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Indentation behavior of a closed-cell aluminum foam at elevated temperatures

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Abstract. A series of deep indentation and uniaxial compression tests of closed-cell aluminum foams at room temperature as well as elevated temperatures were conducted. A flat-ended punch (FEP) was used in the indentation tests. Cross-sectional views of the specimens after tests show that the deformation is roughly confined to the material directly underneath the indenter with slightly lateral spread. It is found that plastic collapse strength and energy absorption of the specimens are temperature dependent in both loading conditions. Tear energy of the foam in FEP indentation depends on the indentation depth and temperature.

Introduction

Aluminum foams are widely used in automotive and aerospace industries as core materials for sandwich structures due to their ultra-light weight and other attractive mechanical properties [1]. A good understanding of indentation responses of aluminum foams is necessary to predict and assess their potential damages. Aluminum foams may potentially be used in environments where high temperature and high stresses are involved as for example in the transpiration cooled rocket nozzles, in the cooling system of the burning chamber in gas and steam turbines and heat shielding for aircraft exhaust [2]. Their high-temperature mechanical properties are desired. Moreover, reliable experimental data with temperature effects are imperative in numerical simulations and designs for applications at extreme temperatures.

Research on the indentation properties of metallic foams has mainly been focused on room temperature behavior. Static indentation tests of metal foams [3, 4] show that plastic deformation of metal foams was localized in the region just underneath the indenter. Dynamic indentation tests have also been conducted [5-8] and results show that the indentation resistance increases significantly at velocities greater than 10 m/s. However, their indentation responses at elevated temperatures have been much less documented and the concern of the temperature effects on the mechanical properties of aluminum foams is so far only limited to uniaxial compressions [2, 9, 10].

The present study aims to obtain some information concerning the effect of temperature on the indentation behavior and energy absorption of closed-cell aluminum foam via conducting deep indentation tests with a flat-ended punch at different temperatures.

Materials and Experiments

The closed-cell aluminum foam used in the present study is produced by liquid state processing using TiH2 as a foaming agent and has an average cell size of ~3 mm and a relative density of ~20%.

Cell size, sample size, indenter diameter and indentation depth are critical to quantification of the indentation responses, so precautions have been taken to eliminate these size effects [4]. Specimens with dimensions of Φ30 mm × 60 mm were cut from a block for compressive tests, and those with dimensions of 100 mm × 100 mm × 60 mm for indentation tests. The indenter diameter is about 10 times the average cell diameter, ensuring the measured response representative of the average response of the foam. Indentations are more than one indenter diameter away from the free edge of the foam block and the maximum indentation depth is fixed to half of the specimen thickness to avoid edge effects. The lubrication effect is also considered.

An MTS810 test system was used to carry out the tests under displacement control with a nominal rate of 0.06 mm/s. A flat-ended punch (FEP) with 30 mm in diameter was used and a rigid substrate support covering the entire area of the specimen was put underneath the specimen panels. For comparison purposes, uniaxial compression (UC) tests were conducted on cylindrical specimens. All tests were carried out at four different temperatures: 25°C (room temperature, RT), 200°C, 350°C and 500°C. The deviation from each test temperature was within 5°C.

Results

Typical load-displacement curves are shown in Fig. 1. Due to the good reproducibility of the experiments, three tests were done and one curve was given for every loading case. The UC tests exhibit an initial elastic regime and a peak load which indicates the start of the plastic collapse of the cell walls. The response of FEP indentation is somewhat similar to that seen in the UC. An elastic regime is followed by an oscillating plastic regime wherein localized plastic collapse propagates from one cell band to another. The load for FEP indentation is significantly larger in comparison with UC at the same temperature. This corresponds to the fact that the indenter has to tear the cell walls at its periphery.

