Damping properties of open cell microcellular pure Al foams

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Damping behaviours of the open cell microcellular pure Al foams fabricated by sintering and dissolution process with the relative density of 0·31–0·42 and the pore size of 112–325 μm were investigated. The damping characterisation was conducted on a multifunction internal friction apparatus. The internal friction (IF) was measured at frequencies of 1·0, 3·0 and 6·0 Hz over the temperature range of 298–725 K. The measured IF shows that the open cell pure Al foam has a damping capacity that is enhanced in comparison with pure Al. At a lower temperature (~400 K), the IF of the open cell pure Al foams increases with decreasing relative density, with decreasing pore size and with increasing frequency. The IF peak was found at the temperature range of 433–593 K in the IF curves. It is clear that the IF peak is relaxational type and the activation energy associated with the IF peak is about 1·60 ± 0·02 eV. Defect effects can be used to interpret the damping mechanisms.

Keywords: Al foam, Damping properties, Internal friction, Sintering

Introduction

Damping capacity is a measure of a material’s ability to dissipate strain energy during vibration under cyclic loading or wave propagation.¹ When utilised effectively in a structural application, this property allows undesirable noise and mechanical vibration to be passively attenuated and removed to the surroundings as heat. Recently, metal foams have attracted extensive attention owing to their excellent functional properties. One example is Al foam.² Al foam possesses a unique combination of properties, such as impact energy absorption capacity, air and water permeability and favourable sound absorption properties, and is expected to use not only as a building material but also as a new functional material. Al foam materials with a cellular structure are increasingly used in engineering applications which require an understanding of their damping behaviour.³⁻⁶ The present work has revealed that the damping capacity of Al foams fabricated by infiltration or by adding a foaming agent to the molten metal, increases as the relative density decreases and, generally, at a rate of several times higher than that of the parent materials.³⁻⁹ However, to our knowledge, there is little research concerning the damping behaviours of the Al foams fabricated by powder metallurgy, especially the Al foams with an average pore size of less than half of a millimetre, and the authors have, as yet, little understanding about damping features and structure dependence of this kind of Al foams. Hence, the present investigation studies the damping properties of the open cell microcellular pure Al foams produced by sintering and dissolution process (SDP)¹⁰ over a wide range of temperatures, frequencies and strain amplitudes.

Experimental

The SDP was utilised in preparing the Al foam specimens, which was developed by Zhao et al.¹⁰ This processing technology includes blending the Al powder and the NaCl particles with a given diameter, compacting the mixture and sintering it followed by soaking it in water to leach out the NaCl particles. Such materials were used in the present study as commercially pure Al powder with a mean diameter of 30 μm as the matrix and NaCl particles with a mean diameter ranged from 112 to 32 μm as the spaceholder. The Al particles are rounded while the NaCl particles have an irregular polygonal shape. The volume fraction of the Al powder was varied from 0·40 to 0·30. In order to guarantee the uniform distribution of the Al₂O₃ particulates in the matrix, it was thoroughly mixed with the aluminium powder before the addition of the salt particulates. The mixed powders were uniaxially compacted at 250 MPa in a stainless steel rectangular mould, and then sintered at 660 °C for 20 h in a resistance furnace with ambient temperature of ~20 °C. After the sintering was finished, the compact was pressed out of the rectangular mould and put into water to allow the NaCl particles dissolved. The morphology of the fabricated microcellular Al foam is shown in the Fig. 1. The pore structure of the foams was characterised by a Sirion 200 FEG field emission scanning electron

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microscope (FESEM). Figure 2 shows the pore morphologies of the open cell pure Al foams with different pore sizes. The pores basically inherited the shape of the NaCl particles and connected with curved channels, characterised with an open structure. The damping specimens, which were cut by using an electric sparking machine, are rectangular bars with the dimensions of $3.0 \times 2.0 \times 65.0$ mm. The morphologies of the unused and used damping specimens are shown in the Fig. 3.

The specimen density is determined from its weight and physical dimensions. From this density, the foam relative density can then be obtained, i.e.

$$\rho_{Rd} = \frac{\rho}{\rho_s} \quad (1)$$

where $\rho_{Rd}$ denotes the foam relative density, $\rho$ is the density of the open pore Al foam, and $\rho_s$ is the density of the bulk Al.

