other situations. But the former formulas for evaluating the tensile strength of porous bodies[1,9,10] are mainly based on the various powder sintered materials containing isolated voids such as sintered iron and steels, they generally suit one or several specific preparing means and materials directively, and have the better practical effect in the lower porosity range. Among them, majority are the empirical

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and half-empirical ones. In contrast to them, from the simplified treatment and approximate deduction according to the three-dimensional reticulated structure feature of high porosity materials, the present paper has derived the simple evaluation formulas commonly suiting high porosity metals produced by various technologies and made of different materials. By examinationally applying those formulas to an electrodeposition-type nickel foam, their effects have been comparatively analyzed, and the superior has been found.

2 APPROXIMATE DEDUCTION AND RESULTS ABOUT EVALUATION FORMULAS

2.1 Fundamental hypothesis for physical model

Isotropic high porosity metals take the three-dimensional reticulated structure with their metal wires linking in the light of diagonal lines of cubes, which consists of many octahedron void units like body-centered cubic lattices (see Fig.1(a)), and the centrosymmetrical axis of a unit octahedron is in the tensile direction (see the arrow direction in Fig.1(a)). When the maximum normal stress (σ_{max}) achieves the tensile strength value (σ_0) of the corresponding compact material at any position within the metal wires and the nodes of the unit octahedron, the fracture leading to the integral destruction of the porous body will emerge. At this time, the external tensile stress on the integral porous body is the tensile strength (σ) of this porous material.

Fig.1(a) shows the isolation analysis model taken from mass interlinked unit octahedrons contained in the porous body. When the material is brittle, the node positions are stable during tension. While the material has plasticity, the unit octahedron can be lengthened by tension. But as an approximate calculation, and for deduction convenience, the transfer of tension from the outside may be aimed at mainly, and the binding force vertical to the external load might as well not be considered temporarily.

2.2 Simplified treatment and relevant dimensions about unit octahedron

For convenience, the edges of the unit octahedron may be considered as cylinders, and the internal vacancies of the edges themselves may be also considered as cylinder hollows. Let the porosity of continuous voids (i.e. main voids) outside the metal wires and constituted by linkup of the metal wires be θ', and the porosity of the internal vacancies within the metal wires θ'', so the total porosity is $\theta = \theta' + \theta''$, meanwhile, $\theta' \gg \theta''$. In addition, let the length of the edges of

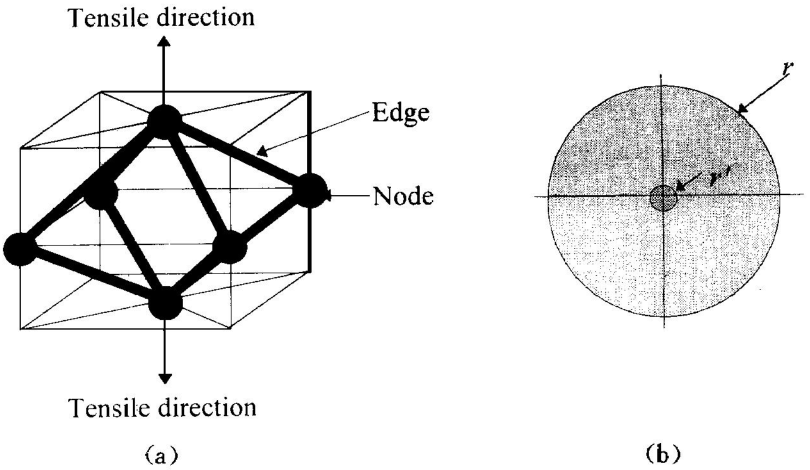

Fig.1 Schematic diagram for analyzing tensile strength of high porosity materials
(a) —Unit octahedron; (b) —Cross-section of edge

the cube containing the unit octahedron be a, and the following relations may be obtained according to the solid geometry and relationships between volume proportions combined with Fig. 1:

the edge length of the octahedrons

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

the edge diameter of the octahedrons

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

the hollow diameter of the edges

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

2.3 Internal fracture ways and corresponding tensile strength appearance of porous body

Let the external nominal tensile stress on the porous body be σ, thus the load on the unit octahedron is $p = a^2 \cdot \sigma$, and the action force on each edge is

$$p' = \frac{1}{4}p = \frac{1}{4}a^2 \cdot \sigma$$

The components of force p' in the edge axis and vertical direction with the edge axis are p_1 and p_2 respectively, and Fig. 2 is the plane figure consisting of four opposite edges within the unit octahedron.

