Effects of Cell Geometry on the Compressive Properties of Nickel Foams*

Yasuo Yamada¹, Cui'e Wen¹, Koji Shimojima¹, Mamoru Mabuchi¹, Mamoru Nakamura¹,
Tadashi Asahina¹, Tatsuhiko Aizawa² and Kenji Higashi³

¹Materials Processing Department, National Industrial Research Institute of Nagoya,
Hirate-cho, Kita-ku, Nagoya 462-8510, Japan

²Research Center for Advanced Science and Technology, The University of Tokyo,
Komaba, Meguro-ku, Tokyo 153-8904, Japan

³College of Engineering, Department of Metallurgy and Materials Science, Osaka Prefecture University,
Gakuen-cho, Sakai, Osaka 599-8531, Japan

The compressive properties of three kinds of nickel foams with different cell sizes were investigated. The stress—strain curves showed a plateau region. The cell size had a minor influence on the plateau stress when the stress was normalized with the relative density and the yield stress of the cell edge material. Compressive tests were also performed under loading conditions along different axes in the foam with elliptical cells. As a result, the foam was stronger for loading in the major axis direction, compared with in the minor axis direction. Therefore, it has been demonstrated that the cell aspect ratio produces a certain influence on the plateau stress of foam, whereas the cell size appears to have a negligible effect.

(Received April 24, 2000; Accepted July 3, 2000)

Keywords: metal foam, mechanical property, cell size, cell aspect ratio

1. Introduction

Metallic foams exhibit unique combinations of excellent mechanical, thermal, electrical and acoustic properties that provide opportunities for a wide range of applications.^{1–3)} Among lightweight metallic materials, nickel foams are highly interested since they can be used as electrodes of nickel cadmium and nickel metal hydride batteries for electric vehicles, catalysts, diesel particulate filters, silencers and so on due to their high thermal conductivity, low density, high damping capacity and excellent potential for impact absorbing energy.^{4–6)}

Normally, the compressive stress—strain curve for a metallic foam shows an elastic region at a low stress followed by a plateau region, truncated by a densification region in which the stress steeply rises. The properties of metallic foams can be made to alter significantly, depending on cell-edge (wall) materials, volume fractions of solids, geometry of cell structures and microstructures of cell edges (walls).^{7–10)} Gibson and Ashby¹¹⁾ showed that the mechanical properties of metallic foams are largely determined by their relative densities. According to the Gibson-Ashby model,¹¹⁾ the most important structural characteristic of a foam is its relative density, ρ/ρ_s (the density of the foam, ρ , divided by that of the solid material, ρ_s). The relationship between the relative stress and the relative density is given by¹¹⁾

$$\sigma_{pl}/\sigma_{ys} = C(\rho/\rho_s)^{3/2} \quad (1)$$

where σ_{pl} is the plateau stress of the foam, that is, the flow stress in a plateau region, σ_{ys} is the yield stress of the cell edge material and C is a constant. This equation indicates that the plateau stress of the foam is proportional to the yield

stress of the cell edge material and the three-seconds power of the relative density. However, compressive tests of various metallic foams have demonstrated that the mechanical properties are also affected by the geometry of cells¹²⁾ and the microstructures of cell edges (walls).¹³⁾ Furthermore, a study on aluminum foams¹⁴⁾ revealed that when the sample possesses an equal apparent density, the ultimate compressive strength increases with decreasing pore size. Gibson and Ashby¹¹⁾ theoretically analyzed the effect of cell aspect ratio on the plateau stress. However, there are few experimental data¹⁵⁾ to understand the effect of cell aspect ratio on the plateau stress. The purpose of the present paper is to experimentally investigate the influences of the cell geometry, that is, the cell size and the cell aspect ratio on the mechanical properties of nickel foams with an open-cellular structure.

2. Experimental Procedures

The materials used in the present experiments were commercially available open-cell nickel foams (with a trade name of Celmet). Three kinds of nickel foams were selected as foams A, B, and C. The cell size and cell aspect ratio were measured based on micrographic observations. Areas surrounded by cell edges were converted to areas of an ellipse by a commercial software (Image-Pro Plus). The cell size was estimated as an average value of $(4A/\pi)^{0.5}$, where A is the area of an ellipse. To estimate the cell aspect ratio, the directions parallel to and perpendicular to the loading direction were taken into consideration. The method of measuring the cell aspect ratio is schematically shown in Fig. 1. Also, the hardness of cell edge materials was examined by micro-Vickers hardness tester. The testing load of hardness was 25 grams. The characteristics of the nickel foam samples are listed in Table 1.

