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Dynamic Compressive Behaviour of Closed-Cell Foam Materials Using Load-Measuring Apparatus with Opposite Load-Cells

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Abstract. It is necessary to evaluate the mechanical properties of foam materials at wide range of strain rates, since these materials have the strain rate dependence of strength. In this study, we evaluated the dynamic compressive behaviour of the closed-cell foam materials using the load-measuring apparatus with opposite load-cells, which is applying the drop-weight testing machine. In order to measure large deformation at dynamic strain rate range, universal rate range load-cell, which can reduce the influence of the reflected stress wave, was used. In addition, load equilibrium can evaluate using opposite load-cells which consist of movable (drop-weight) and stationary load-cells. In this study, the commercially available ALPORAS closed-cell aluminum foam was used. From the results of quasi-static tests, three deformation processes of elastic response, plateau deformation and densification were confirmed in stress-strain relation. Within the set of experiments, the closed-cell aluminum foam was locally deformed from cells with low strength and the stress variation occurred during plateau deformation, regardless of the strain rate. In addition, it was clarified that the stress equilibrium was not achieved at the dynamic strain rate. This is thought to be a phenomenon caused by local deformation of cell structure.

1 Introduction

The foam structure has various characteristics such as lightweight, impact absorption, sound absorption, and waterproof characteristics [1]. Among others, the shock absorption characteristics [2-4] are widely used for the cushioning materials during the transportation of the precision equipment, the packaging materials for foods, and the high-speed transportation equipment.

The foamed aluminum, which is a kind of foamed metal, has a cell structure and a lightweight structure, and also has properties of aluminum. Therefore, it is expected to be widely used for industrial material in the future. In order to know the impact absorption characteristics of the foamed aluminum, it is necessary to acquire an accurate stress-strain relation of the foamed structure. In the previous study, the quasi-static properties (10^{-1} s^{-1} or less) using a universal testing machine and the impact properties (10^2–10^3 s^{-1}) using a split Hopkinson pressure bar (SHPB) method [5, 6] have been evaluated in the foamed aluminum [7, 8]. However, since the dynamic strain rate (10^0–10^1 s^{-1}) is difficult to measure with the universal testing machine or SHPB method, the research paper are very few, regardless of the foam structure.

Furthermore, there is a possibility that the dynamic stress equilibrium may not be established during compressive deformation due to the non-uninform deformation caused by the foam shape at a dynamic strain rate or higher in the case of the foamed structure. Many current studies of the foam structure do not consider the effect of this dynamic equilibrium condition.

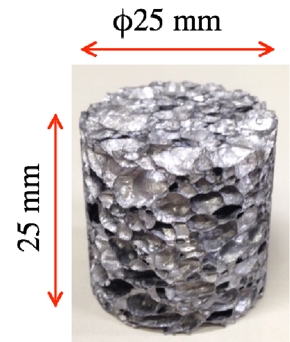

Fig. 1. Photograph of ALPORAS specimen.

Therefore, in this study, we evaluated the compressive behaviour of the closed-cell foam materials at the dynamic strain rate using the load-measuring apparatus with opposite load-cells, which is applying the drop-weight testing machine.

2 Experimental method

2.1 Specimen

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The closed-cell aluminum foam used in this study is ALPORAS developed by Kobe Steel [7, 8]. It is made of

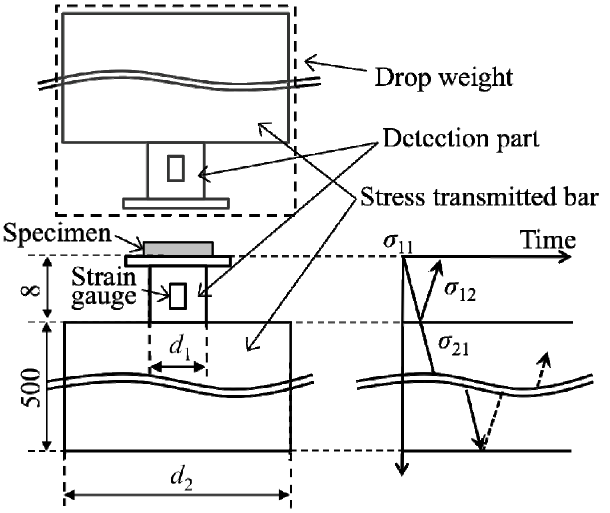


Fig. 2. Schematic view of apparatus for dynamic compression test and its stress wave propagation.