2.3.1 Node fracture

The position yielding the maximum stress in the node should be at the joining section connecting four upper edges and four lower edges of the unit octahedron, which is the node neck, so this position may be believed as the one where prior destruction takes place. Considering the filling in technology, the above-mentioned section area can be approximately derived from the geometrical relations in Fig. 2 and equations (1) ~ (3):

$$S \approx k[(\frac{rL}{a/2})^2\pi - (\frac{r'L}{a/2})^2\pi]$$
$$= k[\frac{\sqrt{3}}{4}(1-\theta')a^2 - \frac{\sqrt{3}}{4}\theta''a^2]$$
$$= \frac{\sqrt{3}}{4}k(1-\theta'-\theta'')a^2$$
$$= \frac{\sqrt{3}}{4}k(1-\theta)a^2$$

So the maximum stress in the node is

$$\sigma_{max} \approx \frac{p}{S} = \frac{\sigma \cdot a^2}{\frac{\sqrt{3}}{4}k(1-\theta)\cdot a^2}$$
$$= \frac{4\sqrt{3}}{3k} \cdot \frac{\sigma}{1-\theta}$$

where k means the proportional coefficient. When $\sigma_{max} = \sigma_0$, $\sigma \approx \sqrt{3}/4 \cdot k(1-\theta)\cdot\sigma_0$, which is simply written as

$$\sigma \approx K \cdot (1-\theta)\cdot\sigma_0 \tag{4}$$

this is the tensile strength of porous material while the node fracture causes the integral destruction of the porous body, where K depends on both the material sort and preparation technology which affect the specific structure situation of the porous body.

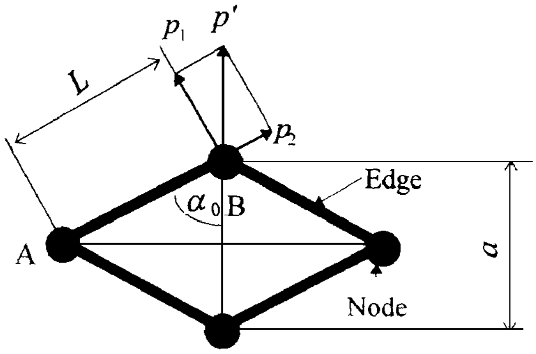

Fig. 2 Force analytical schematic for unit octahedron
(where α_0 expresses the original included angle between the edges and the centrosymmetrical axis of the unit octahedron, and A and B express the side and top nodes respectively.)

2.3.2 Edge fracture

As to a single unit octahedron within the porous body imposed a tensile force, the external load upon it may be considered at the upper and lower nodes, and the included angle between the edges and the centrosymmetrical axis tends to decrease. On the basis of the different plasticity of materials, there are three possible situations for the edge fracture, i.e., the edge has no revolution at all, turns some angle and turns to the same direction as the external load. On the first and second situations, the edge may be thought as the cantilever whose side node (A) is stable and top node (B) suffers the external load (see Fig .2) . The approximate calculations are taken by means of the relative theory in elastic mechanics, presuming the section doesn't change during the edge revolution.