Compressive tests were carried out at room temperature with an initial strain rate of 10^{-3} s^{-1} . Three specimens with a

*This Paper was Presented at the Spring Meeting of the Japan Institute of Metals, held in Yokohama, on March 29, 2000.

Fig. 1 A schematic illustration of a measurement method of the cell aspect ratio.

Table 1 Nickel foam sample characteristics.

Specimen	Cell Size* (mm)	Hardness (Hv)	Density (kg/m ³)
Foam A	3.52	135	417.2
Foam B	2.14	190	419.7
Foam C	1.49	190	419.3

*An average of $(4A/\pi)^{0.5}$, where A is the area of an elliptical cell.

size of 20 mm × 20 mm × 10 mm (height × length × width) were tested for each kind of foam in the major axis direction of elliptical cells. In addition, compressive tests were carried out in the minor axis direction of elliptical cells for foam B.

3. Results and Discussion

Optical micrographs of the three kinds of nickel foams are shown in Fig. 2. The cells were slightly elliptical. The aspect ratio of elliptical cells was measured by using Image Pro Plus. The average cell aspect ratios were 1.21, 1.27 and 1.32 in the foams A, B and C, respectively.

Figure 3 shows the nominal stress—nominal strain curves of the three kinds of nickel foams, where the loading direction is parallel to the major axis of elliptical cells. The stress—strain curve can be divided into three stages, that is, an elastic deformation stage at the beginning of deformation, a plateau

stage with a nearly constant flow stress to a large strain of approximately 60%, and a densification stage where the flow stress rapidly increases. Although the cell sizes in the foams A, B and C are different with each other, deformation occurs in a similar manner with three stages in these foams.

Equation (1) indicates that the plateau stress is proportional to the yield stress of the cell edge material and the 3/2 power of the relative density. Therefore, the yield stress of the cell edge material and 3/2 power of the relative density must be taken into consideration to compare the compressive properties of the three kinds of foams. The normalized stress—nominal strain curves are shown in Fig. 4, where the normalized stress is the nominal stress divided by the product of the yield stress of the cell edge material and the 3/2 power of the relative density. In the present study, the yield stress of the cell edge material is taken to be the 1/3 hardness of the cell edge material.¹⁶⁾ It should be noted that the normalized stresses of the three kinds of foams were roughly the same. Furthermore, there was little difference in the strain to a densification region in these foams. Therefore, it is suggested that the cell size has a minor influence on the compressive properties of foams.

Figure 5 shows the influence of the cell aspect ratio on the compressive properties in foam B, where loading directions were parallel to the major axis in the curves “b”, or parallel to the minor axis in the curves “a”. The flow stress is normalized by the same way as mentioned above. The normalized stress in the direction parallel to the major axis is higher than that parallel to the minor axis. Therefore, it is demonstrated that the cell aspect ratio strongly affects the compressive properties of foams.

According to the Gibson and Ashby's model,¹¹⁾ the influence of the cell aspect ratio on the plateau stress can be given by

$$(\sigma_{pl}^*)_b/(\sigma_{pl}^*)_a = 2R/(1 + 1/R) \quad (2)$$

where R is the cell aspect ratio, $(\sigma_{pl}^*)_b$ is the plateau stress for loading in the major axis direction of cells and $(\sigma_{pl}^*)_a$ is the plateau stress for loading in the minor axis direction of cells. A quantitative comparison of the experimental results with the model may be done by substituting a measured value for R . The cell aspect ratio of the foam B was 1.27. Substituting the value of 1.27 for R leads to the plateau stress ratio

$$(\sigma_{pl}^*)_b/(\sigma_{pl}^*)_a = 1.42 \quad (3)$$

Fig. 2 Micrographs of the open-cellular nickel foams. (a) Foam A, (b) Foam B, (c) Foam C.

Fig. 3 The nominal stress—nominal strain curves of the open-cellular nickel foams.