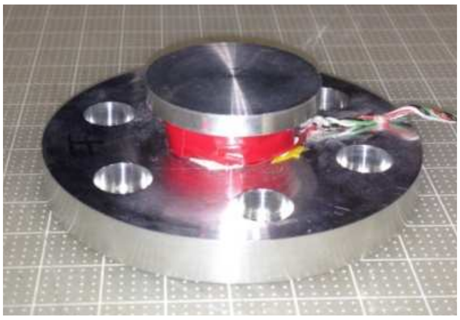


Fig. 3. Photograph of stress detection part for load cell.

pure aluminum and has high impact absorption characteristics. Figure 1 shows a photograph of the specimen. The specimen is a cylindrical shape having a diameter of 25 mm and a height of 25 mm.

2.2 Quasi-static compression test

For confirmation of the basic deformation behaviour for the closed-cell aluminum foam, the quasi-static compression test was performed at the initial strain rate of 1.0×10^{-3} s^{-1} and 1.0×10^{-2} s^{-1} at room temperature using an universal testing machine (Instron, 5500R).

2.3 Dynamic compression test

The dynamic compression test was carried out using the load-measuring apparatus with opposite load-cells [9]. Details of the developed testing apparatus are described below. A schematic view of apparatus for dynamic compression test and its stress wave propagation is shown in Fig. 2. In this study, the universal rate range (URR) load-cell (Fig. 3) was used [10-12]. This consists of a stress detection part with semiconductor strain gage and a stress-transmitted bar. The stress wave applied by compressive deformation of the specimen is transmitted to the stress detection part and then to the stress-transmitted bar.

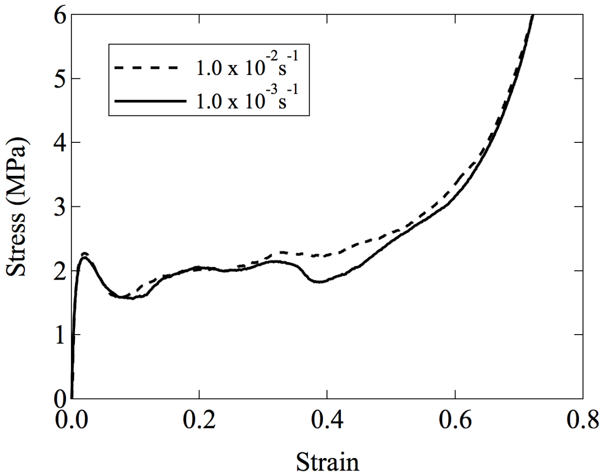


Fig. 4. Typical stress-strain relationship in the quasi-static test.

At this time, the following equation was obtained by the equilibrium of force and the continuity of particle velocity at the boundary between the detection part and the stress-transmitted bar [10-12].

$$\sigma_{21} = \frac{2}{1 + A_2 / A_1} \sigma_{11} \tag{1}$$

where, A_1 is the cross-sectional area of the detection part, and A_2 is the cross-sectional area of the stress-transmitted bar. In addition, σ_{11} is an incident wave to the detection part, and σ_{21} is a transmitted wave to the stress-transmitted bar.

In the case of $A_1 << A_2$, $\sigma_{21} << \sigma_{11}$ is obtained from Eq. (1), and the stress wave transmitted to the stress-transmitted bar becomes extremely small. Therefore, the reflected stress wave transmitted through the stress-transmitted bar and reflected from the lower end of the stress-transmitted bar and reaching the stress detection part is also exceedingly small. Therefore, the influence of the reflected stress wave can be ignored by the structure of this URR load-cell, and the stress of the specimen can be measured for a long time.