(i) Brittle fracture approximation without revolution of the edge

Referring to Fig .2 , there are

$$\begin{aligned} p_1 &= p'\sin a_0 \\ &= p' \cdot (\sqrt{2}/2)\, a \cdot (1/L) \\ &= (\sqrt{6}/12) \cdot a^2 \cdot \sigma \qquad (5) \\ p_2 &= p'\cos a_0 \\ &= p' \cdot (1/2)\, a \cdot (1/L) \\ &= (\sqrt{3}/12) \cdot a^2 \cdot \sigma \qquad (6) \end{aligned}$$

As for a cantilever, the section where the maximum bending moment is produced ought to be at the support root theoretically. However, the edge isn't even actually, and the fracture generally takes place at a relatively weak position, which can arise in any place from A to B at the roughly equal opportunity according to actual conditions. Hence, the prior fracture position may be taken as the middle of the edge synthetically. For calculation convenience, the hypothesis might as well be done that the fracture is caused by the minimum load bearing area of the edge middle leading to the partial stress concentration. Assuming that the shape variation of that section is its internal and external diameters all becoming $1/n$ time of the even edge, where n is a constant number more than 1 and decided by the production conditions, from equations (1) and (4), the bending moment of the prior fracture position can be approximately expressed as

$$\begin{aligned} M &= p_1 \cdot \frac{L}{2} = \frac{\sqrt{6}}{12} \cdot a^2 \cdot \sigma \cdot \frac{\sqrt{3}}{4} a \\ &= \frac{\sqrt{2}}{16} a^3 \cdot \sigma \qquad (7) \end{aligned}$$

Connecting relations (2) and (3), the bending sectional modulus of the prior fracture position of the edge can be derived as

$$\begin{aligned} z &\approx \frac{\pi}{32}\left[\frac{(2 \cdot \frac{r}{n})^4 - (2 \cdot \frac{r'}{n})^4}{(2 \cdot \frac{r}{n})}\right] \\ &= \frac{1}{96 n^3}[(1 - \theta')^2 - (\theta'')^2] \cdot \sqrt{\frac{\sqrt{3}}{\pi(1 - \theta')}} \cdot a^3 \qquad (8) \end{aligned}$$

Thus the maximum normal stress causing by bending moment M can be deduced from relations (7) and (8) as

$$\sigma_1 \approx \frac{M}{Z} \approx \frac{2n^3 \sqrt{6\sqrt{3}\pi(1 - \theta')}}{(1 - \theta')^2 - (\theta'')^2} \cdot \sigma \qquad (9)$$

Besides, referring to relations (2), (3) and (6), the tensile stress produced by p_2 can be acquired as

$$\sigma_2 \approx \frac{p_2}{\pi(\frac{r}{n})^2 - \pi(\frac{r'}{n})^2} = \frac{n^2}{1 - \theta} \cdot \sigma \qquad (10)$$

From relations (9) and (10) the total maximum normal stress of the edge middle can be got as

$$\begin{aligned} \sigma_{\max} &= \sigma_1 + \sigma_2 \\ &\approx \left\{\frac{2n^3 \sqrt{6\sqrt{3}\pi(1 - \theta')}}{(1 - \theta')^2 - (\theta'')^2} + \frac{n^2}{1 - \theta}\right\} \cdot \sigma_{an} \end{aligned}$$

when $\sigma_{\max} = \sigma_0$, σ in the above formula matches the integral tensile strength of the porous body, so the apparent tensile strength of the porous body is

$$\begin{aligned} \sigma &\approx \sigma_0\left[\frac{2n^3 \sqrt{6\sqrt{3}\pi(1 - \theta')}}{(1 - \theta')^2 - (\theta'')^2} + \frac{n^2}{1 - \theta}\right]^{-1} \\ &= \left\{\frac{[(1 - \theta')^2 - (\theta'')^2] \cdot}{n^2[(1 - \theta')^2 - (\theta'')^2] +} \rightarrow \right. \\ &\quad \left. \leftarrow \frac{(1 - \theta)}{2n^3 \sqrt{6\sqrt{3}\pi(1 - \theta')} \cdot (1 - \theta)}\right\} \cdot \sigma_0 \end{aligned}$$

this formula is deduced on the basis of the hypothetical regular structure, and other shape-variations except the above mentioned one during the tension course of the edge aren't considered, nor is the complication of the fine structure and vacancies of the porous body under actual condition. For those factors are mainly affected by the material sort and practical technology for preparing the porous bodies, the above formula should be revised with a constant K' presenting both of the material sort and production conditions. Through the simple mode of coefficient multiplication, it changes into

