Strength Enhancement of Aluminium Foams and Honeycombs by Entrapped Air under Dynamic Loadings

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Abstract

The strength enhancement of cellular metals including aluminium foams and honeycombs under dynamic compression is experimentally studied in the present paper, with a focus on the intermediate strain rate from 1 to 200 s\textsuperscript{-1}. Previously data in this range are very limited due to the difficulty in the experimental techniques. The plateau stress in relation to the strain rate of these materials is discussed based on experimental results and compared with data from literature. It has been found that the studied cellular metals are sensitive to the strain rate in plateau stress but not in densification strain. The causes of the strength enhancement are then discussed with a focus on the contribution of the entrapped air during compression. The results show that the pressure change of the entrapped air during dynamic compression is a direct source of strain hardening for aluminum honeycombs whereas it has less influence on the strain hardening of aluminum foams.

Keywords: cellular metals, strain rate effect, intermediate strain rate, entrapped air

1. Introduction

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Cellular materials, including metallic honeycombs and foams, have high strength to weight ratio and good energy absorption capacity, which make them attractive for many structural applications in automotive and aerospace industries. Abundant studies on the quasi-static and high strain rate compression of these materials have been conducted in the past decades to reveal the relations between the relative density, strain rate and plateau stress [1-9]. However, due to the complexity of these materials under dynamic loading, the studies on the strengthening mechanisms of cellular materials are still limited both experimentally and theoretically, especially in the intermediate strain rate range from 1 to $10^2$ s$^{-1}$. Zhao et al. [5] summarized four main sources of the strength enhancement from the study on the impact behavior of metallic cellular materials. The present authors conducted a series of experimental study on the dynamic crushing of aluminum foams and honeycombs [10-14] at intermediate strain rates. It has been found that strength enhancement of cellular materials was mainly from two macroscopic sources. Firstly, the plateau stress increased with the increase of strain rate. Secondly, under dynamic compression, a significant strain hardening was observed, which was attributed to the increase of the pressure of the entrapped air in honeycombs during the dynamic out-of-plane compression [10, 11].

In this paper, the dynamic compressive properties of aluminium foams are further studied over the strain rates from $10^{-3}$ to 200 s$^{-1}$ by using MTS and Instron machines. The relationship between plateau stress, relative density and strain rate for Alporas aluminium foams is experimentally fitted and analysed together with data from literature. Similar semi-empirical relationship for aluminium honeycombs is also discussed after comparing the experimental data obtained by the present authors in literature [10] and [11] with those from literature. Possible reasons for the strength enhancement are finally discussed, with an emphasis on the entrapped air contribution in dynamic compression.
2. Experimental procedure

2.1. Materials and sample preparation

Alporas closed-cell aluminium foams and HexWeb® CR III aluminium honeycombs are studied in this paper. Alporas aluminium foams have a nominal relative density of 10%, with the actual values ranging from 8% to 12%. The average cell size of Alporas foams is approximately 3 mm. The properties of the Alporas foam used in the current study were listed in Table 1 as provided by the suppliers. Cylindrical Alporas foam specimens with 50 mm diameter and 50 mm thickness were prepared by wire cutting. Each specimen contains more than 7 cells in all directions to avoid the boundary effect [1]. A typical test specimen was shown in Fig. 1a. Three types of HexWeb® CR III honeycomb (5052-H39) with different cell size and cell wall thickness were carefully cut according to the construction of periodical “Y” shape units [10]. The detailed experimental study on the intermediate strain rate compression of honeycombs can be found in two previous papers by the present authors [10, 11]. Honeycomb specimens contained 9×9 cells, which was large enough to represent the bulk properties of materials previously studied [10].

2.2 Quasi-static and dynamic testing

Quasi-static and low strain rate tests were conducted on an MTS machine. The MTS machine has a load capacity of 250 kN and can reach a maximum velocity of 0.2 m/s in compressive tests. The load cell of the MTS machine was calibrated from 2.5 kN, which provided sufficient accuracy for the current study. During the compression, specimens were placed on the fixed lower platen. The upper platen moved downwards to crush the specimens. Constant velocities of 5×10⁻⁵, 5×10⁻⁴, 5×10⁻³ and 5×10⁻² m/s, respectively, were applied to specimens corresponding to nominal strain rates of 10⁻³, 10⁻², 10⁻¹ and 1 s⁻¹, respectively, for specimens
50 mm thick. The nominal strain rate was defined as the ratio of the loading velocity to the original thickness of the specimen. When the specimen was compressed, the thickness of the specimen decreased. Although the loading velocity was constant, the instant strain rate changed with the instant specimen thickness. Thus a nominal strain rate was defined and used in the manuscript. The nominal strain rate was defined as the ratio of the loading velocity to the original thickness of the specimen.

