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A testing method for tearing energy of aluminum foams

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ABSTRACT

This paper proposes a novel testing method to investigate the tearing energy of metallic foams under quasi-static indentation. The method involves a specimen with pre-cuts, which is then subjected to indentation by a rigid block of appropriate size. Experiments were conducted with aluminum foam (ALPORAS) with a relative density in the range of 7–11%. The force–displacement curve of the indenter was obtained, which showed stages of the indentation/tearing process. A new equation was derived to calculate the tearing energy of the foam based on the measured force as well as the densification strain of the foam, which was overlooked in the previous studies. The values of the tearing energy from the present experiments were then correlated, empirically, to the relative density of the foam, which showed a linear relationship. The densification strain in the compacted zone was also investigated.

1. Introduction

As a lightweight energy-absorbing material, aluminum foam has been widely used in modern industries such as automotive industry and aerospace engineering [1–3]. Interests in mechanical properties of this material especially the energy-absorbing mechanism have been growing in the decade [4–13].

When this material is used as an impact resistant structure [14], tearing plays an important role in failure of foams. Several studies have been conducted to obtain tearing energy of metallic foams, but essentially one or two methods [15,23,28]. Olurin et al. [15] used a series of flat-bottomed circular cylindrical punches with different diameters in indentation experiments to separate tearing energy from the total energy dissipated in indentation. Conventional fracture toughness tests were also conducted in their research [16] and the steady-state toughness J_{ss} was obtained and compared with the tearing energy of the foam in the indentation tests. The tearing energy was higher than steady-state toughness J_{ss} in their study. Ramachandra et al. [17,18] experimentally investigated the indentation behavior of an aluminum foam under dynamic loads. Ramamurty and Kumaran [19] used indenters with different cone angles to study tearing energy and shearing energy in indentation tests. In order to examine the shape of the compacted zone of the aluminum foam, X-ray tomography was employed in the work by Kasar et al. [20]. Relationships between size of the deformation zone, the radius of the indenter, the depth of the indentation and the relative density of the material were observed in their study. Lu et al. [21,22] studied, experimentally and numerically, the indentation of the aluminum foam and the sandwich panels with aluminum foam cores. The tests were conducted under both quasi-static and dynamic loading.

Olurin et al. [28] conducted a bearing test to obtain tearing energy of aluminum foam. A cylindrical fastener passed through and projected from both sides of a foam panel. It was pulled through the panel by two equal forces at either end normal to the axis of the cylinder. By subtracting the energy dissipated by compressing the foam ahead of the fastener from total energy, they calculated tearing energy of this foam.

Recently, Hou et al. [23] investigated both the shear strength and the tearing energy of CYMAT foam through quasi-static shearing tests. Tearing energy was obtained by dividing the total energy by fracture area of specimen.

The purpose of this study is to provide a new testing method for the tearing energy of aluminum foams. It is more efficient than previous ones, where for each foam a series of indenters with different sizes together with different specimens (though nominally the same) had to be employed. In current study, only one indenter with one specimen is needed. Specimens were pre-cut with initial cracks and then indented with a rigid block of matching size. Thus, initially the external force was needed to compress the foam only without tearing. When the initial cut length was about to exhaust, the force increased and then reached another stead-state, corresponding to both compression and tearing of the foam. From the recorded force and displacement of the indenter during the experiments, the tearing energy of the aluminum foam was then deduced. Further analysis was

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conducted to reveal the relationship between tearing energy and relative density of the foam. Photographs were taken to observe the deformation details of the aluminum foam. The values of tearing energy obtained were also compared with those from the previous researchers.

2. Materials and method

Commercial closed-cell aluminum foam, ALPORAS, was used in this study. This foam was made from aluminum with 1.5% of Ca and 1.5% of Ti as well. The average pore size is ~4 mm and the nominal relative density of this material is ~0.09 as provided by the manufacturer. The exact mass of the specimen was measured before tests to determine the relative density of the specimen, knowing the specimen volume. The relative density of the specimens was then calculated as the density of the specimen divided by 2750 kg/m^3.

Both the compression tests and indentation tests were carried out at room temperature. Compression tests were conducted on 15 mm thick foam blocks 100 mm wide and 100 mm high. Two types of specimens were used in the indentation tests. Both of them were blocks of $100 \times 100 \times 50$ mm^3, but for the second type of specimens two cuts of 20 mm depth were made from the top surface of the specimen, as shown in Fig. 1. The distance between these two cuts was set at 28 mm, which covers about 7 cells. Gibson et al. [24,25] found that the normalized unloading Young's modulus and normalized plastic collapse strength change little when the ratio of specimen's length and cell size exceeds 6. A steel plate was used for support underneath the foam block during the experiments. A flat-headed punch was used in the indentation tests. The indenter was made of mild steel, which can be considered rigid compared to the aluminum foam. To eliminate friction between the specimen and the indenter, the shank of indenter was chamfered at an angel of 45°. The configuration and the dimension of the indenter are also shown in Fig. 1. Note that the projected area of the indenter covers ~80 cells, which ensures that the data obtained from the tests represents the average response of this material.

