EVALUATION ON ELASTIC MODULUS OF CLOSED-CELL ALUMINUM ALLOY FOAM

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BACKGROUND

In recent years, metallic foams have grown in use in a variety of engineering applications due to their lightweight structure and unique combination of physical, mechanical, thermal, electrical and acoustic properties. For example, it has become a potential material for vibration suppression components in various engineering applications requiring lightweight structure [1]. Designing for such applications will require more detailed knowledge of their mechanical properties and behavior. The flexural modulus, one of the most important properties in mechanical design for predicting vibration behaviour, has not yet been measured accurately. The work presented in this paper will focus on evaluating the elastic modulus of aluminum alloy foam by conducting experimental investigations.

MATERIALS AND METHODS

Foam Materials

Three types of closed-cell aluminum alloy foam (Alporas, Shinko Wire) were used in the present study; foam density, average cell diameter as measured based on ASTM E112, and cell-wall thickness are given in Table 1. From Foam A to C, the density is increasing whereas the cell diameter and cell-wall thickness no increasing or decreasing tendency could be found. The materials showed a high degree of isotropy with no significant spatial or rotational variation (Figure 1) as also reported by Simone and Gibson [2]. Inside of the material consists of closed-cell structure while the surface consists of open-cell structure.

<table>
<thead>
<tr>
<th>Foam</th>
<th>Density, kg/m³</th>
<th>Cell diameter, mm</th>
<th>Cell-wall thickness, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam A</td>
<td>168</td>
<td>3.98 ± 0.09</td>
<td>0.05 – 0.10</td>
</tr>
<tr>
<td>Foam B</td>
<td>263</td>
<td>2.82 ± 0.10</td>
<td>0.01 – 0.20</td>
</tr>
<tr>
<td>Foam C</td>
<td>351</td>
<td>2.90 ± 0.07</td>
<td>0.05 – 0.70</td>
</tr>
</tbody>
</table>

Compression Test

Compression tests were conducted using a displacement-controlled universal testing machine (Autograph AGS-H, Shimadzu). The specimens were chosen to have a square cross section of 25 mm x 25 mm and height of 50 mm to avoid the size effect as explained by Andrews et al. [3]. The top and bottom surfaces were polished to give a uniform contact area and lubricated to reduce friction on the platens. All tests were carried out at room temperature at a displacement rate of 1 mm/min; loading and unloading was performed several times and the compressive
Young’s modulus, $E$, was determined by evaluating $\Delta\sigma/\Delta\varepsilon$, the gradient of nominal stress with respect to true-strain $\varepsilon = \ln(1+\varepsilon)$.

![Cross section photographs of the materials.](image)

(a) Foam A  (b) Foam B  (c) Foam C

Figure 1. Cross section photographs of the materials.

**Tension Test**

Tension tests were carried out using the same testing machine, temperature and displacement rate. The tensile Young’s modulus was also derived from $\Delta\sigma/\Delta\varepsilon$ for initial and reloading curves. It was found that the grips of the universal testing machine can cause large deformation near the ends of the specimen, affecting measurements of the stress-strain relation; to minimize this effect, length was maximized as suggested by Hwang et al. [4]. Specimens of Foam C with 25 mm $\times$ 20 mm cross section were prepared in five initial gage lengths (35, 60, 90, 110 and 130 mm). The specimen was gripped 30 to 40 mm from both ends.

**Flexural Vibration Test**

Flexural moduli were determined by measuring the natural frequency of vibration of free-hanging specimens in response to impact (Figure 2). Impact was made using an impact hammer (086B03, Piezotronics) with a steel-tipped head; the resulting vibrations were measured using an accelerometer (352C23, Piezotronics) attached to the specimen surface using adhesive glue (Alonalfa, JIS S 6040). Signals from impact hammer and accelerometer were acquired by digital oscilloscope (DL716, Yokogawa) through a signal conditioner (480C02, Piezotronics). Preliminary tests confirmed that measured natural frequencies were independent of the positions of impact and accelerometer detection.

