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ScienceDirect

Scripta Materialia 103 (2015) 26–29

Scripta MATERIALIA

www.elsevier.com/locate/scriptamat

A phenomenological approach to yield strength in nanoporous metal foams

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Received 29 January 2015; revised 25 February 2015; accepted 25 February 2015
Available online 7 March 2015

This work discusses a phenomenological model enabling the estimation of yield strength for nanoporous metal foams. A regular lattice of relatively massive cubic junctions joining six thick ligaments with square cross section is used to describe the foam structure. The characteristic lengths of ligaments and nodes are estimated from experimental data. The yield strength of the structure is related to the plastic moment of individual ligaments. Model predictions are in fairly good agreement with experimental findings.

Keywords: Porous material; Nanostructured material; Metals and alloys; Yield phenomena; Modeling

Nanoporous (NP) metal foams are the focus of one of the most rapidly growing areas of investigation in materials science [1–8]. The considerable interest they attract can be ascribed to the set of unique physical and chemical properties they exhibit. These not only show great promise for advanced technological application, but also raise fundamental issues challenging the current understanding of the relationship between structure and properties [1–8].

Consisting of a disordered porous network of nanometer-sized ligaments connecting relatively massive nodes, the structure of NP metals is characterized by high degree of randomness, bi-continuous interpercolating topology, reduced dimensionality and high surface area-to-volume ratio [9–11]. Whereas these features definitely affect electronic, optical and chemical properties [4,5,12,13], size effects alone can hardly explain the overall mechanical behavior of NP metal foams [13–15]. First, NP metals obtained by spontaneous or driven dealloying rarely exhibit ligaments with characteristic length below 10 nm, which is the typical size range for smooth size effects to emerge [16]. Second, experimental and theoretical findings suggest that mechanical properties do not depend on length scales only, but on the combination of characteristic lengths with local and global morphology [14,17–20]. This makes the link between structure and mechanical properties particularly hard to unfold.

The attempts of rationalizing the mechanical properties of NP metals based on their intimate connection with porosity and connectivity mostly rely upon the phenomenological model developed by Gibson and Ashby [21,22]. Originally proposed to account for the mechanical behavior of open-cell macroporous foams, the model relates the deformation of the porous solid to the bending behavior of individual ligaments [21,22]. Starting from a geometric lattice of thin beams, Young's modulus and yield strength are predicted to vary with the relative density ϕ as ϕ^2 and $\phi^{3/2}$ respectively [21,22]. Predictions agree with experimental measurements for macroporous foams with ϕ lower than 0.1 [21,22], whereas less satisfactory results are obtained for NP metal foams [3,8–10,17–20].

This is due to the differences between macroporous foams and NP metals, which make the Gibson and Ashby's model generally unsuited for the latter class of materials. NP metals indeed exhibit ϕ values significantly larger than 0.1, typically between 0.3 and 0.6 [17]. Ligaments have thickness comparable with length, and their flexural response is correspondingly depressed [17,23]. Moreover, a significant mass agglomeration at ligament junctions is observed, which reduces the effective ligament length susceptible of bending [17,23]. Mass agglomeration and thick ligaments contribute to the enhancement of Young's modulus and yield strength [17], both larger than the Gibson and Ashby's model predictions. Such quantities are also affected by the degree of structural disorder, and there is no doubt that the realistic description of NP metal foams requires dealing with a random arrangement of ligaments and pores [11,24]. Unfortunately, this is also one of the most challenging issues in the field.

That being said, it has been already shown that an improved description of the NP metal elastic behavior can be obtained without additional assumptions by considering a geometric unit cell including massive nodes and thick ligaments [25]. In particular, Young's modulus values in the proper experimental range are predicted for NP Au, by far the most investigated NP metal [17,23,25]. Following the same approach, the present study demonstrates that

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http://dx.doi.org/10.1016/j.scriptamat.2015.02.029
1359-6462/

comparable improvement is obtained in the prediction of yield strength.

This work relies upon the accurate analysis of SEM micrographs aimed at estimating thickness and length of individual ligaments. Such analysis does not account for the three-dimensional character of the NP structure. As discussed in detail elsewhere [23], this necessarily introduces systematic errors and uncertainties that keep quite small, though. These do not influence the phenomenological model proposed to predict yield strength, and can be readily eliminated once an improved description of the NP metal structure becomes available.

A typical SEM micrograph illustrating the NP Au structure is shown in Figure 1a. It can be seen that ligaments and pores of different size and shape distribute irregularly across the bi-continuous connected structure. The detailed inspection of restricted areas allows estimating thickness, t, and length, h, of ligaments as well as the extension of nodes, $t+2d$, to a satisfactory accuracy degree. The obtained normalized distributions p for t, h, and $t+2d$ are shown in Figure 1b–d respectively. In agreement with literature [26], distributions are not Gaussian. Rather, they exhibit a Poissonian character. The t, h, and $t+2d$ estimates indicate that ligaments are thick and mass significantly agglomerates at nodes, reducing the portion of ligaments effectively involved in bending.