$$\begin{aligned} \sigma &\approx K' \cdot \left\{\frac{[(1 - \theta')^2 - (\theta'')^2] \cdot}{n^2[(1 - \theta')^2 - (\theta'')^2] +} \rightarrow \right. \\ &\quad \left. \leftarrow \frac{(1 - \theta)}{2n^3 \sqrt{6\sqrt{3}\pi(1 - \theta')} \cdot (1 - \theta)}\right\} \cdot \sigma_0 \qquad (11) \end{aligned}$$

When θ'' equals zero or can be regarded as small enough, there are

$$\theta' = \theta,\ (1-\theta') = (1-\theta),\ (\theta'')^2 = 0$$

and σ can be derived from relation (11):

$$\sigma \approx \frac{K'}{n^2}\cdot\left\{\frac{(1-\theta)^2}{(1-\theta)+2n\sqrt{6\sqrt{3}\pi(1-\theta)}}\right\}\cdot\sigma_0 \tag{12}$$

In addition, if θ is big enough, for example, more than 70%, then

$$\frac{(1-\theta)}{2n\sqrt{6\sqrt{3}\pi(1-\theta)}} = \frac{\sqrt{2\sqrt{3}\pi}}{12\pi n}(1-\theta)^{1/2} < \frac{\sqrt{2\sqrt{3}\pi}}{12\pi n}(1-0.7)^{1/2} < \frac{0.05}{n} \ll 1$$

that is $(1-\theta) \ll 2n^3\sqrt{6\sqrt{3}\pi(1-\theta)}$

So σ can also be achieved from relation (12):

$$\sigma \approx \frac{K'(1-\theta)^2}{2n^3\sqrt{6\sqrt{3}\pi(1-\theta)}}\cdot\sigma_0 = K\cdot(1-\theta)^{1.5}\cdot\sigma_0 \tag{13}$$

where $K = K'/(2n^3\sqrt{6\sqrt{3}\pi})$, is still a factor depending on the material sort and preparing technology. This is the formula evaluating the tensile strength of porous materials in the abovementioned situation.

(ii) Plastic fracture approximation with edge taking a certain geometrical deflection

Observing the tension of the porous body made from materials having some plasticity, it can be found that, with the tensile force increasing gradually, the internal wires of the porous body deflect to decrease the included angle with the tension direction, namely, the unit octahedron is gradually elongated. When the tensile force reaches some value making the maximum stress within the edge exceed the tensile strength of the compact body, the edge will turn to a corresponding limit position and fracture.

When the edge is pulled to deflect, the antimoment M_r against external load, upon the edge and produced by the side node (i.e., the fixed end of cantilever) will raise along with increasing edge deflection magnitude. And as to a given deflection magnitude, the larger the bending sectional modulus Z, the larger the antimoment M_r. Hence, M_r at the fracture position might as well be thought as

$$M_r \approx \beta\cdot Z\cdot\sin(\alpha_0-\alpha) \tag{14}$$

where β is a proportional coefficient depending on the material ($\beta=0$ to the soft materials), α is the included angle between the external tensile force and the edge at the limit fracture position, and $0<\alpha<\alpha_0$. Besides, item $(\alpha_0-\alpha)$ is taken sine for simplifying calculation.

Corresponding to Fig.2, the bending force p_1 and tensile force p_2 on the edge imposed by the external tensile force are respectively

$$p_1 = p'\sin\alpha = a^2/4\cdot\sigma\cdot\sin\alpha \tag{15}$$

$$p_2 = p'\cos\alpha = a^2/4\cdot\sigma\cdot\cos\alpha \tag{16}$$

where σ is the external tensile stress on the porous body at the fracture time.