Fig. 4 The normalized stress—nominal strain curves of the open-cellular nickel foams, where the normalized stress is the nominal stress divided by the product of the yield stress of the solid and the 3/2 power of the relative density.

Fig. 5 The normalized stress—nominal strain curves of foam B, where the normalized stress is the nominal stress divided by the product of the yield stress of the solid and the 3/2 power of the relative density. (The loading direction *a* is parallel to the minor axis of elliptical cells; The loading direction *b* is parallel to the major axis of elliptical cells.)

From the experimental results, averaged values of the normalized stress at $\varepsilon = 30\%$ were 0.30 for loading in the major axis direction and 0.23 for loading in the minor axis direction, respectively. Therefore, the ratio of plateau stress in the experimental results ($=1.34$) approximately agrees with the theoretical value calculated by eq. (3) ($=1.42$).

4. Conclusions

The influences of the cell geometry on mechanical properties of nickel foams under compressive loading have been studied. The results are summarized as follows:

- (1) The cell size had a minor influence on the compressive properties of the foams investigated in the present study.
- (2) The aspect ratio of elliptical cells had an important influence on the mechanical response. The experimental results were consistent with the Gibson-Ashby model.
- (3) Therefore, it has been demonstrated that the cell aspect ratio produces a certain influence on the plateau stress of foam, whereas the cell size appears to have a negligible effect.

Acknowledgment

The authors gratefully acknowledge the financial support of the Ministry of Education, Science, Culture and Sports, Japan as the Priority Area "Platform Science and Technology for Advanced Magnesium Alloys".

REFERENCES

- 1) J. Banhart and J. Baumeister: *J. Mater. Sci.*, **33** (1998), 1431–1440.
- 2) S. K. Maiti, L. J. Gibson and M. F. Ashby: *Acta Mater.*, **32** (1984), 1963–1975.
- 3) M. Otsuka, N. Houjo, A. Kojima, M. Itoh and E. Ishii: *Proc. Int. Sym., Light Mater. for Trans. Sys.*, ed. N. J. Kim, Cent. for Adv. Aerospace Mater., (1993), p. 435–444.
- 4) Y. Sugimura, J. Meyer, M. Y. He, H. Bart-smith, J. Grenstedt and A. G. Evans: *Acta Mater.*, **45** (1997), 5245–5259.
- 5) A. E. Simone and L. J. Gibson: *Acta Mater.*, **46** (1998), 2139–2150.
- 6) M. Honda: *Materia Japan*, **38** (1999), 470–474.
- 7) Y. Yamada, K. Shimojima, Y. Sakaguchi, M. Mabuchi, M. Nakamura, T. Asahina, T. Mukai, H. Kanahashi and K. Higashi: *Mater. Sci. Eng.*, **A280** (2000), 225–228.
- 8) Y. Yamada, K. Shimojima, Y. Sakaguchi, M. Mabuchi, M. Nakamura, T. Asahina, T. Mukai, H. Kanahashi and K. Higashi: *Mater. Sci. Eng.*, **A272** (1999), 455–458.
- 9) T. G. Nieh, J. H. Kinney, J. Wadsworth and A. J. C. Ladd: *Scripta Mater.*, **38** (1998), 1487–1494.
- 10) J. L. Grenstedt and K. Tanaka: *Scripta Mater.*, **40** (1999), 71–77.
- 11) L. J. Gibson and M. F. Ashby: *Cellular Solids, Structure and Properties*, Pergamon Press, Oxford, (1988), p. 1–510.
- 12) H. Bart-smith, A. F. Bastawros, D. R. Mumm, A. G. Evans, D. J. Syceck and H. N. G. Wadley: *Acta Mater.*, **46** (1998), 3583–3592.
- 13) P. H. Thornton and C. L. Magee: *Metall. Trans.*, **6A** (1975), 1253–1263.
- 14) F. Simancik, J. Kovacic and N. Sediakova: *Proc. of the 1998 Powder Metall. World Cong. & Exhibit.*, European Powder Metall. Association, UK, **5** (1998), p. 245–250.
- 15) T. G. Nieh, K. Higashi and J. Wadsworth: *Mater. Sci. Eng.*, **A283** (2000), 105–110.
- 16) E. Andrews, W. Sanders and L. J. Gibson: *Mater. Sci. Eng.*, **A270** (1999), 113–124.