Dynamic compressive tests were conducted on an Instron 8800 high rate testing system, as shown in Fig. 1b. The system is equipped with VHS software, which helps to maintain a constant velocity during the compression of specimens. The Instron machine can achieve a maximum velocity of 10 m/s in compression and has a load capacity of 100 kN. The Kistler load cell of the Instron machine was calibrated in a range of 20 kN, which ensured the accuracy of the measurement. Honeycomb specimens were sitting on the lower platen. During the compression, the lower platen moved upwards together with the specimen to impact the upper fixed platen. To prevent the specimens from dis-connecting with the low platen during the compression, very thin and weak glue was used to stick the specimen to the lower platen. This Instron machine was used to conduct tests at nominal strain rates 10, 100 and 200 s$^{-1}$, for which the corresponding crushing velocities are 0.5, 5 and 10 m/s, respectively, for specimens 50 mm thick.

The experimental data obtained by MTS and Instron machines were identical at compressive velocity 0.05 m/s, as experimentally demonstrated previously [10]. Therefore, the stress-strain curves characterized by the two machines could be analyzed together. Details of the tested foams are summarized in Table 2 and data for dynamic compression of honeycombs can be found in two papers of the present authors [10, 11], which are only cited and analyzed in the present paper.
2.3. Data processing

There are great uncertainties to determine the densification strain and the plateau stress by using normal methods. Therefore, energy efficiency method proposed by Avalle et al. [15] was employed in the current work. The energy efficiency coefficient (function of strain), \( \eta \), is defined by

\[
\eta(\varepsilon) = \frac{1}{\sigma(\varepsilon)} \int_0^\varepsilon \sigma(\varepsilon') d\varepsilon
\]  

(1)

The strain range of the integral in Eq. (1) was set to be from 0 to \( \varepsilon \). The densification strain was then defined as the point where the efficiency coefficient reached the maximum on the efficiency-strain curve, i.e., \( \varepsilon_d = \varepsilon[\eta(\varepsilon)]_{\text{max}} \).

\[
\left. \frac{d\eta(\varepsilon)}{d\varepsilon} \right|_{\varepsilon_d} = 0
\]  

(2)

The plateau stress, \( \sigma_{pl}^* \), can then be calculated by

\[
\sigma_{pl}^* = \frac{\int_0^{\varepsilon_d} \sigma(\varepsilon') d\varepsilon}{\varepsilon_d}
\]  

(3)

The densification strain and plateau stress for all tested foam specimens are listed in Table 2.

3. Results and discussion

3.1. Strain rate effect on aluminium foams

The stress-strain curves of Alporas aluminium foams with similar relative densities (approximately 9%) are plotted in Fig. 2, which show that the foam strength maintained at the same level for quasi-static (10\(^{-3}\) s\(^{-1}\)) and low strain rate (10\(^{-2}\) and 10\(^{-1}\) s\(^{-1}\)) compression whereas it increases significantly in the strain rate range from 1 to 10\(^2\) s\(^{-1}\). Therefore, Alporas
closed-cell aluminium foams have positive strain rate sensitivity. To evaluate the effect of strain rate, a semi-empirical relationship between the plateau stress, relative density and strain rate could be applied, which is [16]:

\[
\frac{\sigma_{pl}^*}{\sigma_{ys}} = A(1 + B\dot{\varepsilon}^p)(\rho / \rho_s)\]

(4)

where \(\sigma_{ys}\) is the yield stress of cell wall materials, for Alporas foams, \(\sigma_{ys} = 130\) MPa; \(A, B, p\) and \(n\) are parameters whose values can be obtained by fitting the experimental data. The equation is composed of two uncoupled terms. The first term defines the contribution of strain rate and the second one the effect of relative density. Parameter \(n\) normally has a value larger than 1.5. Herein \(n=1.67\) is employed, which was determined from a previously experimental work by the present authors [12]. Using the plateau stress data in Table 2, parameters \(A, B\) and \(p\) have values as 0.63, 0.20 and 0.13, respectively. Therefore, the stress-strain relation for Alporas foams in the current study is

\[
\frac{\sigma_{pl}^*}{\sigma_{ys}} = 0.63(1 + 0.20\dot{\varepsilon}^{0.13})(\rho / \rho_s)^{1.67}
\]

