# High Gn shock-cushioning and Energy-absorption-performance analysis on aluminum foam-polyurethane composite

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Abstract

Based on the requirement of energy absorption at high shock and overload, aluminum foam-polyurethane composite has been researched. The energy absorption capacity of the three materials, as well as energy absorption capacity of the aluminum foam-polyurethane composite under different shock and different thickness, has been researched. The research results are obvious: under the same material parameters and 8000gn shock conditions the energy absorption capacity of the aluminum foam-polyurethane composite is better than the monomer of the aluminum foam or the polyurethane. Under the same shock conditions, the thicker the composite is, the more energy it absorbs. Under the same materials, the more acceleration speed, the more energy it absorbs. Aluminum foam-polyurethane composite can cushion and absorb energy under the acceleration speed of 8000gn. Finally the results were validated by compression behavior test.

Key words: ALUMINUM FOAM-POLYURETHANE, COMPOSITE, ENERGY ABSORPTION, SHOCK, FINITE ELEMENT

## 1. Introduction

The research and development of metal foams started since the 1940s. The earliest was the patent technology of Sosnick[1] who prepared metal foams through the gasification of low melting point substance in the metal. In 1956, Borksten Research Laboratory Inc. first successfully prepared aluminum foam through molten body direct foaming process [2]. Then Foamalum Corp. and Italy Corp. put this technology into practice[3].

So far people have done a lot of researches on the property of aluminum foams which are prepared by different production technologies[4-5], and also discussed the influence of cell structure and specimen size on the compressive strength of aluminum foam[6-17].

Hidekazu Sueno investigated effects of specimen thickness on the tensile strength of lotus-type porous copper[6].The effect of particles was investigated by E. W. Andrews using both water solutions and an aluminum melts[7]. BAUMEISTER J found and discussed a non-linear dependency of metal foam properties on the density[8]. Stress and strain of aluminum foam, polyurethane and aluminum foam-polyurethane composite were researched via Ansys software by Mingsi Qi et al.[9], but the results were not verified by experiments. Gibson L J discoursed knowledgeably on subjects of the cellular solids: structure and properties[10]. Baels JT, ThompsonMS examined the compression properties of an aluminium foam containing a nonuniform density gradient[11]. Xiaoqing Cao discussed effects of heat treatment on dynamic compressive properties and energy absorption characteristics of open-cell aluminum alloy foams[12].

Zhihua Wang studied on the dynamic compressive properties of open-cell aluminum alloy foams[13]. An experimental investigation into the strain rate sensitivity of a closed-cell aluminum foam at room temperature and under compression loading was conducted by PAUL A and RAMAMURTY U[14]. HAN F S researched compressive deformation and energy absorbing characteristic of foamed aluminum[15]. CRUPI V MONTANINI R discoursed aluminum foam sandwiches collapse modes under static and dynamic three-point bending[16]. VAIDYA discussed impact and post-impact vibration response of protective metal foam composite sandwich plates[17]. People also have done a lot of researches on the property of polyurethane [18-20], but there are few reports on the energy absorption of aluminum foams-polyurethane composite on compressive and energy absorption properties.

## 2. Shock-cushioning And Energy-absorption-performance Research of Aluminum Foam-polyurethane Composite

Based on the requirement of energy absorption at high shock and overload, aluminum foam-polyurethane composite was researched. The composite is a combination with the aluminum foam as base body and the polyurethane as reinforcing body. The paper analyzed the stress and strain of aluminum foam, polyurethane and aluminum foam-polyurethane composite by using finite element analysis method, then via energy absorption curves, carried on a contrastive study on energy absorption capacity of the three materials, at last analysed absorption performance of the composite at different impact conditions and different thickness. Table 1 shows the material parameters used in this paper.

**Table 1.** Material parameters

| Material | Young modulus (GP) | Poisson ratio | Density (kg/m3) |
|---|---|---|---|
| Aluminum foam | 1.2 | 0.3 | 365 |
| Polyurethane | 10 | 0.3 | 361 |

Cushioning model is shown in figure 1, the five small cylinders are aluminum foam materials, and the rest is polyurethane material. The diameter of the smallest cylinder is 10mm, and the largest cylinder is 40mm. The thickness of the cylinder is 12mm.