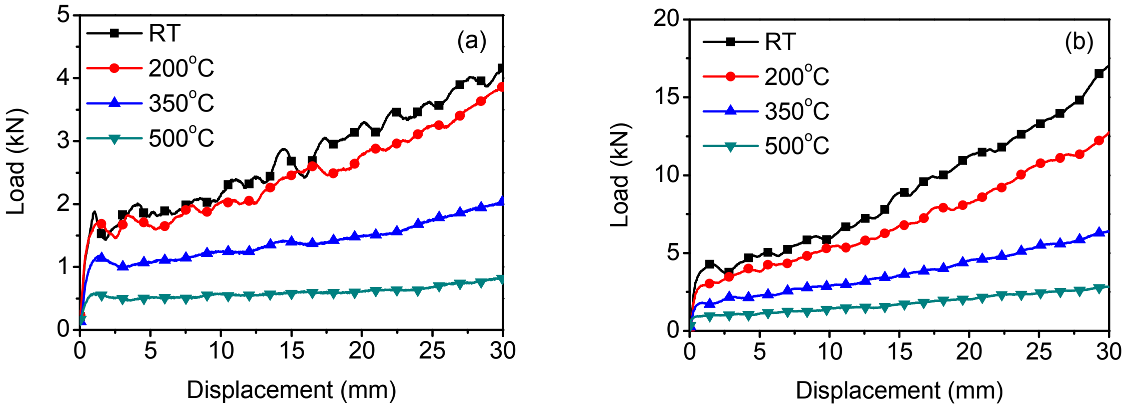

Fig. 1 Typical load-displacement curves at different temperatures for (a) UC and (b) FEP indentation tests

A typical cross-sectional image of the specimen subjected to FEP indentation is shown in Fig. 2. Deformation was localized and a crushed zone was found, which is not only concentrated underneath the indenter but also slightly spreads outwards, forming a truncated cone-shaped shear plug (marked with dash lines). This is possibly due to the relatively large relative density of the foam tested. Increasing the indentation depth, the deformation zone is no longer cylindrical and the size of the deformation zone becomes a little larger. This is different from that observed in the previous studies [3, 5, 6] on low density ALPORAS® foams. Tear lines (marked with oval outlines) which are not perpendicular to the vertical axis of the indenter are also observed. With the deepening of indentation, the compacted foam gets into the underneath undeformed foam, thus tear lines are generated and extended ahead of the indenter.

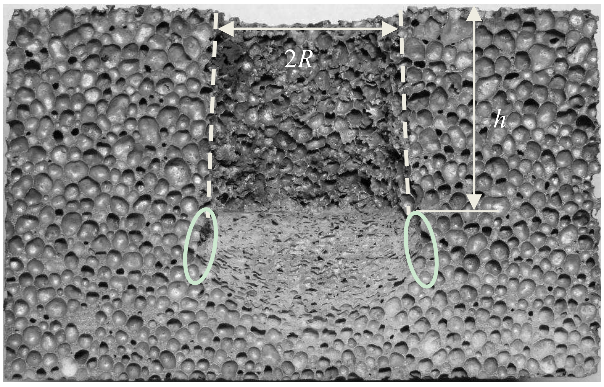

Fig. 2. Cross-sectional photographs of the specimens subjected to FEP indentation

For FEP indentations at different temperatures, no perceptible difference either in deformation size or in shape was discerned. However, with respect to the tear line length, no major difference could be found among specimens tested at different temperatures, and quantitative analysis of the variation of tear line length with test temperature is difficult due to the large cell size of the foam.

Discussion

Plastic Collapse Strength. The plastic collapse strength in this study corresponds to the first peak load which reflects the initiation of the cell band collapse. Variation of plastic collapse strength with the test temperature for both UC and FEP indentation is plotted in Fig. 3a, in which $T_m = 660$°C is the melting temperature of the solid material from which the cell walls of the foam are made.