Connecting relations (1) and (15), the maximum bending moment arising from p_1 at the fracture position (that is also the middle of the edge, the same reason as (i)) can be obtained as

$$M_{max} \approx p_1\cdot L/2 = \sqrt{3}/16\cdot a^3\cdot\sigma\cdot\sin\alpha \tag{17}$$

Combining relations (2), (3) and (16), the tensile force produced by p_2 in the edge fracture section can be gained as

$$\sigma_2 \approx \frac{p_2}{\pi(\frac{r}{n})^2-\pi(\frac{r'}{n})^2} = \sqrt{3}\cdot\cos\alpha\cdot\frac{n^2}{1-\theta}\cdot\sigma \tag{18}$$

For σ_2 is distributed over the section centrosymmetrically, it makes no contribution to the moment of force at the fracture place.

Utilizing the moment equilibrium principle for the fracture position, there is

$$M_r + (\sigma_0-\sigma_2)\cdot Z = M_{max} \tag{19}$$

Introducing relations (8), (14), (17) and (18) into (19), σ can be achieved through arrangement:

$$\sigma \approx \left\{\frac{[\beta(\sqrt{2}\cdot\cos\alpha-\sin\alpha)+\sqrt{3}]\cdot}{6\sqrt{3\pi\sqrt{3}}\cdot(1-\theta')^{1/2}\cdot}\rightarrow \leftarrow\frac{[(1-\theta')^2-(\theta'')^2]\cdot}{(1-\theta)\cdot\sin\alpha+}\rightarrow \leftarrow\frac{(1-\theta)}{3[(1-\theta')^2-(\theta'')^2]\cos\alpha}\right\}\cdot\sigma_0 \tag{20}$$

revising it like (i), then

$$\sigma \approx K'\cdot\left\{\frac{[\beta(\sqrt{2}\cdot\cos\alpha-\sin\alpha)+\sqrt{3}]\cdot}{6\sqrt{3\pi\sqrt{3}}\cdot(1-\theta')^{1/2}\cdot}\rightarrow\right.$$

$$\leftarrow \frac{[(1-\theta')^2-(\theta'')^2]\cdot}{(1-\theta)\cdot\sin\alpha+} \rightarrow$$

$$\leftarrow \left.\frac{(1-\theta)}{3[(1-\theta')^2-(\theta'')^2]\cos\alpha}\right\}\cdot\sigma_0 \qquad (21)$$

where K' and β are respectively the correct coefficient and the proportional constant both depending on the material sort and the technological conditions, α_0 and α are respectively the original and the minimum included angle between the edge and the axis, and, $\alpha_0 = \arcsin(\sqrt{3}/3)$, $0 < \alpha < \alpha_0$.

The deflection angle ($\alpha_0 - \alpha$) of the edge at the fracture time will increase along with increasing limit bending moment ($M_{max} = \sigma_0 Z$) bearable to the edge, and decrease along with enhancing bending sectional modulus (Z), so it can be roughly considered for the calculation convenience as $\sin(\alpha_0 - \alpha) = \gamma(\sigma_0 Z/Z) = \gamma\sigma_0$, where γ is the proportional coefficients determined by the specific material, hence α is the peculiar limit deflection included angle depending on the specific material too. Let

$$C = K'[\beta(\sqrt{2}\cdot\cos\alpha - \sin\alpha) + \sqrt{3}]$$

$$K_1 = \frac{6\sqrt{3}\sqrt{3}\pi}{C}\cdot\sin\alpha$$

$$K_2 = \frac{3}{C}\cdot\cos\alpha$$

then σ can be derived from relation (21) as

$$\sigma \approx \frac{[(1-\theta')^2-(\theta'')^2]\cdot}{K_1(1-\theta')^{1/2}\cdot(1-\theta)+} \rightarrow$$

$$\leftarrow \frac{(1-\theta)}{K_2[(1-\theta')^2-(\theta'')^2]}\cdot\sigma_0 \qquad (22)$$

where C, K_1 and K_2 are all the coefficients decided by the specific material, i.e., decided by the material sort and technology for manufacturing the porous body.