(5)

To minimize the effect of slight variation in the relative density, the plateau stress \(\sigma_{pl}^*\) is normalized by the relative density, \((\rho / \rho_s)^{1.67}\), and plotted against the strain rate in Fig. 3. Experimental data for other closed-cell foams from literature [2-4, 13, 14, 17-19] in quasi-static and high strain rate compression were also normalized with \((\rho / \rho_s)^{1.67}\) and are plotted in Fig. 3 for comparison. In literature, the quasi-static properties of foams are usually measured by universal testing machine and high rate properties are measured by split Hopkinson pressure bar. Clearly, the present experimental study covered a transition strain rate between quasi-static (\(\dot{\varepsilon} < 10^{-3}\) s\(^{-1}\)) and high strain rate (\(\dot{\varepsilon} > 10^{2}\) s\(^{-1}\)) compression of Alporas foams. The relationship defined by Eq. (5) could describe the trend of the strength enhancement of Alporas foams.
Figure 4 illustrates the change of densification strain with the increase of strain rate from $10^{-3}$ to $10^2$ s$^{-1}$. It is acknowledged that theoretically the densification strain has a linear relationship to the relative density [1]. However, it has still not been clear for the dependence of densification strain on the strain rate due to the discrete nature of foam materials. From the trend shown in Fig. 4, the average densification strain at different strain rates is almost constant, at approximately 0.53. The variation of data could be seen as natural dispersion of the material characteristics. The results are slightly different from Shen et al.'s findings [14], who observed a decrease in densification strain from 0.52 to 0.5.

### 3.2. Strain rate effect on aluminium honeycombs

The experimental study on the dynamic out-of-plane compression of aluminium honeycombs from previous two papers by the present authors [10, 11] showed that aluminium honeycombs were also strain rate sensitive, i.e., the plateau stress increased with strain rate. Applying a similar method to that for foams, the out-of-plane plateau stress of honeycombs could be normalized by the $t/l$ ratio based on a semi-empirical equation:

$$\frac{\sigma^\ast_{pl}}{\sigma_{ys}} = 3.93(t/l)^{1.52}(1+0.11e^{0.21})$$

(6)

where $t$ and $l$ are the cell wall thickness and edge length of honeycomb, respectively; $\sigma_{ys}$ is the yield stress of cell wall materials, aluminium alloy 5052, and $\sigma_{ys} = 292$ MPa. The normalized plateau stress, $\sigma^\ast_{pl} / (t/l)^{1.52}$, of the experimental data in [10, 11] are then plotted against the strain rate in Fig. 5. The best fitted curve, described by Eq. (6), is plotted in Fig. 5 as a solid line. For comparison, experimental data from literature [5, 6] are also plotted in Fig. 5. Experimental studies on the out-of-plane compression of honeycombs were mainly
conducted under quasi-static loadings [1, 8]. Limited study could be found on the dynamic compression. Moreover, most of the studies on high strain rate crushing were conducted using split Hopkinson pressure bar (SHPB). Due to limitation of SHPB technique, it was very difficult to obtain stress-strain curves up to the densification region. So far, we have only found stress-strain curves in references [5] and [6] which contain densification regions. Also the honeycombs employed in both [5] and [6] were made of the same aluminium alloy (5052-H39) [6] or similar one (5052) [5] as those used in the current study. Therefore the experimental data from these two papers ([5] and [6]) are also cited here and compared with our results.

Figure 5 showed that the results obtained by Xu et al. [10, 11] are located in the middle range of strain rate tested (from $10^{-3}$ to 200 s$^{-1}$), which is the transition between quasi-static and high strain rates. However, the fitted solid curve (Eq. (6)) is not in a good agreement with the experimental data from literature at high strain rates larger than 200 s$^{-1}$. Using all the data included in Fig. 5, another semi-empirical equation can be obtained as follows.

$$\frac{\sigma_{pl}^*}{\sigma_{ys}} = 4.31 \left( \frac{t}{l} \right)^{1.52} (1 + 4.93 \times 10^{-4} \varepsilon^{1.04})$$

(7)

The line defined by Eq. (7) is plotted in Fig. 5 as the dashed line.