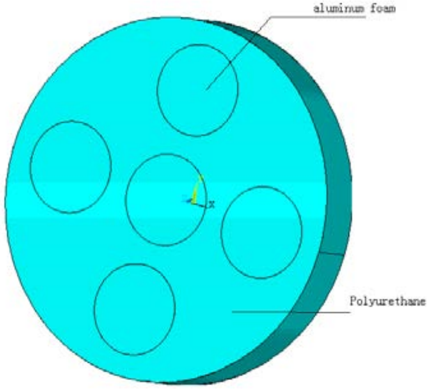

**Figure 1.** Cushioning module

The underside of the finite element model is imposed by $Z$ direction constraints, loaded with 8000gn($m/s^2$) acceleration. Finite element mesh model is composed of nodes and grid unit which are divided by free meshing modules.

Through free meshing, geometric entities were divided into a finite element model of nodes, and then was imposed constraints and loads. Stress and strain of the nodes under constraints and loads were gotten, and stress and strain of the geometric entities were drawn through interpolation functions.

### 2.1 The stress research on aluminum foam, polyurethane and aluminum

The stress cloud of aluminum foam cushioning model is shown in figure 2, from which it can be seen that the stress is imbricated distribution and it becomes smaller and smaller from the bottom up. The maximum stress is 244385 Pa, and the minimum stress is 69451 Pa. The stress cloud of polyurethane model is shown in figure 3. Its stress distribution is similar to that of aluminum foam. They are imbricated distribution and become smaller and smaller from the bottom up. The maximum stress value is 0.119E7 Pa, and the minimum stress value is 337872 Pa.

The stress cloud of composite is shown in figure 4, from which it can be seen that the stress is like stacked distribution, and it gets smaller and smaller from the bottom up, and the maximum stress concentrates on the junction of polyurethane and aluminum foam. The minimum stress is distributed on the aluminum foam. The maximum stress value is 0.165E7 Pa, and the minimum stress value is 35183 Pa.

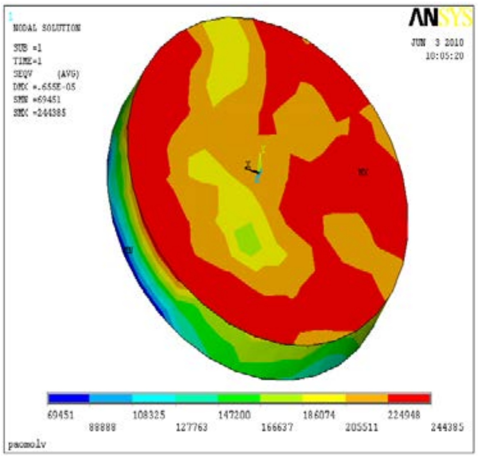

**Figure 2.** Stress cloud of aluminum foam model

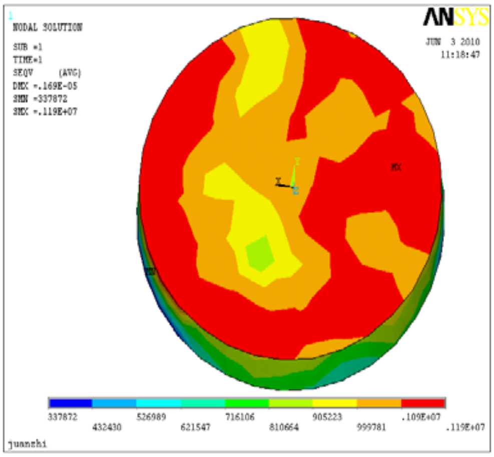

**Figure 3.** Stress cloud of polyurethane model

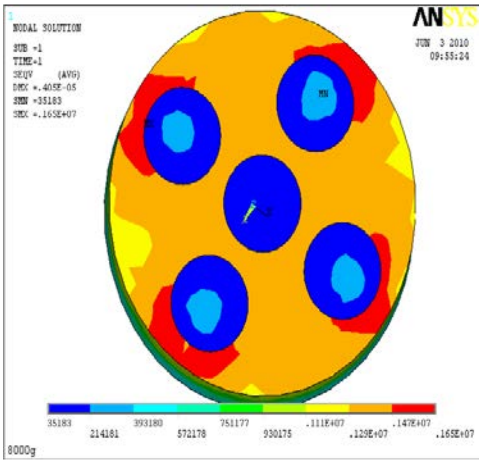

**Figure 4.** Stress cloud of composite model

The maximum stress concentrates on the junction of polyurethane and aluminum foam, and the change region is very small. But its stress value changes greatly, and its stress is more concentrated, and the junction region occurs damage easily. When the shocking energy is large, the stress concentrates on the final layer and the composite appears wide range of yield deformation.