When $\theta'' = 0$ or small enough, there is $\theta' = \theta$ or $\theta' \approx \theta$, σ can be got from relation (22) approximately as

$$\sigma \approx \frac{(1-\theta)^2}{K_1(1-\theta)^{1/2} + K_2(1-\theta)}\cdot\sigma_0 \qquad (23)$$

Eq.(23) is the calculation formula evaluating the tensile strength for high porosity metals approximately. Testing the tensile strengths of the porous bodies made from the same material (which is the same sort of material and produced by the same method) for several different porosities, substituting the outcomes into the above formula and solving the binary linear equation sets, and constants K_1 and K_2 can be acquired for the corresponding material. Then, the tensile strength of this porous material can be evaluated for any given porosity by means of the formula.

(iii) Pliabilitic fracture approximation with edge deflecting completely

It is supposed that the edge won't fracture till the edge turns to the same direction as the external load thoroughly. For simplicity, the pliability of the edge near the node is still believed to be so high that the crackles and other defects causing the prior fracture won't emerge during the tension course. At this time, the fracture strength, σ, is the pure normal stress on the edge. No matter whether the shape and size of the fracture section change or not during all the course, it can be achieved by reduction proportion of the area enduring the load as well as relations (2) and (3):

$$\sigma \approx K''\cdot\frac{4(\pi r^2 - \pi r'^2)}{a^2}\cdot\sigma_0$$

$$= \frac{K''}{\sqrt{3}}\cdot(1-\theta)\cdot\sigma_0$$

$$= K_2\cdot(1-\theta)\cdot\sigma_0 \qquad (24)$$

where K'' and K_2 are also constants depending on the material sort and technology.

(iv) Simplified approximation for edge fracture with moderate deflection

This case is similar to (ii), and between (i) and (iii), so the tensile strength can be approximately expressed as

$$\sigma = K\cdot(1-\theta)^{1\sim1.5}\cdot\sigma_0 \qquad (25)$$

When the material possesses the moderate plasticity, there is roughly

$$\sigma = K\cdot(1-\theta)^{1.25}\cdot\sigma_0 \qquad (26)$$

3 APPLICATION AND VERIFICATION OF FORMULAS

3.1 Experimental material as well as preparation and test of samples

The experimental materials employed the nickel foams developed by metal nickel electroplating on the polyether sponge sheet about 2 mm thick, whose preparing procedures were primarily soaking the sponge in the conductive colloid, electrodepositing nickel on the soaked sponge and reduction-pyrolysis of the electroplated sponge. Keeping the other technological conditions stable, just altering the electroplating time, the porous nickel plates with different porosities and 2 ~ 3 mm thick were obtained. Referring to Ref. [7], a die was used to cut samples of nickel foams to standard dimensions for the tensile strength test. The samples 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, with its loading error less than 1 %. The original length between clamps padding rubber mutts was 8 cm, and the samples were pulled at a constant rate of 8.2 mm/min, which approaches 0.13 mm/s in Ref.[7]. The measuring ranges were always adjusted according to the practical tension values during the test course, so as to make the fracture tension not only within the measuring range but also close to the measuring range limit as far as possible, and do the measure errors get to the least. Only samples fractured in the neck region were accepted as valid, every four samples were tested for the same porosity, and the mean value of the tensile strength was taken. All tests were made at about 25 ℃.

3.2 Results and formula applications

As for the present experimental material, there are $\theta'' < 2\%$ and $\theta > 88\%$, so the error brought by regarding $\theta'' \approx 0$ and $\theta' \approx \theta$ is less than 2 %. Moreover, as the node strength is far higher than that of the edge one, the fracture will take place at the weak position just within the edge. Besides, the metal wires of this material take a certain deflection during the tension course. Therefore, here only two formulas (23) and (26) were used for verifying them and comparing their effects.