Figure 6 shows the dependence of densification strain of honeycombs under out-of-plane compression on the strain rate. The densification strain is in a range of 0.72 to 0.83 and appears to be independent of strain rate, which is similar to the above discussion for the closed-cell aluminium foams.

3.3. Possible reasons for strength enhancement
As discussed previously, strengths of Alporas closed-cell aluminium foams and HexWeb® CR III aluminium honeycombs increase with both strain rate and strain. However, the mechanisms for this strength enhancement is still unclear, which might be from the strain rate sensitivity of the cell wall materials, micro-inertia effect, the effect of shock wave at high velocity impact and the contribution of entrapped air. It was acknowledged that strength enhancement mechanism of cellular materials was the interaction of all these factors [5].

Strength enhancement includes the strength increase with strain rate, and also the strength increase with strain. The latter is defined as strain hardening in the current paper. A significant contribution to the strain hardening and thus strength enhancement is the effect of entrapped air, which was studied by many researchers [5, 9]. Gibson and Ashby [1] proposed a method to evaluate the strength enhancement due to the air pressure increase for foam materials in compression.

\[
\Delta \sigma = \frac{P_0 \varepsilon_d (1 - 2\nu^*)}{1 - \varepsilon_d (1 - 2\nu^*) - \rho / \rho_s}
\]  

where \(\nu^*\) is the Poisson’s ratio for foam. Poisson’s ratio for closed-cell foam depends on the details of the cell shape and is independent of the relative density and in post-collapse regime, \(\nu^* \approx 0\) [1]. \(P_0\) is the atmosphere pressure (0.1 MPa). Equation (8) gives the overall contribution of the entrapped air in dynamic compression (toward densification). It relates the strength enhancement to the densification strain of foams and contains no detailed information on how the entrapped air comes into effect during the compression. However, from the above experimental study and discussion of the dynamic compression of foams and honeycombs, the densification strain is independent of strain rate. Therefore, the entrapped air contribution under dynamic loadings cannot be evaluated effectively by Eq. (8).
The present authors experimentally studied the contribution of the entrapped air for honeycombs under dynamic loadings [11] and proposed a method to estimate it. Assuming the compression is isothermal, the leakage of the air can be determined by

\[ \delta = 1 - \frac{PV}{P_0V_0} \]  \hspace{1cm} (9)

where \( P_0 \) is the pressure of atmosphere at room temperature (0.1MPa), \( V_0 \) is the initial volume of the entrapped air, \( P \) and \( V \) are the instantaneous air pressure and volume, respectively. Assuming the leakage of the air (\( \delta \)) in the compression is uniform, the pressure change (\( \Delta P \)) for honeycombs due to the entrapped air in the dynamic out-of-plane compression can then be derived as [11]

\[ \Delta P = P_0 \cdot \left( \frac{1}{1 - \varepsilon} - 1 \right) \cdot (1 - \frac{\dot{\delta}}{\dot{\varepsilon}}) \]  \hspace{1cm} (10)

where \( \dot{\delta} \) is the leaking rate of air and \( \dot{\delta} = \partial \delta / \partial t \), which is experimentally shown to be dependent on the strain rate and independent of the thickness to edge length (t/l) ratio of honeycombs [11]. When \( \varepsilon = 10^2 \) s\(^{-1}\) and the specimen is fully sealed at both ends, \( \dot{\delta} = 8 \) s\(^{-1}\) [11].

Combining Eqs. (6) and (10), the stress-strain relation for honeycombs under out-of-plane compression can be obtained as

\[ \sigma_{pl}^* = C_1 \sigma_y (t/l)^k (1 + C_2 \dot{\varepsilon}^p) + \Delta P \]  \hspace{1cm} (11)

It should be mentioned that in Eq. (11), parameters \( C1, C2, k \) and \( p \) are determined from specially designed tests on honeycomb specimens with both ends open, i.e., entrapped air can fully escape and entrapped air effect could be neglected. The parameters fitted from the testing results of literature [11] are 4.09, 0.11, 1.55 and 0.20, respectively, for honeycomb specimens with t/l ratio 0.00924.