In the present study, the measure of damping capacity utilised is the inverse quality factor $Q^{-1}$. The damping behaviour is characterised by internal friction (IF) and measured by a multifunction internal friction apparatus (MFIFA) through forced vibration under a continuous changing temperature cycle. This apparatus was developed in 1987 by the Institute of Solid State Physics, Chinese Academy of Sciences. The schematic diagram of MFIFA is referred to Ref. 11. This apparatus consists, basically, of an inverted torsion pendulum, a temperature programmer and a photoelectron transformer. An IBM PC 486 computer and 8087 processor control all measurements, and data can be processed in real time. The IF expressed by $Q^{-1}$ can be automatically displayed on the screen of the computer. The calculations of the inverse quality factor by the MFIFA are based on the following forced vibration equation

$$m \frac{d^2x}{dt^2} + k^*x = F \quad (2)$$

$$k^* = k_1 + ik_2 = k_1(1 + i \tan \phi) \quad (3)$$

where $m$ denotes the mass of the vibrating system, $x$ the displacement, $t$ the time, $k^*$ the elastic constant, $F$ the external sinusoidal time varying force, $k_1$ and $k_2$ refer to the real and imaginary parts of the complex modulus of the specimen respectively, $\phi$ the phase angle at which the strain of specimen lags the stress applied on the
specimen. From $k_1$ and $k_2$, the damping capacity, in terms of $Q^{-1}$ can be calculated from

$$Q^{-1} = \tan \phi = \frac{k_2}{k_1}$$

(4)

Annealing treatment was performed at 753 K for 2 h before measurement to eliminate the effect of solidification stress. The IF values as a function of temperature were determined at a continuous changing temperature rate of 4 to 8 K min$^{-1}$ and at three discrete frequencies 1-0, 3-0 and 6-0 Hz in sequence. The range of the maximum excitation torsional strain amplitude is $15 \times 10^{-6}$ to $40 \times 10^{-6}$. The resolution of the IF measurement was 10$^{-4}$.

Results and discussion

Figure 4 shows the IF for the open cell pure Al foam and pure Al over the temperature range of 298–725 K at a heating rate of 6 K min$^{-1}$ at 3-0 Hz, lines represent IF peaks without the high temperature IF background. The high temperature IF background $Q_b^{-1}$ is commonly assumed to be

$$Q_b^{-1} = A + B \exp[-C/(k_BT)]$$

(5)

where $A$ and $B$ are constants, $C$ the energy constant and it is slightly dependent on the temperature, $k_B$ the Boltzmann constant, $T$ the absolute temperature. From Fig. 4, it can be seen that after combining macroscopic pores into pure Al, the IF is improved comparing with IF of parent material. Another, it can be seen that the lower the foam relative density in the same pore size, the higher the IF of the open cell pure Al foams. For the pure Al foam and pure Al, the IF seems to be approximately temperature independent until the temperature reaches 400 K, and over that temperature, IF becomes temperature dependent and IF peaks appear in the temperature range of 433–593 K in the IF curves. For the open cell pure Al foams, the location of the peaks is relative density dependent, and it shifts toward higher temperatures as the relative density increases.

To clarify the mechanism of the IF peak in the pure Al foam, further investigations were carried out. Figure 5 shows that during ascending temperatures, the IF peak is frequency dependent, i.e. the peak position shifts towards higher temperature with increasing frequency, and the shapes of the three IF peaks are similar. It is clear that the IF peak is relaxational type and the activation energy associated with the IF peak is about $1.60 \pm 0.02$ eV (see the IF peaks with the high temperature IF background subtracted in Fig. 5). The high temperature IF background increases exponentially with increasing temperature. The activation energy obtained from the peak temperature and the frequency meet the Arrhenius relationship. The activation energy associated with the IF peak suggests that the mechanism of the relaxation process is also the viscous sliding along grain boundaries.