The set of t, h, and $t+2d$ values can be used to predict the yield strength of NP Au foams using a phenomenological mathematical model. The model describes the NP Au structure as an ordered arrangement of the structural unit schematically shown in Figure 2a and b, consisting of a cubic node with sides $t+2d$ long connecting six semi-ligaments of length $h/2$ and square cross section of area t^2. Whereas t is the ligament thickness, d roughly measures the mass aggregated at nodes. The unit is enclosed in a cubic unit cell of side $l=t+2d+h$. It is here worth noting that the use of such unit necessarily prevents considering the effects of structural anisotropy and morphological details that have been shown to affect the mechanical behavior of macroporous foams [27,28].

For a bulk metal, the unit cell volume l^3 is fully occupied by the mass $\rho\, l^3$, being ρ the bulk density. On the contrary, the NP metal occupies only the fraction of cell volume corresponding to the mass $[(t+2d)^3+3t^2h]\rho$, thus exhibiting a density to $\rho_{NP}=[(t+2d)^3+3t^2h]\rho/l^3$. Therefore, the relative density is equal to

$$\phi=\frac{\rho_{NP}}{\rho}=\left(\frac{t}{l}+2\frac{d}{l}\right)^3+3\left(\frac{t}{l}\right)^2\frac{h}{l}. \quad (1)$$

When $t\ll l$ and $d=0$, Eq. (1) simplifies to $\phi=(t/l)^3+3(t/l)^2$, in agreement with the Gibson and Ashby's model prediction obtained including the density contribution of cell corners [21,22].

It has been recently shown that the simple Euler–Bernoulli theory is unable to satisfactorily describe the bending behavior of thick ligaments in NP metals [25,29]. To such aim, transverse shear deformation effects must be taken into account, which can be done using the hyperbolic shear deformation theory [30–34]. For a thick simply supported uniform isotropic beam of length h with a central concentrated load P as the one depicted in Figure 2b, such approach predicts a maximum transverse deflection at the ligament middle point equal to [25]

$$w=\frac{Ph^3}{48EI}\left[1+2.4(1+\nu)\frac{t^2}{h^2}\right], \quad (2)$$

where E and ν are Young's modulus and Poisson ratio of the material respectively, and $I=t^4/12$ is the moment of the beam cross-sectional area. Based on Eq. (2), the load P can be expressed as

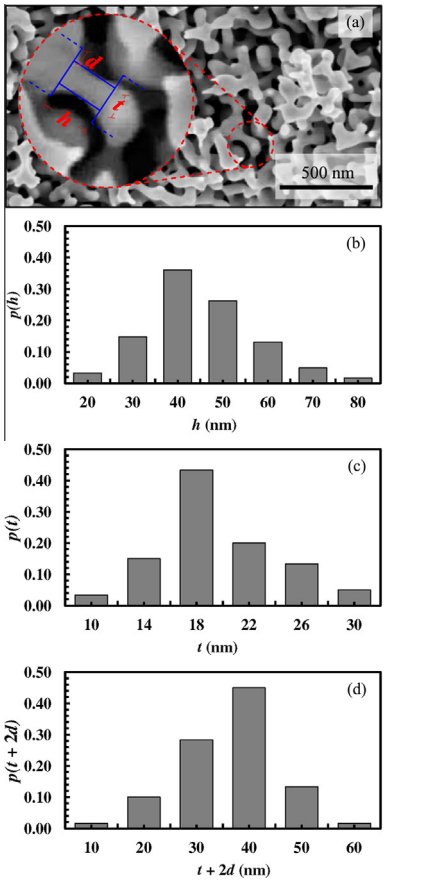

Figure 1. (a) SEM micrograph of a NP Au foam, re-elaborated from [2]. Characteristic lengths of ligaments and nodes are shown in the inset. The statistical distributions p of ligament length h, (b), ligament thickness t, (c), and extension of nodes $t+2d$, (d).

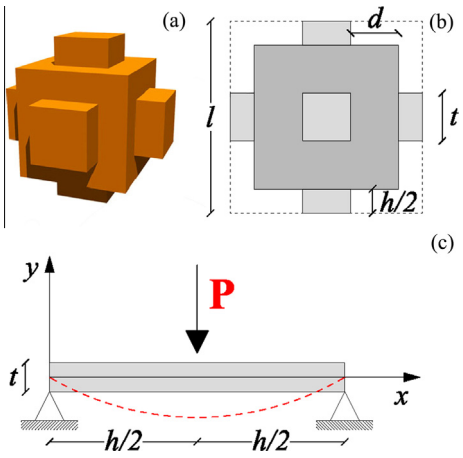

Figure 2. (a) The cubic unit cell of the NP metal structure. (b) Characteristic lengths of the cell. (c) Schematic depiction of the bending behavior of a free supported beam.