Relationship between tensile strength and porosity for high porosity metals

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Abstract An analysis model has been established according to the structure feature of high porosity metals, and the mathematical relationship between the tensile strength and porosity for this material has been derived from the model. Moreover, the corresponding theoretical formula has been proved good to reflect the variation law of tensile strength with porosity for high porosity metals by the example experiment on nickel foam.

Keywords: **high porosity metal, tensile strength, porosity.**

The high porosity metals developing rapidly in recent years are produced by some methods different from the traditional powder sintering technology, such as the electrodeposition on organic porous bodies and the metal gas phase deposition on organic porous bodies[1—4], with their porosity reaching over 80%, and mostly reaching 90-odd percent. These materials may be used for battery electrode matrices, catalyst carriers, electrochemical process cathodes such as in electric composition, heat exchangers, silencer materials and other structural and functional materials in many aspects[1—5], so they are put into practice more and more widely. Obviously, the structure and property of this material differ from those of low porosity and compact materials greatly. Tensile strength is an important characteristic for engineering materials, so it is important to find out the quantitative relationship between tensile strength and porosity for high porosity metals. In this paper, a structural model has been developed aiming at the feature of high porosity metals, the quantitative formula between tensile strength and porosity has been derived for these metals, and the example experiment on nickel foam showed that the above-mentioned theoretical formula was in agreement with the test results.

1 The structure model and relationship formula between tensile strength and porosity for high porosity metals

1.1 The structure model of high porosity metals

Isotropic high porosity metals take the three-dimensional reticulated structure with their metal wires linked in the light of diagonal lines of cubes. This structure consists of many octahedron void units continuous and well distributed like body-centered cubic lattices (see fig. 1(a)), which can embody the structure feature. The centrosymmetrical axis of the unit octahedron is in the tensile direction (see the arrow direction in figure 1(a)).

1.2 Relationship formula between tensile strength and porosity

For convenience, the edges of the unit octahedron may be considered as the cylinders, and the internal vacancies of the edges themselves as the 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''. Then the total porosity is $\theta = \theta' + \theta''$, and meanwhile, $\theta' \gg \theta''$. Joints (nodes) of metal wires have "fullness", so fractures of porous metals generally take place at the wire bodies weaker than node. An edge is segregated from the unit octahedron as the force analysis object, and the edge fracture is believed to be caused by the inner maximum normal stress (σ_{max}) achieving the tensile strength value (σ_0) of the corresponding compact material, and the external tensile stress on the integral porous body presents the tensile strength (σ) of this porous material at this time. Based on material mechanics, two extreme situations are considered. One is no revolution at all for the edge, similar to pure brittle fracture, and the other is turning to the same direction as the external load for the edge when fracture occurs. In addition, the edge section is presumed not to change during the first situation.

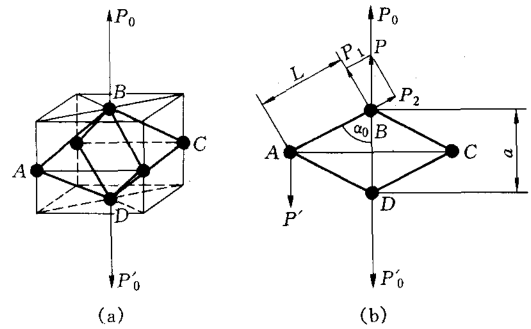

Fig. 1. Schematic diagram for analyzing the tensile strength of high porosity materials. (a) The unit octahedron; (b) force analysis of the edge in the unit octahedron.

Figure 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 the 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 tension from the outside may be aimed at mainly, and the binding force perpendicular to the external load might not be considered temporarily, since this binding force is relatively small when the material has long-strip shapes with the external load in the long direction, and the tensile samples are generally the long strips with external tension in their axis direction.

In fig. 1(b), a is the edge length of the cube containing the unit octahedron, L is the edge length of the unit octahedron, and P is the average load on the single edge top (B), equal to one fourth of the total load on the unit octahedron top, P_0, whose equilibrant is the force on the bottom end (D) of the unit octahedron, P'_0. Besides, P_1 and P_2 are two components of force P parallel and perpendicular to the edge axis on point B of the edge, respectively.

As to the edge AB segregated from the unit octahedron, force P' on the side-point A is given by the adjacent edges, which is the equilibrant of load P on the top B, and transferred to D from A eventually. When the turn (or turn tendency) of the edge AB around the end A is considered, P' may be regarded as the inner force of the porous body system, and has no contribution to the moment of force. By means of the extreme situation of elastic mechanics, namely, the situation between the elasticity and the plasticity, the fracture strength is calculated approximately for two porous materials containing the plastic and the brittle. When the unit octahedron is tensioned along the axis in the first situation, the included angle between the edges and the centrosymmetrical axis tends to decrease. Therefore, for convenience of deduction and operation, 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 (figure 1(b)).