In the load-measuring apparatus with opposite load-cells, two URR load-cells at the lower part (stationary) and the upper part (movable) were used. In addition, the URR load cell at the upper part was used as a falling weight. By measuring and comparing the stress-strain relation of the upper and the lower parts, it is possible to evaluate the equilibrium of force (dynamic stress equilibrium) of the specimen as with the SHPB method.

The state of dynamic deformation was photographed at 6000 fps using high-speed video camera; HX-3 manufactured by Nac Image Technology.

3 Results and discussion

3.1 Quasi-static compression test

Typical stress-strain relationship obtained from the initial strain rate of 1.0×10^{-3} s^{-1} and 1.0×10^{-2} s^{-1} is shown in Fig. 4. Three deformation processes commonly occurring in the compressive characteristics of the foamed structure were confirmed, which was the elastic response, the plateau

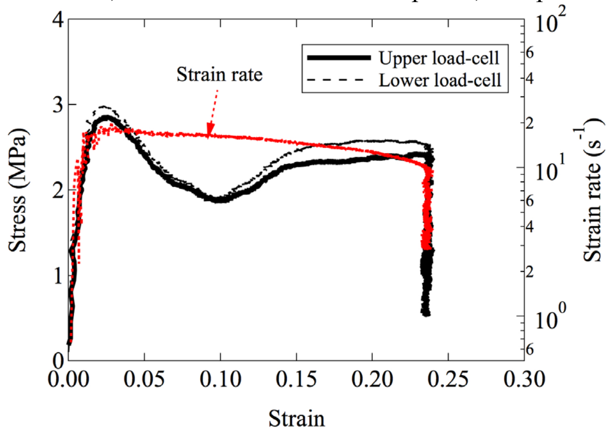


Fig. 5. Stress-strain relationship obtained from the upper and the lower load cell and strain rate-strain relationship in the dynamic test.

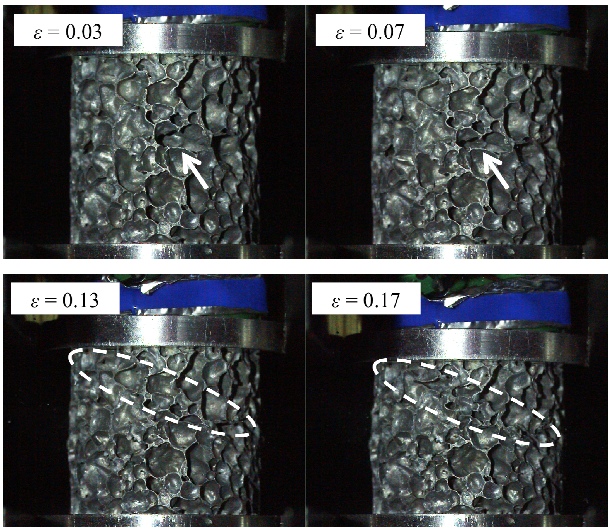
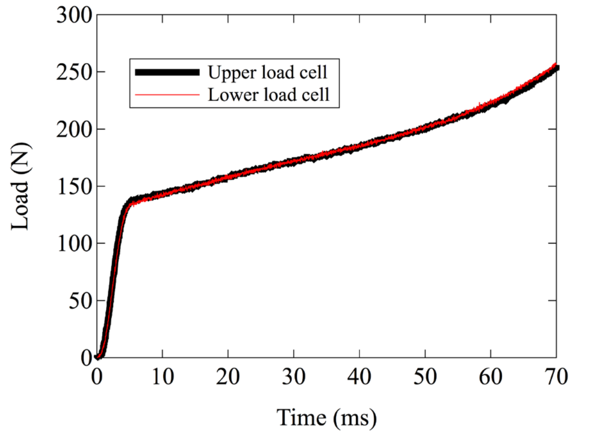


Fig. 6. Images of the dynamic deformation in the strain rate of approximately 1.5 × 10^1 s^{-1} at strain of 0.03, 0.07, 0.13 and 0.17.

