REFINED NUMERICAL SIMULATION OF THE MECHANICAL BEHAVIOUR OF HOLLOW SPHERE STRUCTURES

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ABSTRACT

Metallic Hollow Sphere Structures (MHSS) is a member of cellular metal family which have air cavities while the boundaries are made of solid metals. It offers plenty of advantages and are applicable in many fields such as automotive or architecture. In this project, two major problems pertaining sintered MHSS were studied which are porosity in sphere walls and geometrical imperfection due to contact between spheres. Finite element analysis is the only methodology used in this project. The main objective of this project is to procure the mechanical properties of MHSS by incorporating the effect of these two problems into simulations. The analysis was divided into two parts which are porosity model and sphere model. The porosity models were used to obtain the mechanical properties of base material steel by taking porosity in sphere walls into account. Two different models were generated which are PC (primitive cubic) and FCC (face-centered cubic) which act as idealised porosity. These values were then used in sphere models as the material properties for MHSS. There are two different sphere models which are the 1.6 mm and 2.6 mm model. Geometrical imperfection effect is applied in these models. The simulations were run by mimicking a compression test. Initial findings proved that Young's modulus, E, yield stress, σ_Y and Poisson's ratio, υ, change with porosity percentage. The appropriate mechanical properties for 1.6 mm and 2.6 mm MHSS were acquired and used in MHSS simulations. Simulation results showed that the material properties decrease from no porosity model to FCC model. However, the difference between simulations and experimental results are big, which means better models need to be built to obtain better results.

ABSTRAK

Struktur sfera berongga metalik (MHSS) ialah sebahagian daripada keluarga logam bersel yang mempunyai rongga udara dan dinding logam. Ia mempunyai pelbagai kelebihan and boleh diaplikasikan dalam pelbagai bidang seperti automotif dan seni bina. Dalam projek ini, dua masalah utama tentang MHSS ‘sintered’ telah dikaji iaitu dinding sfera yang poros dan ketidaksempurnaan geometri yang disebabkan oleh pertembungan antara sfera-sfera. Hanya kaedah unsur terhingga digunakan dalam projek ini. Objektif utama projek ini adalah untuk mendapatkan sifat mekanikal MHSS dengan mengambilkira kesan dua masalah yang dikaji dalam simulasi. Analisis dibahagikan kepada dua bahagian iaitu model poros dan model sfera. Model poros digunakan untuk mendapatkan sifat mekanikal bahan asas iaitu keluli dengan mengambilkira kesan poros dalam dinding sfera. Dua model berlainan dihasilkan iaitu PC (kubik primitif) dan FCC (kubik pertengahan muka) yang bertindak sebagai kesan poros yang ideal. Nilai-nilai ini digunakan dalam model sfera sebagai sifat mekanikal untuk MHSS. Terdapat dua model sfera yang berlainan iaitu model 1.6 mm dan 2.6 mm. Ketidaksempurnaan geometri ditunjukkan dalam model-model ini. Simulasi dijalankan dengan meniru ujian mampatan dalam eksperimen. Penemuan awal menunjukkan bahawa Modulus Young, E, tegasan alah, σ_Y and nisbah Poisson, υ, berubah dengan peratusan poros. Sifat-sifat mekanikal yang berkaitan untuk MHSS 1.6 mm dan 2.6 mm diperoleh dan digunakan dalam simulasi MHSS. Keputusan simulasi menunjukkan bahawa sifat-sifat mekanikal berkurang dari model tanpa poros kepada model FCC. Bagaimanapun, perbezaan antara keputusan simulasi dan eksperimen adalah besar yang menunjukkan model simulasi yang lebih tepat perlu dibina untuk mendapatkan keputusan yang lebih tepat.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Cellular solids are materials with high porosity which are divided into distinct cells [1]. The boundaries of these cells are typically made of solid polymer, ceramic or metal, while the internal regions are air cavities. Cellular metals therefore exhibit densities which are typically below 10 % of their corresponding base materials. It is similar to cellular structures that exist in nature such as bone, cork and in foods such as bread.

Cellular metals have plenty of well-known advantages such as its high ability for energy adsorption, good damping behaviour, sound adsorption, excellent heat insulation and high specific stiffness. Combination of these properties provides opportunity for potential applications such as in automotive, aviation or space-industry. However, despite more than 30 years of intensive scientific research few industrial applications of these technologies can be found. Prominent limiting factors are unevenly distributed material parameters and relatively high production costs.

Cellular metals are divided in to 6 categories which are foams, metallic hollow sphere structures (MHSS), Lattice block material, honeycombs, lotus type porous material and model structures. Lattice block materials have less variation in physical properties. These structures are manufactured by investment casting and therefore exhibit well-defined, reproducible geometry (periodic 3D truss structure). However, it does not flourish due to several factors such as high costs, limited to open celled structures and anisotropic properties caused by the microstructural orientation. Metallic hollow sphere structures (MHSS) form a new group of advanced composite materials characterised by high geometry reproduction leading towards more stable mechanical and physical properties. The MHSS combines the well-known advantages of cellular metals without major scattering of material properties.

