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Numerical evaluation of the stacking effect of spheres on the mechanics of tailor-made aluminum foams

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ABSTRACT

The effect of different stacking of simple cubic (SC), body centered cubic (BCC) and face centered cubic (FCC) on the compressive characteristics of tailor-made aluminum foams (TMFs) was evaluated by the use of both response surface methodology and finite element technique. Quadratic polynomial models for describing the mechanical characteristics in terms of cell size (D), cell wall thickness (t) and height of cell layers (h) were developed. The statistically developed models revealed that t/D ratio has the most significant effect on the compressive characteristics of TMFs while the cell size showed a complex effect on the structural stiffness. Furthermore, despite the negligible importance of D, h is directly related to the strain hardening leading to an increase in plateau stress at higher value of t/D and h/D. Moreover, it was indicated that FCC arrangement has higher densification while SC arrangement absorb more energy during deformation.

1. Introduction

Metal matrix syntactic foams (MMSFs) were introduced as a class of composite materials in which hollow/porous spheres are embedded in a continuous metal matrix [1]. The mechanical properties and energy absorption capability of MMSFs are the decisive factors in their application as the energy and sound absorbents, collision dampers and as the material of hulls and shells in the deep-sea applications, aeronautics and automotive industries [2–4]. Many researchers have focused on enhancement of mechanical properties and energy absorption capability of MMSFs [2,5–10]. The MMSFs can effectively provide opportunities for further tailoring the energy absorbing properties of the material [11–13]. This can be accomplished by the appropriate selection of matrix and heat treatment regimen as well as the reinforcement composition, wall thickness, diameter and volume fraction [14,15].

A survey of previous literature provides some information about the modeling/simulation of MMSFs. Most of the modeling/simulation works have focused on the evaluation of elastic behavior of the MMSFs. Marur [16] studied the elastic behavior of hollow microsphere filled composite by using analytical and numerical approach; also, the influence of particle distribution on the elastic moduli properties was evaluated using 2D and a full 3D finite element method. Although his analytical and numerical results had a good agreement, there was a slight incompatibility in moduli due to different particle distribution. Bardella et al. [17] developed a micromechanical model employing finite element technique for the prediction of the effective elastic moduli of syntactic foams. Besides, Marcadon and Feyel [18] quantified the contributions of both the stacking architecture of hollow spheres and the constitutive material's mechanical properties on the mechanical behavior of metallic hollow-sphere structures under quasi-static compressive loads. In addition, Gao et al. [19] showed that the hexagonal close packed (HCP) arrangement is the best choice for the energy absorption purpose because of its highest plateau stress; however, the difference in the specific energy absorption of the various regular packaging arrangements implies the crucial role of the relative wall thickness h/R rather than packaging pattern. Santa Maria et al. [3,5,20] proposed a model based on both theoretical and experimental approaches for the prediction of mechanical properties of metal matrix syntactic foams. The main advantage of their work is the consideration of mechanical and physical properties of the matrix together with the ceramic hollow spheres and volume percentage of the hollow spheres. Moreover, Orbulov and Májlinger [21] and Antunus et al. [22] employed a multi-phase model to predict the compressive behavior of MMSFs. Their results indicated that the rigidity of the matrix is the most influential factor on the mechanical properties of the MMSFs. Also, they reported that the mechanical behavior of the samples is related to the size and volume fraction of the hollow spheres, elastic properties of both spheres and matrix and thickness of the hollow spheres.

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Despite the attempts for obtaining an adequately precise mechanical response for MMSFs by the use of various modeling/simulation approaches, almost always there is a deviation between the experimental data (obtained via mechanical testing) and the predictions which mainly stems from the non-controllable distribution of the hollow spheres inside the matrix and also, the formation of a brittle phase as a result of chemical reaction between matrix and hollow spheres. It should be noted that the mechanical properties of MMSFs are greatly affected by hollow sphere materials, geometry and distribution [14]. In addition, during the production, sphere walls might be subjected to cracking (especially in brittle spheres) due to the external pressure. The aforementioned factors lead to a decrease in mechanical properties of MMSFs and limit their application and reproducibility. Moreover, a survey of previous literature on the failure of MMSFs provides no clues as to whether any relation between the composition of matrix/hollow sphere wall and the bonding layer between them exists or not. Recently, Tailor-made Metallic Foams (TMFs) have been introduced as a new generation of MMSFs with enhanced mechanical properties and energy absorption capability due to the ordered and uniform distribution of polymeric spheres as hollow spaces [23].