The measured natural frequencies were used to calculate the flexural modulus, $E_f$, based on Bernoulli-Euler beam theory [5] using equation (1),

$$
E_f = \left( \frac{2\pi f_n L^2}{\lambda_n^2} \right)^2 \frac{\rho A}{I}
$$

(1)

where $f_n$ is the flexural vibration natural frequency, $L$ is the specimen length, $I$ is the second moment of area, $\rho$ is the density, $A$ is the cross section area, and $\lambda_n$ is the Eigen value constant related to the boundary conditions. Given free-free beam conditions, values of $\lambda_n$ for the first, second, and third flexural vibration modes are 4.730, 7.853, and 10.996, respectively.

The specimens were prepared by cutting the foam blocks with various dimensions. Foam A and C were cut with the same cross section of 30 mm $\times$ 20 mm at lengths of 300 and 200 mm while Foam B was cut with cross section 20 mm $\times$ 10 mm at lengths of 100, 150, 200, 250 and 300 mm.
RESULTS AND DISCUSSIONS

The elastic moduli measured by compression, tension, and flexural vibration test are summarized in Table 2. A significant discrepancy is found between values of $E_f$ and corresponding values of $E$; depending on the foam density, $E_f$ is found to be 3 - 4.5 times greater than $E$.

Table 2. Elastic moduli obtained from the tests

<table>
<thead>
<tr>
<th>Foam</th>
<th>Density, kg/m$^3$</th>
<th>$E_f$, MPa</th>
<th>Tensile $E$, MPa</th>
<th>Compressive $E$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>168</td>
<td>607 ± 76</td>
<td>–</td>
<td>205 ± 13</td>
</tr>
<tr>
<td>B</td>
<td>263</td>
<td>1121 ± 80</td>
<td>–</td>
<td>289 ± 7</td>
</tr>
<tr>
<td>C</td>
<td>351</td>
<td>1641 ± 201</td>
<td>309</td>
<td>369 ± 25</td>
</tr>
</tbody>
</table>

“-“ denotes no test

Gibson and Ashby [6] derive an equation for the effective Young’s modulus of a closed-cell foam subject to uniaxial loading. The two principal terms of the equation, with coefficients $C_1$ and $C_2$, denote the contributions of cell-edge bending and cell-face stretching, respectively:

$$\frac{E}{E_s} = C_1 \left( \frac{\rho}{\rho_s} \right)^2 + C_2 \frac{\rho}{\rho_s}$$  \hspace{1cm} (2)

Each term is a function of $\frac{\rho}{\rho_s}$, the foam density relative to that of its parent material. Ashby et al. [1] proposed a fixed ratio of 5:3 between $C_1$ and $C_2$. Fitting equation (2) to compression test results using this ratio gives good agreement, resulting in the form:

$$\frac{E}{E_s} = 0.0615 \left( \frac{\rho}{\rho_s} \right)^2 + 0.0369 \frac{\rho}{\rho_s}$$  \hspace{1cm} (3)

However, the ratio was found not to achieve good agreement for normalized values of $E_f$. Curve fitting shows optimum agreement using a different ratio of roughly 5:1 as given in equation (4).

$$\frac{E_f}{E_s} = 0.5537 \left( \frac{\rho}{\rho_s} \right)^2 + 0.1111 \frac{\rho}{\rho_s}$$  \hspace{1cm} (4)
The difference in ratios implies that the effect of cell-edge bending is more prominent in flexural vibration. This indicates that the mechanism of cell deformation in flexural vibration differs from that under uniaxial loading. Figure 3 illustrates schematically the cell deformation mechanism. The cell is supposed to consist of four cell-edges [6]. When the specimen is subjected to uniaxial loading, two of four cell-edges undergo bending deformation (Figure 3(a)). However, in flexural vibration, the resultant deformation places all four cell-edges in bending (Figure 3(b)); this additional bending effect results in higher stiffness under flexural vibration conditions.

CONCLUSIONS

The elastic moduli of closed-cell aluminum alloy foams under compressive and tensile loading and flexural vibration was evaluated experimentally. The results confirmed that the flexural moduli of all foams were significantly greater than the corresponding compressive/tensile Young’s moduli. Our analysis suggests this to be due to the difference in cell deformation mechanisms between uniaxial loading and flexural vibration conditions.

REFERENCES

5. S. P. Timoshenko, D. H. Yang, and U. Weaver, Engineering Vibrations, Mashinostroenie, Moscow, 1985