A new powder metallurgy based manufacturing process enables the production of metallic hollow spheres of defined geometry [2]. This technology brings a significant reduction in costs in comparison to earlier applied galvanic methods and all materials suitable for sintering can be applied. EPS (expanded polystyrol) spheres are coated with a metal powder-binder suspension by turbulence coating. Depending on the parameters of the sintering process, the micro-porosity of the sintered cell wall can be adjusted. In the subsequent debindering process, the EPS spheres are pyrolysed. The increase of carbon content of the sintered metal by the diffusion of the incinerated binder and polymer causes degradation of mechanical properties but increases corrosion resistance. Special reducing processes are required to reduce this effect. The whole process can be summarised into Figure 1.1.

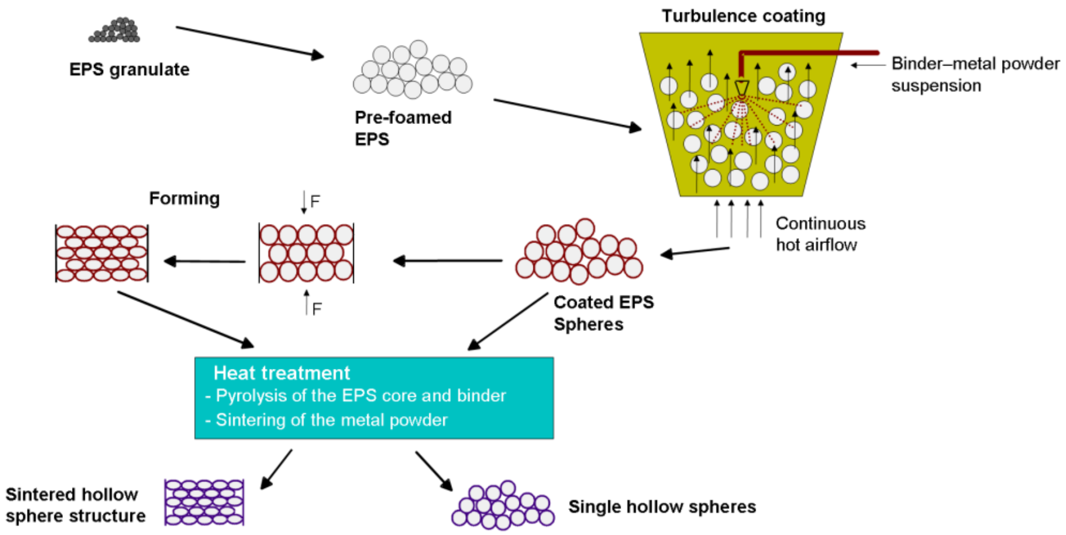

Figure 1.1 MHSS Production [2]

Various joining technologies such as sintering, soldering and adhering can be used to assemble single hollow spheres to interdependent structures. Adhering is the most economic way of joining and therefore are attractive for a wide range of potential applications. Another important advantage is the possible utilisation of the mechanical behaviour and morphology of the adhesive layer as a further design parameter for the optimisation of the structure's mechanical properties for specific applications. In the case of synthetic morphology, the hollow spheres are completely embedded within the adhesive matrix. In contrast, the adhesive is concentrated at the contact points of neighbouring spheres for partial MHSS. Consequently, partial MHSS also exhibit interconnected porosity.

However, the micrographs taken after production on the spheres reveal the existence of geometrical imperfections and porosity in the sphere walls. The contact between two spheres causes the wall to deform or creating a flat surface at the contact area. Further enhancement of the image reveals porosity in the wall. These two defects may cause major errors in simulations of MHSS. As a result, new models have to be created to take into account the effects of these two defects.

1.2 Objectives

Several objectives have been set in this project which are

- to investigate the porosity effect on the mechanical properties through idealised simulations
- to model different arrangements of spheres by taking into consideration the idealised geometrical characterisation
- to perform and evaluate elasto-plastic simulations of MHSS using the results from the porosity investigation

1.3 Scopes

Several scopes have been selected to set the boundary of this project such as

- sintered MHSS
- all arrangements (primitive cubic (PC), body-centered cubic (BCC), face-centered cubic (BCC) and hexagonal centered (HC)
- geometric imperfection and porosity are considered
- only mechanical properties such as Young’s modulus, E, Poisson’s ratio, ν
- both elastic and elasto-plastic analysis

1.4 Methodology

Only numerical analysis is used here. The overall analysis is started by creating the model in SolidWorks and saved as .STEP file. This format is chosen because everything can be exported in contrast to popularly used .IGES file which only exports the edges of a model. Meshing is done using FEMAP and the meshed model is exported to MSC. Marc for actual simulation. The results of simulations are tabulated and charts are generated.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There are three major types of cellular metals which are popular for research which are foams, honeycombs and metallic hollow sphere structures (MHSS). Among these three, metallic foams, both open and closed cells, are the most researched materials. Research scopes for cellular metals in general are normally the mechanical or thermal properties of the material. Researchers employ theoretical, numerical analysis and experiment to obtain the results but numerical analysis and experiments are more widely used.