### 2.2 The stress research on aluminum foam-polyurethane composite

The strain cloud of aluminum foam cushioning model is shown in figure 5, from which it can be seen that the strain distribution of the cushioning model is similar to that of the composite. It is also circular distribution, but the strain value of the aluminum foam is increased from the left lower to upper. The maximum strain value is 0.655E-5 $m^3$, and the minimum strain value is 0.166E-5 $m^3$.

The strain range of aluminum foam is small, and the energy absorption of aluminum foam mainly depends on the yield phase, which is in accordance with the theory. In theory, aluminum foam has three stages: elastic phase, yield phase and dense phase. Elastic stage of aluminum foam consists in small strain range, and the strain is commonly less than 0.05, and the stress-strain curve is a straight line within the interval. The most important energy absorption phase of aluminum foam is the yield stage. In theory, the main characteristics of this phase are that the strain remains almost unchanged as the strain increased. However, unlike other polymers, the yield platform stage of aluminum foam is not flat. From above, aluminum foam at high stress absorbs a large amount of energy. This shows, aluminum foam structure is easy to damage when absorbing energy.

The strain cloud of polyurethane cushioning model is shown in figure 6, from which it can be seen that its strain distribution is similar to that of aluminum foam, it is also circular distribution. But it spreads like ripples from the bottom, and the more outside the larger the strain is. The maximum strain value is 0.169E-5 $m^3$, and the minimum strain value is 0.628E-7 $m^3$.

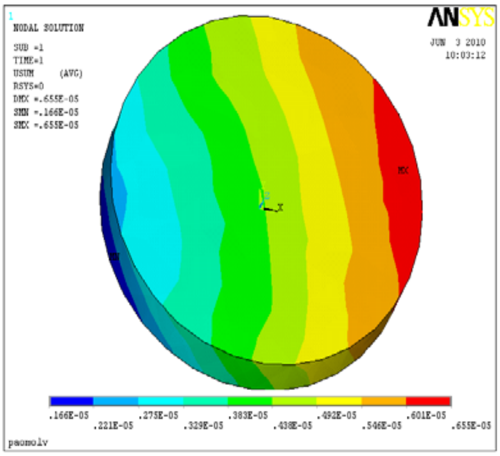

**Figure 5.** Strain cloud of aluminum foam model

The strain range of polyurethane is larger than that of aluminum foam, which means that polyurethane is more sensitive than aluminum foam. Polyurethane also has three stages of degeneration. Compared with aluminum foam it has a larger elastic strain range. Commonly the strain is less than 0.1, and polyurethane has a long, smooth and low stress platform, it indicating that polyurethane can absorb a large amount of energy at lower stress. That is to say, polyurethane material is not easily destroyed during energy absorption period. Its elastic phase is long and it can restore its deformation under large stress.