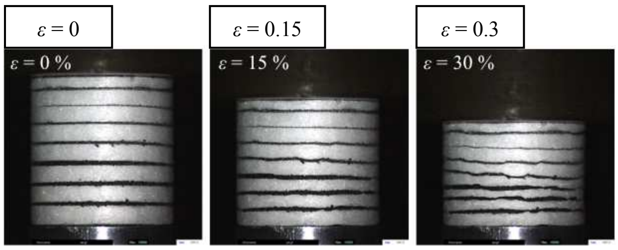
deformation and the densification. The stress variation due to the collapse of cells occurred in the plateau deformation region. However, there is no significant difference in the plateau stress value between the two quasi-static strain rates. In addition, the elastic response and the stress of densification almost agreed at these strain rates. Therefore, no change in flow stress due to the increase of the strain rate is observed in the quasi-static strain rates.

3.2 Dynamic compression test

An example of the stress-strain relationship obtained from the dynamic test is shown in Fig 5. The strain amount was deformed to about 0.23 due to the kinetic energy of the falling weight. Thus, the flow stress in densification could not be obtained. The strain rate during deformation almost did not change, and the average strain rate of the dynamic test was approximately 1.5 × 10^1 s^{-1}. It is an issue in the future to collapse the specimen by increasing the falling weight.



(a) Load-time relation



(b) Images of dynamic deformation

Fig. 7. Example of load-time relationship of the foamed polymeric material made by bead foaming at the strain rate of 8.7 × 10^{-1} s^{-1} (a), and images of the dynamic deformation at strain of 0 (before deformation), 0.15 and 0.3 (b).

As with the quasi-static test, the stress variation due to the collapse of cells can be confirmed from the initial stage of deformation. In addition, the flow stress of the dynamic test increased as compared with the quasi-static test, which indicated the influence of the strain rate. This result is the same as previous study [7, 8]. However, the values of the flow stress obtained from the upper and lower load cells showed different results in the later stage of deformation, which indicated that the dynamic stress equilibrium was not established.

3.3 Observation of dynamic deformation

We attempted to check the deformation state from the images of the high-speed camera. Figure 6 shows the images of the dynamic deformation at each strain.

In the deformation process in which the stresses are almost equilibrated between 0.03 and 0.07 strains, the deformation has progressed around the cell near the centre indicated by the arrow in the figure. On the other hand, in the process of 0.13 to 0.17 strains where stress equilibrium was not established, it was found that the region of the shear direction covered by the broken line in the figure was deformed. When observed this deformation region in detail, the cell deformation concentrates in the vicinity of the upper load cell, and almost no deformation occurs in the vicinity of the lower load cell. Therefore, if the deformation occurs near the centre, the stress values measured upper and lower load cells show equilibrium. However, it was clear that the stress equilibrium does not occur if local deformation occurs outside the centre.

In the previous study, the authors have conducted observational experiments using high-speed video camera on the similar dynamic test of the foamed polymeric material made by bead foaming (foamed polymeric material). This specimen is a cylindrical shape having a diameter of 30 mm and a height of 30 mm. Figure 7 shows the load-time relation of the foamed polymeric material at the strain rate of 8.7×10^{-1} s^{-1}, and the images of the dynamic deformation using high-speed video camera. The load-time relations of the upper and lower load-cells are in agreement. However, this material locally indicated the non-uniform deformation, as can be seen from the change of horizontal line for the specimen. On the other hand, this deformation has occurred in almost all areas. Thus, it has been clarified that the stress equilibrium is established in this foamed polymeric material.

To summarize the above results, it was found that the region where local deformation occurs was important for the establishment of stress equilibrium at dynamic strain rate.

4 Summary

In this study, we evaluated the compressive behaviour of the closed-cell foam materials at the dynamic strain rate using the load-measuring apparatus with opposite load-cells, which is applying the drop-weight testing machine, and its appearance was observed using a high speed camera.

(1) The foamed aluminum was locally deformed from cells with low strength in the plateau deformation region, regardless of the strain rate, which leaded to the stress variation.

(2) The stress equilibrium was not established at the dynamic strain rate. This is considered to be a phenomenon caused by local deformation.

When deforming locally from the low strength part, it was suggested that the obtained data should be handled carefully. In the future, it is necessary to consider a method of measuring dynamic stress equilibrium of the cell structure where local deformation occurs.

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