Research on the properties of aluminum foam material based on the establishment of engineering model

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Abstract—Aluminum foam material has many excellent characteristics with low density and high-ratio energy absorption. It is suitable for lightweight designs in aviation, automotive and other fields. However, the preparation process and conditions of the foamed aluminum material have an important effect on the material performance parameters. The performance parameters of different batches of products are quite different. Therefore, it brings inconvenience to material application and research. Based on a large number of material experiments, this paper studies the establishment of a finite element simulation model for foam aluminum materials. Cubic non-uniform B-Spline curve method is used to construct free-form surfaces of series materials. Unknown quantity is obtained through a large number of known parameters. At the same time, the parameter curve of the required known quantity is established. The paper provides a method for achieve the purpose of reducing the number of experiments and improving the efficiency of structural designs.

1. Preface
Aluminum foam material has many excellent mechanical properties. Open-cell aluminum foam and closed-cell aluminum foam are two main structural types. Because of their different preparation methods and structural characteristics, they have different mechanical properties and are applied in different occasions. Closed-cell aluminum foam is light and has high-ratio energy absorption. It is often used in structural lightweight designs in fields of aviation, automobile and ship to achieve weight reduction and improve anti-crash ability.

Factors including different methods, type and dosage of additives, temperature control and processing means in producing process will all cause differences in mechanical properties of the aluminum foam materials. Such instability has brought confusion to vehicle structural designers and researchers. Therefore, in this paper, a series of data about aluminum foam materials are studied and a systematic method is developed to model the performance of aluminum foam material and to define its mechanical properties.
The influences on the induction slot parameters and energy absorption characteristics were studied by Wang et al.\cite{1} when using aluminum foam materials to fill the energy absorbing box. The impact test was carried out by hydraulically impacting the test rig, and the process was simulated by Finite Element Method. In Wu et al.\cite{2} studies, 2024 aluminum alloy was produced by adding pore-forming agent, and the compressive yield strength of the material and platform stress value were also studied. The mechanical properties of aluminum foam materials under impact were analyzed in detail in Jae Ung Cho et al.'s\cite{3} studies. The influence of different oxidation voltage and time on the mechanical properties of materials was analyzed in Xu et al.'s\cite{4} studies through Micro-arc Oxidation Method. Wang et al.\cite{5} analyzed the compression characteristics of small-pore aluminum foam at low strain rate. And the conclusion was that the energy absorption efficiency is proportional to porosity. Through ANSYS Method, the deformation process of aluminum foam laminated beam was studied with the impact of bending load in Yu et al.'s studies\cite{6}. In Wang et al.'s studies\cite{7}, the compressive performance and energy absorption capacity of the tubes after high temperature, a batch of circular aluminum foam-filled galvanized steel tube components were designed and made. In Wang et al.'s studies\cite{8}, summary about the affected of strain rate sensitivity, the results show that, at high strain rate, the compressive property of closed cell foam can be affected by the detained gas. In Kang et al.'s studies\cite{9}, the LS-DYNA was used to simulate the propagation law of one-dimensional stress wave in foam aluminum and the stress wave characteristics of foam aluminum.

To sum up, the research on the producing methods, mechanical properties, finite element analysis and application of aluminum foam materials has attracted the attention of scholars at home and abroad. Until now, the related properties of aluminum foam material need to be further studied, and its application in the fields of vehicle and aviation is worthy of further study.

2. Construction of Aluminum Foam Material Engineering Model

2.1. Engineering Representation of Aluminum Foam Material Model
Closed-cell aluminum foam is composed of continuous and uneven cells. Most of the cells are round or oval, with different sizes. The specific micro-structure, shape and material properties are all affected by the producing technology. For example, the changes and fine differences in processing conditions including the type and dosage of additives and preparation temperature will all cause the micro-structure to change and then affect the material’s mechanical properties. Choose a batch of aluminum foam materials and process them through method of WEDM, and the internal structure is shown in Fig. 1. Clear cellular and cell wall structures can be seen and similar circles and ellipses of different sizes are arranged adjacent to each other. When aluminum foam is subjected to external load, the cell walls of aluminum foam support the external force. When the external load reaches the limit of the aluminum foam, the cell walls rupture. The cell walls of aluminum foam are crushed layer by layer in the experiment as shown in Fig. 2. The rupture occurs firstly in the first stressed layer, and then the cell walls rupture layer by layer. Build the simulation model of aluminum foam by using existing computer software and carry out the simulation experiment. The structure of the simulation experiment is shown in Fig. 3. The coincidence degree between the simulation crushing process and the aluminum foam test sample experiment meets the engineering requirements.
Statically compress the aluminum foam test sample with a density of 0.49g/cm³ and get a load-displacement curve as shown in Fig. 4. When the load is 29.25KN, the test sample reaches its yield limit and the first layer is crushed. When the load descends to 21.7KN, the stress of the second layer rises, and then the sample are crushed layer by layer. The structure enters a stress plateau during which the structure can be maintained at low stress for a long time and achieve more energy absorption.
According to existing computer business simulation software, the constitutive relationship of aluminum foam can be applied to the finite element model and establish a finite element model of aluminum foam structure. The agreement between the simulation model and the experimental data reaches 96.6%\textsuperscript{10}. The reason for the error in simulation and experimental data is that the structure of the aluminum foam is uneven while the simulation software constitutive model is treated by homogeneous structure. At the same time, because of the differences in producing process, some cells of the aluminum foam are not complete, so there is a certain error in simulation model and experiment, but the error value is less than 5%. The accuracy of simulation results has met the engineering requirements. In commercial simulation software, several foam constitutive models can be selected, which are respectively used in geopolyurethane foam, anisotropic honeycomb structure, anisotropic open-cell aluminum foam and other materials. The constitutive models are different from that of closed-cell aluminum foam. Therefore, the stress-strain curve must be defined in order to correct the constitutive parameters in the simulation. The variation of parameters of aluminum foam due to the differences in production process brings some difficulties to engineering application and simulation research of the materials. Therefore, it is necessary to develop a method to construct the series parameters of the same type of materials by establishing the experimental data samples according to the known parameters and fitting the unknown parameters.