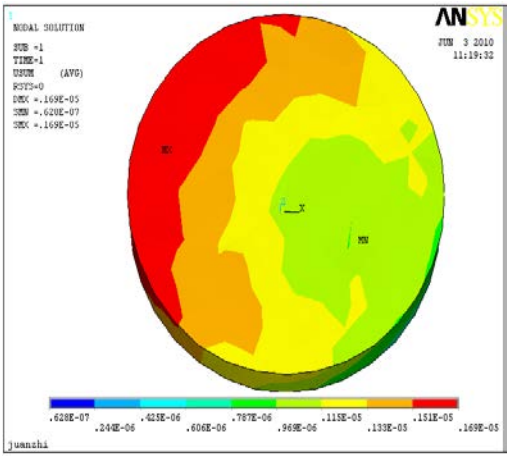

**Figure 6.** Strain cloud of polyurethane model

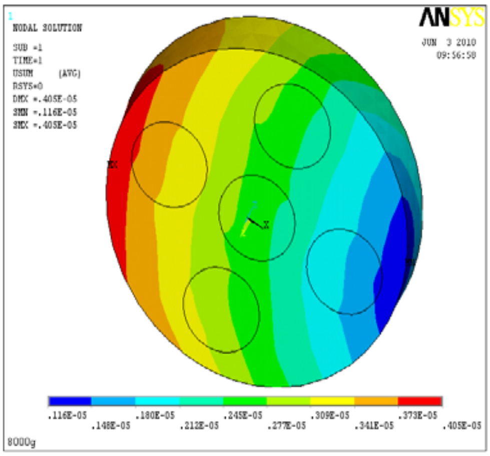

**Figure 7.** Strain cloud of composite model

The strain cloud of the composite model is shown in figure 7, from which it can be seen that the strain is like a circle distribution, and it gets smaller and smaller from left to right. The maximum strain is 0.405E-5 $m^3$, and the minimum strain is 0.116E-5 $m^3$.

The composite has the characteristics of energy absorption in its small strain range, and the main energy absorption phase is also the yield phase. This is similar to aluminum foam. The stress of composite is even smaller than that of foam aluminum, which indicating that at this time polyurethane protects foam aluminum from destroyed. At the same time the stress of polyurethane is increasing and polyurethane produces plastic deformation. Thus, it not only overcomes the shortcomings of aluminum foam and polyurethane, but also performs much better energy absorption.

### 2.3 Comparison of the energy absorption characteristics of three kinds of cushioning materials

**Table 2.** Absorption energy comparison of three materials

| Material | Min stress ($Pa$) | Max stress ($Pa$) | Min strain （$m^3$） | Max strain （$m^3$） | Absorption energy($J$) |
|---|---|---|---|---|---|
| Composite | 35183 | 0.165E7 | 0.116E-5 | 0.405E-5 | 4.67 |
| Aluminum Foam | 69451 | 244385 | 0.166E-5 | 0.655E-5 | 0.86 |
| Polyurethane | 337872 | 0.119E7 | 0.628E-7 | 0.169E-5 | 1.93 |

The paper adopted energy absorption curve method to evaluate the energy absorption characteristics, and energy absorption curve method has the advantage of reflecting the absorption performance by stress-strain curves. Comparison of absorption energy of three materials is shown in table 2, from which the following conclusions can be drawn. At the same parameters and under 8000gn shock conditions, energy absorption of composite is 5.4 times of aluminum foam, and is 2.4 times of polyurethane. When composite is impacted it begins to absorb energy, besides for energy dissipation through their foam deformation, collapse, rupture, cell wall friction and other forms, it can also dissipate part of energy by the friction between the two materials.

### 2.4 Energy-absorption-performance research on aluminum foam-polyurethane composite under different shock-cushioning conditions

The thickness of aluminum foam cushioning material is 12 mm, and 7000gn, 8000gn and 9000gn acceleration were imposed in $Z$ direction at the bottom of the model. Then the stress and strain of the model were analyzed via finite element method. It adopted free meshing modules. The paper adopted energy absorption curve method. Usually energy-absorption ability $C$ [21-23] and energy-absorption efficiency $E$ are used to charaterize energy-absorption characteristic of porous metal. Calculation method of energy-absorption ability $C$ and energy-absorption efficiency $E$ are as follows.

$$C=\int_0^Z \sigma \mathrm{d}\varepsilon \tag{1}$$

$$E=\frac{\int_0^z \sigma d\varepsilon}{\sigma_{\max}\varepsilon_{\max}} \tag{2}$$

In formula(1) and formula (2), $\sigma$ —— compression stress; $\varepsilon$ ——strain; $\varepsilon_{\max}$ ——the max strain; $\sigma_{\max}$ ——the max strain when the displacement reaches $\varepsilon_{\max}$.

Comparison of absorbing energy of different shock-cushioning is shown in table 3, from which we can see that the absorption energy under 7000gn, 8000gn and 9000gn are 2.87, 4.67 and 6.15 $J$ respectively. It means the more acceleration, the more energy it absorbs.