In all the indentation and compression tests, the velocity of the indenter was set at 2 mm/min and the maximum displacement of the indentation was over 70 mm so that all the three typical stages, i.e., elastic deformation, plastic collapse and densification could be recorded. Load, *F*, versus the indention depth, *d*, were recorded. All the specimens and test method are listed in Table 1. In specimen number series, ‘C’ refers to compression test, ‘I’ refers to indentation test, ‘A’ refers to specimens without cuts and ‘B’ refers to specimens with pre-cuts. Photographs were taken during the test to observe the deformation of the foam.

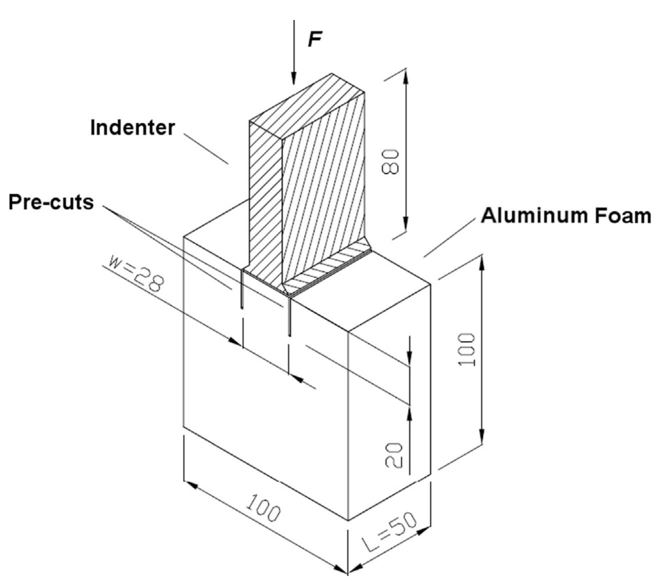

Fig. 1. Sketch of the set-up for indentation test. The specimen is placed on a platen fixed in the universal testing machine. The dimensions are in mm.

Table 1
Dimensions of aluminum foam specimens.

Specimen no.	Specimen dimensions [mm]	Test method	Mass [g]	Relative density [%]
C1	100 × 100 × 15	Compression	3.3	7.9
C2	100 × 100 × 15	Compression	3.2	7.8
C3	100 × 100 × 15	Compression	3.1	7.6
I1A	100 × 100 × 50 without pre-cuts	Indentation	99.4	7.2
I2A	100 × 100 × 50 without pre-cuts	Indentation	98.5	7.2
I3A	100 × 100 × 50 without pre-cuts	Indentation	97.0	7.0
I1B	100 × 100 × 50 with two pre-cuts	Indentation	94.7	6.9
I2B	100 × 100 × 50 with two pre-cuts	Indentation	105.8	7.7
I3B	100 × 100 × 50 with two pre-cuts	Indentation	99.7	7.3
I4B	100 × 100 × 50 with two pre-cuts	Indentation	95.5	6.9
I5B	100 × 100 × 50 with two pre-cuts	Indentation	128.9	9.4
I6B	100 × 100 × 50 with two pre-cuts	Indentation	154.7	11.3
I7B	100 × 100 × 50 with two pre-cuts	Indentation	154.9	11.3
I8B	100 × 100 × 50 with two pre-cuts	Indentation	93.6	6.8
I9B	100 × 100 × 50 with two pre-cuts	Indentation	95.2	6.9
I10B	100 × 100 × 50 with two pre-cuts	Indentation	117.9	8.6
I11B	100 × 100 × 50 with two pre-cuts	Indentation	119.3	8.7
I12B	100 × 100 × 50 with two pre-cuts	Indentation	120.0	8.7
I13B	100 × 100 × 50 with two pre-cuts	Indentation	121.5	8.8
I14B	100 × 100 × 50 with two pre-cuts	Indentation	125.2	9.1
I15B	100 × 100 × 50 with two pre-cuts	Indentation	125.7	9.1
I16B	100 × 100 × 50 with two pre-cuts	Indentation	130.3	9.5
I17B	100 × 100 × 50 with two pre-cuts	Indentation	153.1	11.1
I18B	100 × 100 × 50 with two pre-cuts	Indentation	137.9	10.0
I19B	100 × 100 × 50 with two pre-cuts	Indentation	138.4	10.1

3. Experimental results

Typical curves of normalized force versus normalized indentation depth are shown in Fig. 2 for specimens C3, I9B and I2A, respectively. The relative density of these specimens is ~7%.

Note that the force *F* was normalized with respect to the contact area between the indenter and specimen. The normalized indentation depth was the indentation depth or compression depth *d* divided by the thickness of the specimen *L*. As well known, the curve for the compression test exhibits an elastic regime followed by a plateau, which corresponds to the cell collapse propagating from one cell band to another. Densification