Figure 8 is IF for the open cell pure Al foam over the temperature range of 298–725 K at different heating rates at 3-0 Hz, the lines represent the IF peaks without the high temperature IF background (relative density=0-355; pore size=175 μm). From Fig. 8, it is clearly seen that the peak height decreases with increasing heating rates, and the peak position definitely shifts towards higher temperatures with increasing heating rates.
The IF for the open cell pure Al foam with different pore sizes over the temperature range of 298–725 K at a heating rate of 6 K min$^{-1}$ at 3–0 Hz, is shown in Fig. 9. At a lower temperature (~400 K), IF of the open cell pure Al foams increases with decreasing pore size. It is observed that the height of the IF peak of the open cell pure Al foams is nearly independent of pore size, but the position of the IF peak basically shifts towards lower temperatures with increasing pore size.

Figure 10 shows the IF of the open cell pure Al foams in the maximum activation strain amplitudes ranging from $15 \times 10^{-6}$ to $40 \times 10^{-6}$ measured at 3–0 Hz at a heating rate of 6 K min$^{-1}$ over the temperature range of 298–725 K (relative density = 0.357; pore size = 325 μm). For the present open pore pure Al foams, the IF is independent of the strain amplitude.

In Refs. 7 and 15, through the detailed studies on the damping behaviours of the Al and Al alloy foams at low frequencies, Han et al. have shown that in the structure of Al foams, there exist large quantities of microscopic (dominantly dislocations) and macroscopic (small voids and cracks along the cell walls) defects, in addition to cells and interfaces, resulting in a non-uniform

6 Internal friction of open cell pure Al foam during descending at different frequencies, lines represent IF peaks without high temperature IF background: relative density = 0.355; pore size = 175 μm

7 Arrhenius relationship between circular frequency $\omega$ (2πf) and reciprocal peak temperature (1/T_m) during ascending and descending

8 Internal friction for open cell pure Al foam over temperature range of 298–725 K at different heating rates at 3–0 Hz, lines represent IF peaks without high temperature IF background: relative density = 0.357; pore size = 325 μm

9 Internal friction for open cell pure Al foam with different pore sizes over temperature range of 298–725 K at heating rate of 6 K min$^{-1}$ at 3–0 Hz, lines represent IF peaks without high temperature IF background

10 Internal friction in open cell pure Al foam with different strain amplitudes at 3–0 Hz at heating rate of 6 K min$^{-1}$ over temperature range of 298–725 K: relative density = 0.357; pore size = 325 μm
structures and defect distribution. According to Eshelby’s equivalent inclusion theory, an applied stress can induce significant stress and strain disturbance around pores, leading to intensified heterogeneity and distortions of pore walls. Atoms or vacancies are forced to move and are redistributed within the distorted regions. This response is hysteretic and inevitably causes energy dissipation, leading to the damping capacity to increase. For the Al foams, the lower the relative density at the same pore size or the smaller the pore size at the constant of relative density, the more the interfaces or cracks, and so the higher the damping capacity. This is in agreement with the present experimental results.

In contrast to foams made by infiltration or by adding a foaming agent to the molten metal, Al foams made by SDP have microscopically rough cell surfaces and a less dense matrix. Figure 11 exhibits morphologies of the cell walls in the microcellular Al foams. A large number of micropores or interfaces are dispersed over the cell walls and form numerous channels between the cells. This unique microstructure suggests, according to the previous study, that the Al foams made by SDP may have much improved damping and energy absorption capacity. According to the preparation route and the structure characteristics of the open cell pure Al foams in the present work, it is rationalised that defect effect should be operative mechanism for the Al foams.

Conclusions

Experiments have been carried out to investigate the damping behaviours of open cell microcellular pure Al foams made by SDP with the relative density of 0.31–0.42 and the pore size of 112–325 μm. The damping characterisation was conducted on an MFIFA. The IF was measured at frequencies of 1–0, 3–0 and 6–0 Hz over the temperature range of 298–725 K. The measured IF shows that the open cell microcellular pure Al foam has a damping capacity that is enhanced in comparison with pure Al. At a lower temperature (~400 K), the IF of the open cell pure Al foams increases with decreasing relative density, and increases with increasing frequency. Especially, an IF peak was found at the temperature range from 433 to 593 K in the IF curves. It is clear that the IF peak is relaxationtype and the activation energy associated with the IF peak is about 1.60±0.02 eV. Defect effects can be used to interpret the damping mechanisms.

References