\section*{2.2. Modeling Method of Aluminum Foam Material}

Take a large number of samples of different batches of products from a factory as the experimental objects and carry out basic model experiment. Input the system parameters on the basis of a large number of sample experimental data, and use the sample function, \( \{ P_{ij} \}_{i=0, j=0}^{m, n} \) to present the experimental results. In the formula, \( i \) represents the stress-strain relationship during the test; \( j \) represents material types with different porosity or specific gravity. \( \{ P_{ij} \} \) represents the test sample space of one batch of the material\textsuperscript{11}. The curve is generated by inverse calculation of control points and positive calculation of interpolation surface, and the free-form surface model is generated by Cubic Non-uniform Rational B-Spline Method. The curve shape is controlled by using the condition of multiple node endpoint. The endpoint is tangent to the feature polygon, and the node sequence is controlled by method of cumulative chord length parameterization. Carry out the inverse and positive curve calculation based on the experiment data of batches of materials and establish the data model as shown in Fig. 5. The \( X \) axis is the crushing displacement of the experimental sample, the \( Z \) axis is the density value of the experimental sample material, and the \( Y \) axis is the external load that the test sample bears.
Based on a large number of experiments about aluminum foam, the strain rate effect is not obvious in low-speed (the strain rate is 100~102/s) compression experiments. Only when the material is impacted by medium and high speed (the strain rate is 102~104/s and 104~106/s), the rupture and escape process of the air bag in aluminum foam cells results in the strain rate effect. At this time, the strain rate effect can be reflected in another free-form surface model, which is represented by the rise and fall of the load value on the Y axis.

3. Engineering Application of the Model

On the basis of experiments on batches of materials, the Cubic Non-uniform B-spline Method is used to establish the free-form surface model. The node sequence is determined by the known curve and method of cumulative chord length parameterization. When the experimental curve contains straight lines, miscellaneous points and segments, the curve can be generated by properly selecting the weight factor or taking double, triple, and quadruple nodes. The unknown load-displacement curve parameters of the aluminum foam material with known density can be obtained on the free-form surface of the material. For example, the curve shown in Fig. 6 is the load-displacement curve of the aluminum foam material with a density of 0.32g/cm3 on the free-form surface. On the free-form surface model, take the density value on the Z axis as the known value and build Plane M parallel to Plane XY. Plane M intersects with the free-foam surface, and the intersecting cut value is the unknown parameter to get.

The experimental results show that the solution of unknown quantity on free-form surface is basically consistent with the real experimental value, and the coincidence degree is over 95%. It can be proved that the method of getting unknown parameters by Cubic Non-uniform Rational B-spline Method is feasible and can be applied to the engineering application of aluminum foam materials, so as to reduce the number of experiments and save costs, and provide a method and idea for the designers of automotive aluminum foam materials.
Fig. 6 Load-displacement cubic non-uniform B-spline free curve extension model of aluminum foam material

4. Conclusion
The aluminum foam material is light in weight and has high-ratio energy absorption. It has broad market application prospects. The European Union Lightweight Alliance believes that it is the most promising lightweight material in the 21st Century and will be widely used in aviation, automobile and other fields.

The influence from the producing technology and the parameters such as the type and dosage of additives can cause differences in mechanical properties of the aluminum foam material. Therefore, a more scientific method is needed to facilitate the determination of the parameters of series materials, so as to save much experimental time and cost, and facilitate the structural process design.

In this paper, a lot of experiments and scientific verification have been carried out in research methods, experiments on aluminum foam materials, constructions of parametric curve and free-form surface, owning great accuracy and worth application. It provides convenience for the application of aluminum foam materials in automotive structural design and lightweight design, and provides a method to construct parameters of series materials.

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