Figure 7a shows the contribution of the entrapped air in quasi-static (\( \varepsilon = 10^5 \) s\(^{-1}\)) and dynamic out-of-plane compression of aluminium honeycombs (\( \varepsilon = 10^2 \) s\(^{-1}\)). Under quasi-static
compression, the plateau region of the stress-strain curve for honeycomb is flat, indicating a negligible contribution from the entrapped air. Under intermediate strain rate compression, a strong strength enhancement, i.e. the strength increases with both strain rate and strain, is observed. Employing Eq. (10), the entrapped air contribution to the stress can be subtracted as the dashed curve in Fig. 7a, which shows a plateau region parallel to the quasi-static stress-strain curve. For comparison, the stress-strain relations of the intermediate strain rate out-of-plane compression defined by Eq. (11) by using fitted parameters with and without the entrapped air effect are also plotted in Fig. 7a as the solid curve and dashed line, respectively. It can be concluded that with the increase of strain rate, the plateau stress of honeycombs increases significantly. Moreover, the strain hardening of honeycombs under dynamic out-of-plane compression is mostly from the entrapped air effect.

Aluminium foams are much more complicated three-dimensional cellular structures as compared to two-dimensional honeycombs. Therefore, it is challenging to propose theoretical solution to estimate the contribution of entrapped air. The reasons are as follows. Firstly, it is experimentally difficult to evaluate the pressure increase caused by the entrapped air in foams. Secondly, the leakage of air cannot be assumed to be uniform. Since the entrapped air in a foam specimen is difficult to escape, either in quasi-static or dynamic compression, it can be assumed that there is very limited air escape during crushing, i.e., $\delta = 0$. Figure 7b shows the contribution of the entrapped air to two Alporas foam specimens with an identical relative density of 9.03% under quasi-static ($10^{-3}$ s$^{-1}$) and dynamic ($10^2$ s$^{-1}$) compression. In Fig. 7b, the average stress ($\sigma_{ave}$, dashed straight lines) is calculated by averaging the stress between $0.05 < \varepsilon < 0.2$, i.e., the earlier stage of the plateau region. The effect of entrapped air is then calculated using $\sigma_{ave} + \Delta P$ (dash-dotted curves, $\delta = 0$ from Eq. (10). The stress-strain curves removing the effect of entrapped air from the experimental data
(rectangular symbols) are plotted as the dashed curves ($\dot{\varepsilon} =0$). It can be seen from Fig. 7b that the contribution of the air pressure change to the strength of aluminum foams is much smaller than that for the aluminum honeycombs. It has been revealed in literature [11] that at a strain of 0.5, the pressure increase of entrapped air was only 0.1 MPa for honeycomb specimens and the value increased to approximately 0.4 MPa (4 times the atmosphere pressure) when the strain was higher than 0.8. However, the densification strain for aluminum foams studied was less than 0.6 and the pressure change was only approximately 0.1 MPa, which had a minor effect on the strength of foams with plateau stress higher than 2 MPa in dynamic compression and 1.5 MPa in quasi-static compression. It can be concluded that, unlike honeycombs, whose strain hardening was proved to be mainly from the pressure change of the entrapped air, the strain hardening of foams has different mechanisms. For foams, the entrapped air contributes only a small part.

Apart from the entrapped air effect, there must be some other factors that cause the significant strain hardening of foams. The possible reasons are as follows. Firstly, the cell walls of aluminium foams are easy to rupture. With the increase of strain, the ruptured cell walls are piled up in a complicated way to fill in the space of foams. This pile-up tends to be more intensive toward the densification region and causes the latter strain hardening. Secondly, the lateral inertia effect under dynamic loading may also contribute to the strain hardening of foams. With the crushing progressing, the localized strain rate in deforming bands tends to be much higher than the nominal strain rate. Considering the much larger amount of cells in the deforming bands as compared to honeycombs, it might enlarge the lateral inertia effect and cause the strength enhancement. Thirdly, under very high rate impact the shock wave enhancement may also contribute to the strain hardening. The collapse of abundant cells in the localized deforming bands at very high strain rate might lead to a very different deformation pattern and, therefore, a different mechanism of strength enhancement.
4. Conclusions

A study on the intermediate strain rate compression of aluminum foams and honeycombs has been conducted via MTS and Instron machines over the strain rate from $10^{-3}$ to 200 s$^{-1}$. The strength enhancement of these materials under both quasi-static and dynamic loading was analyzed and compared with data from literature.