The length, diameter and hollow diameter of the octahedron edge may be acquired by the geometry relation and relationship between volume proportions while considering fig. 1. Then the bending sectional modulus of the edge and the bending moment on the edge AB caused by the force P_1 can be obtained by mathematical calculation. Following that, the maximum normal stress in the edge AB originated from P_1 may be derived. By adding this to the stress in AB generated by P_2, the approximate relation expression between tensile strength and porosity for high porosity materials can be achieved as:

$$\sigma = K(1-\theta)^{1.5}\sigma_0, \tag{1}$$

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 is the constant decided by the material sort and preparation technology conditions, and is connected with the direction when materials are anisotropic.

In the second situation, the fracture stress is solely the normal stress, so the following relation can be acquired directly according to the reduction proportion of the area enduring the load:

$$\sigma = K(1-\theta)\sigma_0. \tag{2}$$

By the expression patterns of the above two formulas, it can be found that the difference between two extreme situations shows the index variation of item $(1-\theta)$. Thus, the index between the above two (i.e. 1 and 1.5) should be possessed by most porous materials, and tend to 1 for the metals with good plasticity such as Cu and Sn, while to 1.5 for the metals with poor plasticity such as Ti, so we roughly take the value $(1+1.5)/2=1.25$ for the metals with moderate plasticity such as Ni and Fe. Thereby, the expression between tensile strength and porosity for high porosity general metals can be achieved as:

$$\sigma = K(1-\theta)^{1.25}\sigma_0. \tag{3}$$

The detailed deduction for the above formulas is left out.

2 Experiment for verification

2.1 Sample preparation

The experimental materials employed were the nickel foams developed by metal nickel electroplating on the polyurethane 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 pyrolysis-sintering of the electroplated sponge. The porous nickel plates with different porosities and with a thickness of 2—3 mm were obtained. According to ref. [6], the samples for the tensile strength test were dumbbell-shaped having a total length of 12 cm and a thickness varying 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.

2.2 Test method

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 matts was 8 cm, and the samples were pulled at a constant rate of 8.2 mm/min. Every four samples were tested for the same porosity, and the mean value of the tensile strength was taken. All tests were done at room temperature.

3 Results and discussion

3.1 Test results and calculation values

Utilizing $\sigma_0 = 317$ MPa provided by ref. [7] as the tensile strength of metal nickel, and substituting the mean test values of the tensile strength corresponding to the samples with different porosities into formula (3) successively, we get the 10 corresponding coefficient values. The relative deviation of coefficient value of sample $6^{\#}$ vs. the mean value was found to exceed that of all the other samples notably during computing the mean values. With the relative theories in error analysis and datum treatment, according to Glabs statistics rule, the doubtful judgment was done for the coefficient value of sample $6^{\#}$ by taking the mean value of all samples as the criterion. The result showed that, although we take confidence degree $\alpha = 1.0\%$, the corresponding datum of this sample can be judged to be doubtable and thus abandoned. Therefore, the mean value was calculated only with the other nine samples, and we got $K \approx 0.33$ at last. Substituting the mean coefficient value (0.33) back into the original formula, we can approximately obtain for this nickel foam:

$$\sigma = 0.33(1 - \theta)^{1.25}\sigma_0. \tag{4}$$

The results of the test and calculation with formula (4), as well as the corresponding deviations, are all listed in table 1. The experiment on the nickel foam made by the method in ref. [6], which is what the nickel carbonyl gas decomposes on the foam structure then sinters, showed that the tensile strength of this nickel foam was higher than that of the nickel foam produced by electrodeposition. The relative experimental data in ref. [6] and the corresponding calculation results with the present formula (3) are given in table 2.

Table 1 Test results and calculation values

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/MPa	6.75	6.45	5.40	4.16	3.23	2.48	2.00	1.28	0.63	0.38	
σ'-Computed/MPa	6.91	6.12	5.73	4.06	3.41	(1.99)	1.97	1.22	0.60	0.40	
abs($\Delta\sigma/\sigma$)/%	2.3	5.2	6.0	2.4	5.6	(19.6)	1.7	4.6	4.0	4.5	4.0
abs($\Delta K/K$)/%	2.3	5.5	5.7	2.5	5.3	(24.2)	1.8	4.8	4.2	4.3	4.0

$\Delta\sigma = \sigma' - \sigma$(MPa), $\Delta K = k - K$, where k is the coefficient value computed alone by formula (3) for each porosity sample, and K the mean value of k for all samples (except $6^{\#}$), namely, $k \approx 0.33$. In addition, the other mean values in table 1 were calculated without the data of sample $6^{\#}$.