As to every four single samples for the same porosity, the scatters of all the test values of the tensile strength are not big, and their mean values are listed in Table 1. Utilizing the $\sigma_0 = 490$ MPa provided by Ref. [11] as the tensile strength of metal nickel, and introducing the mean test values of the tensile strength corresponding to the samples with different porosities into the above two formulas successively, the corresponding coefficient values can be derived from solving the ten unary linear equations respectively for formula (26). While for formula (23), ten binary linear equations are got. Combining every porosity equation with the next one, and the last one with the first one, ten equation sets of binary linear equations are composed, and ten sets of coefficient values corresponding to the samples with different porosities are solved out. The relative deviations of coefficient values of 6# sample vs the mean one are found exceeding that of all the other samples greatly for both formulas (23) and (26) during computing the mean values. By means of the related theories in error analysis and datum treatment, according to Glabs statistics rule, taking confidence degree $\alpha = 1.0\%$, the corresponding data of this sample are judged to be doubtable and abandoned, and all the mean values are calculated again with the other nine samples for these two formulas. Substituting the mean coefficient values back into the original formulas, they can be approximately obtained correspondingly:

$$\sigma = \frac{(1-\theta)^2}{1.797(1-\theta)^{1/2} + 2.536(1-\theta)} \cdot \sigma_0 \tag{23'}$$

$$\sigma = 0.213(1-\theta)^{1.25}\sigma_0 \tag{26'}$$

The tensile strengths of those samples are evaluated with the above two formulas, the related calculation results are given in Table 1 together. And the direct visual coincidences between the specific theoretical curves and the practical test dada are presented in Fig.3 together.

4 ANALYSIS AND DISCUSSION

Table 1 and Fig.3 show that the calculation values coincide with the test results well for formulas (23) and (26), but deviate obviously for (13) and (24). This fact is due to a certain deflection of the metal wires of the experimental material during the tension course, and identified by the actual observation. It's also illustrated that metal nickel is a material with the moderate plasticity at the same time.

It's presented in Table 1 that the coefficient in formula (26) is so steady that its relative fluctuation ranges within several percent, which makes the formula utilized very conveniently. That is to say, if the preparation and measurement of samples for getting the specific coefficients are relatively accurate, the calculation errors caused by the coefficient uncertainty are also within several percent when the tensile strengths of the same sort of porous material are computed by the formula whose coefficient is substituted back with any one available. The relative deviations of evaluation values of formula (26′), the multiplied one of formula (26), vs the test ones are within several percent too, this evaluation result may be regarded to be good. Besides, this formula has only one unknown coefficient, which can be solved out easily, and displays an excellent overall application effect for the present experimental material. Nevertheless, the value 1.25 taken as the index representing the material plasticity isn't strict, and there is randomness to some extent in that this value has achieved a

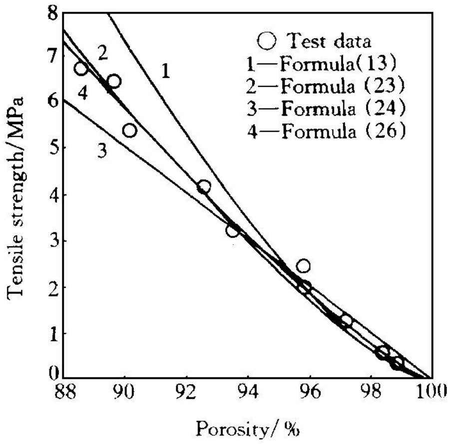

Fig.3 Relationship between tensile strength and porosity for porous nickel produced by electrodeposition