It has been found that both Alporas closed-cell foams and HexWeb® CR III aluminium honeycombs are sensitive to strain rate, i.e., the plateau stress increases with strain rate. However, the densification strain of the studied two cellular materials is insensitive to the strain rate.

The reasons for the strength enhancement of aluminium foams and honeycombs were discussed, with a focus on the entrapped air contribution on the plateau stress. For honeycombs, the pressure change due to the entrapped air contributes significantly to the strain hardening and, hence, the plateau stress. However, entrapped air has a small influence on the strain hardening of aluminum foams. The mechanism for strain hardening of foams is much more complicated and the possible mechanisms have been discussed.

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References


Table 1. Properties of Alporas aluminium foam (data was provided by the supplier)

<table>
<thead>
<tr>
<th>Composition (%)</th>
<th>Density (kg/m³)</th>
<th>Young’s Modulus (GPa)</th>
<th>Shear Modulus (GPa)</th>
<th>Shear Strength (MPa)</th>
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</thead>
<tbody>
<tr>
<td>Al + 1.5%Ca+1.5% Ti</td>
<td>230 ± 20</td>
<td>1.1 ± 0.1</td>
<td>0.33 ± 0.02</td>
<td>1.2 ± 0.05</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Tensile Strength (MPa)</th>
<th>Bending Strength (MPa)</th>
<th>Poisson’s Ratio</th>
<th>Compressive Peak Stress (MPa)</th>
<th>Average Cell Size (mm)</th>
</tr>
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<tbody>
<tr>
<td>1.6 ± 0.2</td>
<td>2.8 ± 0.3</td>
<td>0.33</td>
<td>1.9 ± 0.3</td>
<td>2.88</td>
</tr>
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</table>
Table 2. Summary of tested Alporas aluminium foams

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Velocity (m/s)</th>
<th>Strain Rate (s(^{-1}))</th>
<th>Relative Density</th>
<th>Densification strain</th>
<th>Plateau stress (MPa)</th>
<th>Normalized plateau stress (MPa)</th>
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<tbody>
<tr>
<td>AP-1-1</td>
<td>5(\times)10(^{-5})</td>
<td>10(^{-3})</td>
<td>9.03</td>
<td>0.516</td>
<td>1.68</td>
<td>93.2</td>
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<tr>
<td>AP-1-2</td>
<td>5(\times)10(^{-5})</td>
<td>10(^{-3})</td>
<td>8.81</td>
<td>0.538</td>
<td>1.71</td>
<td>98.7</td>
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<td>AP-1-3</td>
<td>5(\times)10(^{-5})</td>
<td>10(^{-3})</td>
<td>9.52</td>
<td>0.533</td>
<td>1.74</td>
<td>88.5</td>
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<td>5(\times)10(^{-5})</td>
<td>10(^{-3})</td>
<td>8.89</td>
<td>0.514</td>
<td>1.72</td>
<td>98.0</td>
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<td>AP-1-5</td>
<td>5(\times)10(^{-5})</td>
<td>10(^{-3})</td>
<td>11.53</td>
<td>0.512</td>
<td>2.08</td>
<td>76.8</td>
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<tr>
<td>AP-1-6</td>
<td>5(\times)10(^{-5})</td>
<td>10(^{-3})</td>
<td>9.97</td>
<td>0.539</td>
<td>1.86</td>
<td>87.7</td>
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<td>AP-2-1</td>
<td>5(\times)10(^{-4})</td>
<td>10(^{-3})</td>
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<td>0.534</td>
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<td>86.0</td>
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<td>10(^{-2})</td>
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<td>0.531</td>
<td>1.81</td>
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<td>10(^{-2})</td>
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<td>0.532</td>
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<td>93.8</td>
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<td>10(^{-2})</td>
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<td>0.531</td>
<td>1.62</td>
<td>97.3</td>
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<tr>
<td>AP-2-5</td>
<td>5(\times)10(^{-4})</td>
<td>10(^{-1})</td>
<td>10.80</td>
<td>0.532</td>
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<td>97.6</td>
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<td>1(^{-1})</td>
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<td>0.553</td>
<td>1.27</td>
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<td>10(^{-1})</td>
<td>10.76</td>
<td>0.503</td>
<td>2.18</td>
<td>90.3</td>
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<td>AP-3-4</td>
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<td>0.519</td>
<td>1.62</td>
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<td>AP-3-5</td>
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<td>10(^{-1})</td>
<td>9.80</td>
<td>0.532</td>
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<td>1(^{-1})</td>
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<td>0.531</td>
<td>1.62</td>
<td>97.3</td>
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<td>1(^{-1})</td>
<td>8.83</td>
<td>0.533</td>
<td>1.83</td>
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<td>5(\times)10(^{-2})</td>
<td>1(^{-1})</td>
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<td>0.521</td>
<td>1.84</td>
<td>103.0</td>
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<td>5(\times)10(^{-2})</td>
<td>1(^{-1})</td>
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<td>96.6</td>
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<td>112.6</td>
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<td>10(^{-1})</td>
<td>8.96</td>
<td>0.527</td>
<td>2.00</td>
<td>112.1</td>
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<tr>
<td>AP-5-4</td>
<td>5(\times)10(^{-1})</td>
<td>10(^{-1})</td>
<td>9.53</td>
<td>0.519</td>
<td>2.00</td>
<td>101.2</td>
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<tr>
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Fig. 1. (a) A typical aluminium foam specimen and (b) Instron 8800 VHS high rate testing system.