Table 2 The tensile strength of the porous nickel in ref. [6] and the application of the present formula

Sample number	1	2	3	4	5	6	7	8	9	10	11	Mean
θ/%	96.538	96.117	96.904	97.343	97.237	98.050	97.827	97.564	97.554	97.847	98.237	
σ-Test/MPa	2.63	2.61	1.34	1.24	1.65	0.97	1.15	1.33	1.45	1.75	1.25	
σ'-Computed/MPa	2.25	2.60	1.96	1.62	1.70	1.10	1.26	1.45	1.46	1.24	0.97	
abs($\Delta\sigma/\sigma$)/%	14.3	0.3	46.2	30.5	3.0	13.4	9.5	9.2	0.7	28.9	22.5	16.2
abs($\Delta K/K$)/%	16.7	0.3	31.6	23.4	2.9	11.8	8.7	8.4	0.7	40.6	28.9	15.8

In table 2, the mean coefficient value calculated by formula (3) is 0.48, from which the calculation formula is gotten as:

$$\sigma \approx 0.48(1 - \theta)^{1.25}\sigma_0. \tag{5}$$

3.2 Limitation of past relations between tensile strength and porosity for porous materials

Generally, the past relations between tensile strength and porosity for porous bodies are not suitable for high porosity. For example, the formula often used in porous materials (mainly in the sintered powder bodies) is as follows[8]:

$$\sigma = \sigma_0 \exp(-b\theta), \tag{6}$$

where b is the constant determined by technology producing the porous bodies.

Through analysis and comparison with lots of data, it was pointed out that formula (6) coincides with the reality only in a limited porosity range. Afterwards, the grain-collection model for porous bodies was put forward for expanding the porosity application, and the common expression for porous materials was derived as:

$$\sigma = \sigma_0(1 - \theta^2)^2 \exp(-b\theta), \tag{7}$$

and this formula was believed to be suitable for all scopes of porosity variation[9].

The other theoretical equation was derived from the stress-concentration conception by Haynes[10] as:

$$\sigma = \sigma_0(1 - \theta)/(1 + b\theta), \tag{8}$$

where b is a constant depending on the theoretical stress-concentration factor of voids.

For the convenience of visual contrast, the data and the corresponding curves of formulas (3) and (6)—(8) are shown in fig.2(a) for the present experiment, and in fig.2(b) for ref.[6]. Among them, the coefficient K of formula (3) takes 0.33 and 0.48 in fig.2(a) and (b) respectively.

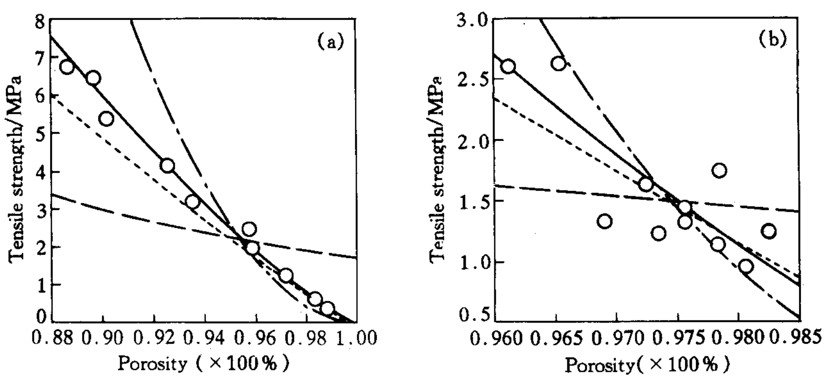

Fig. 2. The relationship between tensile strength and porosity for the nickel foams prepared by electrodeposition (a) and by nickel carbonyl pyrolysis (b). ○, Test data; ——, formula (3); — — —, formula (6); — · — ·, formla (7); - - - -, formula (8).

It can be seen from fig.2(a) and (b) that the test values of tensile strength conform to formula (3) well, but deviate from all of the other formulas greatly, within the experimental porosity range. This shows that formula (3) can express the relationship law between tensile strength and porosity well for porous materials in the high porosity region, but the past relations cannot.