Table 1 Experimental results and application of formulas

Sample number	1	2	3	4	5	6	7	8	9	10	Mean
θ/ %	88.60	89.66	90.19	92.55	93.52	95.79	95.83	97.15	98.38	98.84	
σ test value/ MPa	6.75	6.45	5.40	4.16	3.23	2.48	2.00	1.28	0.63	0.38	
σ F(23′)/ MPa	7.11	6.24	5.81	4.00	3.31	1.83	1.80	1.06	0.48	0.30	
σ F(26′)/ MPa	7.08	6.26	5.86	4.16	3.49	2.04	2.01	1.25	0.62	0.41	
abs($\Delta\sigma/\sigma$)-F(23′)/ %	5.3	3.3	7.6	3.4	2.5	(26.3)	9.9	17.2	24.1	22.2	10.6
abs($\Delta\sigma/\sigma$)-F(26′)/ %	4.8	2.9	8.6	0.0	8.1	(17.9)	0.6	2.3	1.7	7.0	4.0
K_1-F(23′)	-2.822	12.623	-0.268	3.987	-1.600	(80.829)	0.676	0.895	1.623	1.057	1.797
K_2-F(23′)	16.631	-31.400	9.758	-5.832	16.116	(-385.61)	6.907	5.610	-0.114	5.145	2.536
K-F(26′)	0.208	0.225	0.201	0.218	0.202	(0.265)	0.217	0.223	0.222	0.204	0.213
abs($\Delta K_1/k_1$)-F(23′)/ %	257.0	602.4	114.9	121.9	189.0	(4398.0)	62.4	50.2	9.7	41.1	161.0
abs($\Delta K_2/k_2$)-F(23′)/ %	555.8	1338.2	248.8	323.0	535.5	(15305.5)	172.4	121.2	104.5	102.9	393.1
abs($\Delta K/k$)-F(26′)/ %	4.6	3.2	7.8	0.0	7.3	(21.6)	0.5	2.3	1.8	6.4	4.0

① F(23) represents formula (23), and the others are similar;
② $\Delta\sigma/\sigma$ = {[(evaluation value of the tensile strength by formulas)-(test value of the tensile strength)]/(test value of the tensile strength)} × 100 %;
③ k is the mean value of K, $\Delta K = K - k$, and the mean values were calculated without the data of 6# sample for both formulas (23′) and (26′).

good effect for metal nickel, but this taking-value way is still acceptable for an approximate evaluation. As to the taking-value of the index, documents about the metal properties can be referred.

Formula (23) is also pratical, moveover, it has a low sensitivity to the coefficients, but its violently fluctuated constants bring a greater inconvenience to the pre-solution before the formula application, so its overall use effect isn't very good yet.

Beside the porosity which is a important factor, the void shape, void size distribution, defect feature within the material, specific structure fashion of porous bodies, and so on, which are the factors depending on the preparation technology, may all affect the tensile strength of materials to some extent or even greatly. However, all the above factor effects (except the porosity) are just accumulated into the constants presenting the material sort and preparation technology in the present theoretical formulas, and they are quite difficultly expressed by the simple mode of constant multiplication very aptly. Besides, in the present theory, the distance between two node centers is taken as the edge length of the unit octahedron, and the complicated ways of the node transition are not considered. All of these are the important reasons leading to the formula calculation deviation. Of course, the formulas are based on the high porosity, and will cause serious deviation as evaluating for the low porosity. This is the limitation of this evaluation method.

Finally, it's worthy to be pointed out that, the above formulas are all derived on the basis of the isotropic porous materials with high porosity, so their constants should be associated with the tension direction respectively when the materials are anisotropic.

5 CONCLUSIONS

The following simple relations may be used for evaluating the tensile strength of high porosity materials approximately:

$$\sigma = K(1 - \theta)^m \sigma_0 \qquad (01)$$

and

$$\sigma \approx \frac{(1 - \theta)^2}{K_1(1 - \theta)^{1/2} + K_2(1 - \theta)} \cdot \sigma_0 \qquad (02)$$

where σ and σ_0 are the tensile strengths of porous and corresponding compact materials respectively, and θ is the total porosity of porous bodies; K, K_1 and K_2 are all the constants decided by the material sort and preparation technological conditions, and will connect with the direction when materials are anisotropic. In formula (01), m is the plasticity-brittleness index of materials and the firmness index of the nodes, varies from 1 to 1.5, tends to be 1 for materials of high plasticity or porous bodies with the nodes fracturing prior, 1.5 for brittle materials, and 1.25 roughly when materials are the general metals or alloys with moderate plasticity, for example, metal nickel. While formula (02) is available only for the porous bodies with the edges fracturing prior. These two formulas are based on the feature of high porosities, so they can be used only in the high porosity scope, such as the one with the porosity higher than 80%.

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