Fig. 2. Stress-strain curves of tested Alporas aluminium foams with a similar relative density of approximately 9% at various strain rates from $10^{-3}$ to $10^2$ s$^{-1}$.

Fig. 3. Normalized plateau stress of closed-cell foams versus strain rate (*please note data from [4] are for Aluight foams, all other data are for Alporas foams).

Fig. 4. Densification strain of tested Alporas foams versus strain rate.

Fig. 5. Normalized plateau stress of aluminium honeycombs made of aluminium alloy 5052 versus strain rate and comparison with literature data.

Fig. 6. Densification strain of tested aluminium honeycombs versus strain rate.

Fig. 7. Contribution of entrapped air to the strength enhancement of (a) aluminum honeycombs and (b) aluminum foams.
\[ \frac{\sigma_{pl}}{\sigma_s} = 0.63(1 + 0.20\dot{\varepsilon}_p^{0.13})(\rho / \rho_s)^{1.67} \]
\[
\sigma'_{ps} / \sigma_{ys} = 3.93(1 + 0.11t/l)^{0.21}(t/l)^{0.53}
\]

\[
\sigma'_{ps} / \sigma_{ys} = 4.31(1 + 4.93 \times 10^{-4} \dot{\varepsilon}^{1.04})(t/l)^{0.52}
\]
Honeycomb: $t/l=0.00924$

- Experimental data: $\dot{\varepsilon}=10^3$ s$^{-1}$
- Extracting $\Delta P$ from experimental data: $\dot{\varepsilon}=10^3$ s$^{-1}$
- Stress-strain including $\Delta P$: $\dot{\varepsilon}=10^3$ s$^{-1}$
- Stress-strain without $\Delta P$: $\dot{\varepsilon}=10^3$ s$^{-1}$

Alporas foam ($\rho^f/\rho_s=9.03\%$)

- Experimental data: $\dot{\varepsilon}=10^3$ s$^{-1}$
- Extracting $\Delta P$ from experimental data: $\dot{\varepsilon}=10^3$ s$^{-1}$
- Stress-strain including $\Delta P$: $\dot{\varepsilon}=10^3$ s$^{-1}$
- Average stress for $0.05<\varepsilon<0.2$: $\dot{\varepsilon}=10^3$ s$^{-1}$

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- Extracting $\Delta P$ from experimental data: $\dot{\varepsilon}=10^3$ s$^{-1}$
- Stress-strain including $\Delta P$: $\dot{\varepsilon}=10^3$ s$^{-1}$
- Average stress for $0.05<\varepsilon<0.2$: $\dot{\varepsilon}=10^3$ s$^{-1}$
Compressive tests were conducted on aluminium foams at intermediate strain rates from 1 to 200 s\(^{-1}\).

The strain rate effect on aluminium foams and honeycombs were reviewed and compared with data from various sources.

The strength enhancement of aluminium foams and honeycombs were extensively studied and analysed.

Possible reasons of the strength enhancement of aluminium foams and honeycombs under dynamic loadings were discussed.