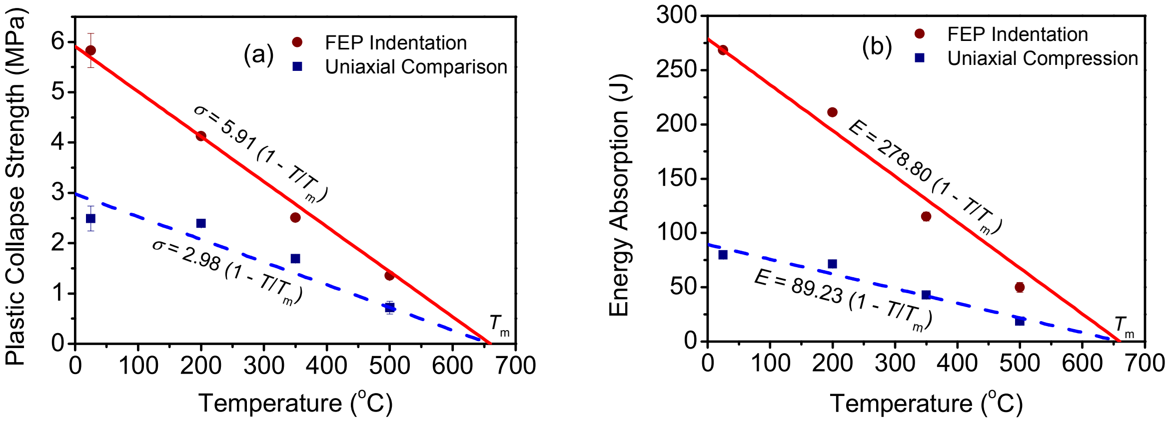

Fig. 3 Variations of (a) plastic collapse strength and (b) energy absorption with test temperature

Plastic collapse in the closed-cell aluminum foam occurs due to the bending of cell walls and stretching of cell faces. For the range of temperatures tested, the plastic collapse strengths in both loading cases decrease almost linearly with the elevation of test temperature. This temperature dependency of the aluminum foam is thought to reflect the temperature dependence of the pre-existing defect substructure and stored dislocations formed during the manufacturing process, and the softening effect observed with increasing temperature is related to the sliding of the grain boundaries of aluminum foams.

Tear Energy. The total force required for FEP indentation can be partitioned into two components: the force that is needed for crushing the foam underneath the indenter, F_c, and the force that is required to tear the cells along the periphery of the indenter, F_t, that is

$$F_{FEP} = F_c + F_t = \pi R^2 \sigma_p + 2\pi R \Gamma, \tag{1}$$

where R is the radius of the indenter, σ_p the compressive plateau strength of the aluminum foam, and Γ the tear energy per unit newly created area. Here, the effect caused by the slight extended deformation zone was neglected in the calculation and this needs further investigation.

Examination of Fig. 1 suggests an obvious linear relationship between Γ and the indentation depth h for each value of temperature. Moreover, from the experimental data obtained in this study, Γ is found to increase linearly with T. Hence, Γ is related to h and T by

$$\Gamma(h,T) = \Gamma_0 \left(1 - \alpha T / T_m\right) + \Gamma_h \left(1 - \beta T / T_m\right) \cdot h / R, \tag{2}$$

where Γ_0 is the initial tear energy at $T = 0$°C and $h = 0$ mm, Γ_h is a displacement-dependent factor, and α and β are dimensionless temperature-dependent factors. For $T_m = 660$°C and $R = 15$ mm in this study, the others are obtained as $\Gamma_0 = 6.68$ N/mm, $\Gamma_h = 61.78$ N/mm, $\alpha = 0.82$ and $\beta = 1.15$. Moreover, the estimated value of Γ at room temperature for $h = 0$ mm is ~6.47 N/mm, agrees reasonably well with the value of ~7.45 N/mm reported by Olurin et al. [3] and ~9.10 N/mm obtained by Ramachandra et al. [5].

Energy Absorption. Fig. 3b summarizes the influence of test temperature on energy absorption, E, of aluminum foam for both FEP indentations and UC. The value of E is evaluated from the area under the force-displacement curve up to a displacement of 30 mm. Fig. 3b shows that E decreases with increasing T in both loading cases but with different slopes. The propagation of plastic collapse from one cell band to another cell band results in an extensive plastic regime in the load-displacement curves (Fig. 1), and hence a great deal of energy absorption. With increasing test temperature, the magnitude of the load in the plastic regime decreases and hence the energy absorption decreases. Whereas a significant difference in the energy absorption between the two types of load conditions at RT is noted, the difference in the energy absorption becomes smaller as the temperature increasing. This can be attributed to the great dependency of the plane-strain tear energy Γ on test temperature.

Observation of Fig. 3b suggests that the energy absorptions of the closed-cell aluminum foam subjected to UC and FEP indentation tend to converge towards 0 as the test temperature approaching $T = T_m$. This corresponds to Fig. 3a which indicates that the plastic collapse strength of UC and FEP indentation come to 0 at $T = T_m$.

Summary

Deep indentation experiments with an FEP on a closed-cell aluminum foam show that the plastic collapse strength and energy absorption decease linearly with increasing test temperature. The tear energy per unit area is dependent on both test temperature and indentation depth and the tear energy extracted from the indentation data agree well with those reported in the literature.

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