3.3 Distinction between the present theoretical model and the past research ways

In the past, study on the tensile strength of porous materials was mainly based on the thought that voids reduce the valid area enduring load and cause the stress concentration. As for the powder-sintering porous metals, their porosity is not high, and voids exist within the porous body in an isolated manner making the stress distribution not even, whose effect on decreasing the material strength sometimes is far higher than the reduction of area enduring load, and thus promotes the material fracture greatly. Consequently, the past theoretical researches suit the powder sintering materials with low and moderate porosity, and need the specific factors of original powder materials during calculation.

However, the high porosity materials developing rapidly in recent years have many new structure features. Their porosity is often 90-odd percent, and their voids are continuous and well distributed, taking the principal part of the total material space, but not the isolated "impurity" or "defect" any longer. Within them, the metal object presents wires interlinked to constitute the isotropic three-dimensional reticulation. Different from the tensile fracture in the load direction for whole metal body in traditional ideas, the fracture of high porosity materials takes the way of "tear fracture" of inner mass metal wires, the constriction impact being little. Targeting those characteristics of the structure and fracture ways of high porosity materials, a simplified geometric model was utilized; simple and convenient macroscopic mechanics analysis was done; the tensile destruction mode of "'bending moment'→'maximum stress'→'tear fracture'" was established for high porosity materials, and the present theoretical formula was derived at last.

3.4 Practicality and availability of the present theoretical model

Table 1 indicates that the relative deviation of the calculation value of formula (4), which was derived from the present model, from the test value of tensile strength of the present experimental material, is no more than 6%. This deviation may be deemed not to be big, and the mean absolute value of this deviation is only around 4%, so we may say, the theoretical values accord with the test ones well. The dispersion degree of the single sample test value for parallel contrast is relatively narrow for each porosity sample, so the present theoretical model may be regarded to embody the structure feature of high porosity materials well, and can reflect the relationship law between tensile strength and porosity for high porosity materials accurately. Besides, the constant in formula (3) fluctuates a little, which is no more than 5.7% except for sample $6^{\#}$, which shows that the coefficient is a definite quantity for the same material produced by the same technology, and further testifies the reliability of the theoretical formula.

When formula (3) was applied to the nickel foam made by nickel carbonyl pyrolysis in ref. [6], the large deviation between the theoretical and test values arose, and the constant item fluctuated violently. That is because the experimental data themselves scatter widely and have the unreasonableness that the tensile strength of the material with higher porosity is strangely higher than that of the same material with lower porosity, which demonstrate that the test value has a great error and that the accuracy is not high enough. In such a case, the relative deviation of calculation value from test value lies between −28.9% and +46.2%, and that of constant, between −31.6% and +40.6%. The theoretical formula is still thought to have got a good application effect. Both the relative calculation results and fig.2(b) display that the relative deviations of the corresponding calculation value from the test one for formulas (6)—(8) are much larger than that for formula (3). In addition, the mean constant $K = 0.48$ in formula (5) is bigger than $K = 0.33$ in formula (4). That is, the tensile strength of nickel foam produced by nickel carbonyl pyrolysis is higher than that of nickel foam with the same porosity produced by electrodeposition, uniform with the experimental result in reference [6].

It is known from the above that the present theoretical model and its relation formula can suit high porosity materials well.

3.5 Others

The conceptions of "octahedron" and "cantilever" were introduced in this paper when the relationship between tensile strength and porosity was deduced for high porosity bodies, which simplified the process greatly. Examined by actual application, the calculation precision of the present formula may be deemed to be quite high, as an approximate evaluation, and the deviation between the calculation and the test can also be acceptable. Of course, if the limited element analysis in structural mechanics is used, and the force is computed while considering the porous body as the netlike frame, it will be geared to reality better, and the calculation precision of the obtained formula may possibly be improved further. However, the deduction will become more complicated correspondingly, so the study in this aspect need be deepened afterwards.

4 Conclusion

The octahedron model based on the structure feature of high porosity materials can reflect some mechanics properties of these materials well, and the relation formula between tensile strength and porosity derived from this model for high porosity bodies made of brittle materials can be expressed as follows:

$$\sigma = K(1-\theta)^{1.5}\sigma_0,$$

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 is the constant depending on the material sort and preparation technology conditions, and will be connected with the direction when materials are anisotropic, while that for high porosity bodies made of pliable materials with excellent ductility can be written as

$$\sigma = K(1-\theta)\sigma_0.$$

As for the metals with moderate plasticity, for instance metal nickel, the corresponding relation can be given roughly as

$$\sigma = K(1-\theta)^{1.25}\sigma_0.$$

The experiment proved that the tensile strength can be calculated by the present formula well for the nickel foam prepared by both electrodeposition and nickel carbonyl pyrolysis.

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