**Table 3.** Comparison of absorbing energy of different shock-cushioning

| Impact acceleration( m/s2 ) | 7000gn | 8000gn | 9000gn |
|---|---|---|---|
| Min stress（$Pa$） | 31049 | 35183 | 39581 |
| Max stress（$Pa$） | 0.129E7 | 0.165E7 | 0.185E7 |
| Min strain（$m^3$） | 0.364E-7 | 0.116E-5 | 0.983E-6 |
| Max strain（$m^3$） | 0.232E-5 | 0.405E-5 | 0.438E-5 |
| Absorption energy($J$) | 2.87 | 4.67 | 6.15 |

### 2.5 Energy-absorption-performance research on aluminum foam-polyurethane composite under different thickness

The thickness of aluminum foam cushioning model were 11 $mm$, 12 $mm$ and 13 $mm$ respectively, and 8000gn acceleration was imposed in $Z$ direction at the bottom of the model. It adopts free meshing modules. Comparison of absorbing energy of different thickness is shown in table 4. The absorption energy of $11\,mm$, $12\,mm$ and $13\,mm$ were 3.91 $J$, 4.67 $J$ and 4.83 $J$ respectively. It means the more thickness, the more energy it absorbs.

**Table 4.** Comparison of absorbing energy of different thickness

| Thickness （$mm$） | 11 | 12 | 13 |
|---|---|---|---|
| Min stress（$Pa$） | 35484 | 35183 | 30465 |
| Max stress（$Pa$） | 0.148E7 | 0.165E7 | 0.177E7 |
| Min strain（$m^3$） | 0.122E-7 | 0.116E-5 | 0.114E-6 |
| Max strain($m^3$) | 0.272E-5 | 0.405E-5 | 0.268E-5 |
| Absorption energy $J$) | 3.91 | 4.67 | 4.83 |

## 3. Experimental Verification

Axial compression test was carried on in North University of China. Compression samples were prepared from chunk of aluminum foam and polyurethane, they were machined into column shape. The density of aluminum foam is $365\,kg/m^3$, and the density of polyurethane is $361\,kg/m^3$.

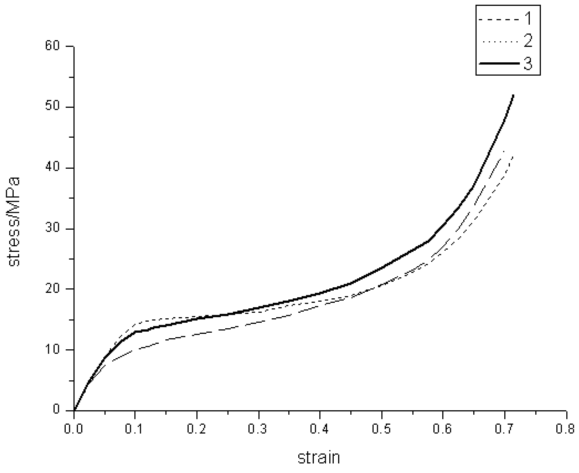

**Figure 8.** Curves of aluminum foam, polyurethane and composites material. 1-curve of aluminum foam, 2-curve of polyurethane, 3-curve of composites material.

In the computer-controlled universal tester of material mechanics, under axial static compression on aluminum foam, polyurethane and aluminum foam-polyurethane composite material, load and compression displacement were respectively gathered automatically by a computer through force, displacement sensors, load-displacement. Then according to specimen thickness and cross-sectional area, the stress-strain curves were gotten. They were shown in figure 8. During the compression phase, the stress rises slowly because the hole walls deform continuously and then strengthen. With density of aluminum foam (or polyurethane and composites material) reducing, yield phase of samples becomes more flat. With the strain increasing, the hole walls contact each other, and this results in direct contact of parent metal, and the farther compression makes the stress increase rapidly with the strain increasing. The samples then enter into the densification stage.

## Conclusion

From the paper, the following conclusions could be drown.

Firstly, aluminum foam-polyurethane composite not only has the good performance of energy absorption within small deformation which is similar to aluminum foam, but also has performance of deformation recovery when it is shocked large stress which is similar to polyurethane. In addition, it has the advantages of composite, that is to say, parts of energy are dissipated by the friction between the two materials so as to increase the absorption energy.

Secondly, on different impact conditions, aluminum foam-polyurethane composite absorbs more energy with shock increasing, and it has the function of energy absorption under 8000 gn.

Thirdly, under the same materials, the more acceleration speed, the more energy it absorbs.

Fourthly, under the same shock conditions, the thicker the composite is, the more energy it absorbs. But the model size should keep with the actual situation.

And at last, stress of composite on the $X$, $Y$ directions changes little, but the $Z$ axis (shock axis) has greater change, especially the stress in combination parts between polyurethane and aluminum foam is rather large. So in design of cushioning models these parts can be thickened or taken other measures to strengthen protection.

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