The aim of the present work is to investigate and model the effect of different architectures (simple, body centered and face centered cubic) on the mechanical properties (both elastic and plastic) and energy absorption characteristics of TMFs based on finite element and statistical analysis. To this end, 3D models of different architectures were developed and studied under quasi-static compression conditions. It is also attempted to elucidate the simultaneous effect of the pertinent parameters (cell diameter, cell wall thickness and the height of the cell layers) and their probable interactions on the energy absorption and mechanical properties of TMFs based on a statistical design, namely response surface methodology (RSM). The mechanical behavior of TMFs with simple cubic stacking of spheres is modeled and then, the effect of different stacking on energy absorption capability of the structures is discussed. The developed models can be helpful for tailoring the final cell structure of TMFs based on favorable mechanical properties.

2. Experimental design for RSM

The main design parameters are illustrated in Fig. 1. The cell wall thickness and height of the cell layers were normalized by cell diameter. Fifteen runs consisting of 6 star points and 4 center points were generated based on RSM employing MINITAB software (15). To develop a second order polynomial model, a central composite design (CCD) was employed to estimate the model coefficients of the three selected factors with each factor set at its high level (+1), low level (−1) and medium level (0). The levels used for these three factors, according to a CCD, are listed in Table 1.

Eq. (1), a quadratic polynomial regression equation, was employed to estimate and predict the response value over a range of input factors' values [24]:

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} X_i X_j \quad (1)$$

in which Y is the response variable (structural stiffness, compressive and plateau strength, and energy absorption up to 50% strain), and b_0, b_i, b_{ii}, and b_{ij} are constant coefficients of intercept, linear, quadratic and interaction terms, respectively. X_i and X_j represent the variables and k is the number of these factors. The variable X_iX_j represents the first order interaction between X_i and X_j (i < j).

The analysis of variance (ANOVA) for quadratic model was performed at 5% confidence level (P-value <0.0.5). The significance and the magnitude of the effects estimations for each variable and all their possible linear and quadratic interactions were also determined.

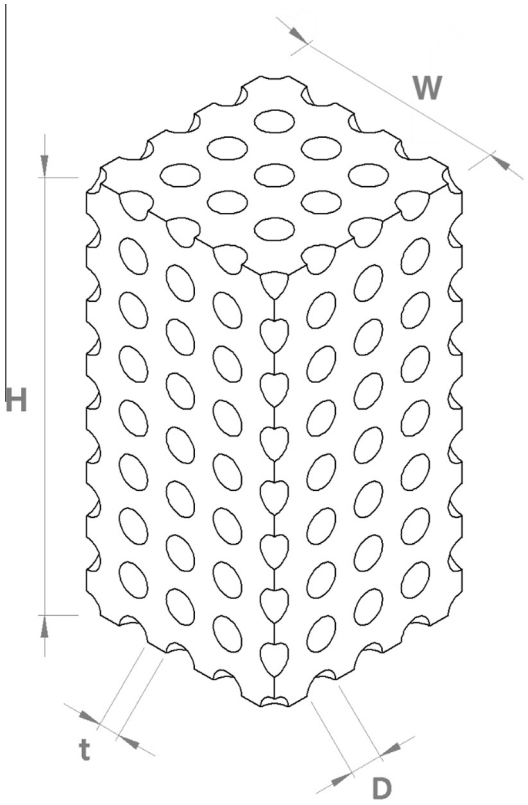

Fig. 1. The main designing parameters of tailor-made aluminum foam.

2.1. Finite element models

One eighth of Simple Cubic (SC), Body Centered Cubic (BCC) and Face Centered Cubic (FCC) stackings were considered for simulation purpose under reflective boundary conditions for different faces of the unit cells (see Fig. 2). Finite element models, consisting of 15 types of each stacking based on CCD, were produced by using commercial code ABAQUS/Explicit v.13.1. The models were designed to evaluate the effects of the geometrical parameters on the mechanical response (especially the crushing behavior) of different packing patterns. The constitutive material was elasto-plastic and homogeneous. Elasticity was considered linear isotropic and plasticity was modeled based on isotropic hardening approach using von-Mises criterion. To model a standard metallic material, different moduli of the constitutive material were regarded as: E = 69 GPa (Young modulus), υ = 0.3 (Poisson's ratio), σy = 100 MPa (yield stress) and n = 0.34 (strain hardening coefficient), respectively. The shear damage criterion was applied in the models. For the shear damage, the equivalent plastic strain at the onset of damage was considered as a function of shear stress ratio:

$$\bar{\varepsilon}_S^{pl}(\theta_S, \dot{\bar{\varepsilon}}^{pl}) = \frac{\varepsilon_S^+ \sin h[f(\theta_S - \theta_S^-)] + \varepsilon_S^- \sinh[f(\theta_S^+ - \theta_S)]}{sinh[f(\theta_S^+ - \theta_S^-)]} \quad (2)$$

$$\theta_S = \frac{(1 - k_S\eta)}{\phi} \quad (3)$$

$$\phi = \frac{\tau_{\max}}{\sigma_{eq}} \quad (4)$$