2.2 Cellular Metals Study

2.2.1 Metal Foams

Sanders and Gibson [3,4] analysed the mechanical properties of the hollow-sphere foams with a PC arrangement which were shown to be close to the theoretical values for closed-cell foams and well above the measured modulus and strength of metallic closed-cell foams [3]. In [4], the elastic moduli and initial yield strength of BCC and FCC packings of hollow-sphere foams were analysed. In general, The FCC packing has superior properties to the BCC and PC packing. The relative elastic modulus shows large anisotropy for BCC packing while the relative elastic modulus of FCC packing is nearly isotropic. The uniaxial yield strength shows less anisotropy than the elastic properties and the tensile and compressive strengths are identical

Öchsner and Lamprecht [5] developed a periodic model of a cellular metal for the fundamental studies of the mechanical behaviour and investigated it numerically under uniaxial compression. The influences of differing hardening behaviours and differing boundary conditions on the characteristics of the materials were investigated. The use of periodic boundary condition reduces CPU computational time dramatically and reasonably good agreements with experimental results were obtained. Based on the proposed concept of a unit cell with periodic boundary conditions, it is possible to derive constitutive equations of cellular equations of cellular materials under complex loading conditions.

2.2.2 Honeycombs

Hayes et al. [6] analyzed the mechanical and thermal behaviours of extruded metal honeycombs (linear cellular alloys or LCAs). LCA is the term used to denote metallic linear cellular materials (LCM). Theoretical estimates were considered for elastic stiffness and initial plastic buckling strength for a range of simple cell shapes under in-plane (IP) compression. Both quasistatic and dynamic experiments were conducted on maraging steel square cell honeycombs processed via a novel method based on extrusion of oxide powders, followed by reduction in hydrogen to achieve the metallic structure. As a conclusion, use of LCAs as heat exchangers is promising because of the high conductivity walls, the high surface area to volume ratio, and the capability to tailor cell size and shape to optimize the tradeoff of pressure drop and heat transfer coefficient. Thermal properties and laminar flow heat transfer relations, including upper and lower bounds on the total steady state heat transfer rate are presented for a unidirectional forced flow LCA heat exchanger with square cells.

Yu et al. [7] investigated the mechanical properties of cellular metals including aluminium honeycombs and foams. The strain-rate effect and microstructural optimization of cellular metals are reported. The in-plane quasi-static and dynamic behaviour of circular-cell aluminium alloy honeycombs was investigated experimentally. The influence of impact velocity on the localized deformation mode and the plateau stress were found. The strain-rate effect and the cell-size effect on the crushing stress of both open-cell and closed-cell aluminium foams are investigated by an improved Split Hopkinson Pressure Bar method. The results reveal that the structural heterogeneity and irregularity have influence on the strain-rate sensitivity of cellular metals. The effect of multi-size cell mix and silicate-rubber filler on the mechanical properties of open-cell aluminium foams is studied. The results show that it is a possible way to improve the mechanical properties of open-cell foams by mixing multi-size cells and by filling silicate-rubber.

2.2.3 Metallic Hollow Sphere Structures (MHSS)

Fiedler and Öchsner [8] addressed the mechanical properties of adhesively bonded MHSS through finite element analysis to determine Young’s modulus and the initial yield stress dependence on the loading direction. Three dimensional unit cell models with primitive cubic arrangement were analysed for two different morphologies, namely syntactic MHSS and partially-bonded MHSS. Primitive arrangement of MHSS spheres can be considered as quasi-isotropic in relation to their linear-elastic behaviour and uni-axial initial yield stresses. This result is independent of the morphology of the structure. This conclusion cannot be transferred to other cubic symmetrical topologies but PC topology exhibited the highest deviation of the distance of spheres in the dependence on the loading direction.

Karagiozova et al. [9] modelled large deformation of MHSS when assuming point connections between the spheres based on the hypothesis of periodic repeatability of a representative block. The elastic deformations were neglected and a rigid perfectly plastic model was assumed for the base material. A structural approach using the limit analysis and the concept of an equivalent structure were then employed to describe the large plastic deformations during post-collapse process of metal hollow spheres, which undergo mainly a snap-through deformation. Stress vs. material density relationships were proposed for different strain levels in each direction of loading. The obtained results can be used to estimate the energy absorbing capacity of MHS materials under quasi-static loading. The theoretical predictions were compared with some test results and reasonable agreement is shown.

CHAPTER 3

BASIC THEORIES

3.1 Basic Theory

The theory behind the numerical analysis on the metallic hollow sphere structures (MHSS) is actually quite simple, especially on the idealised simulation of porosity, because they are 1-D analysis (on y-direction) from the macroscopic point-of-view. Other than that, only elasticity is the region of interest because the objective of this analysis is to acquire two mechanical properties which are Young's modulus, E and Poisson's ratio, υ.

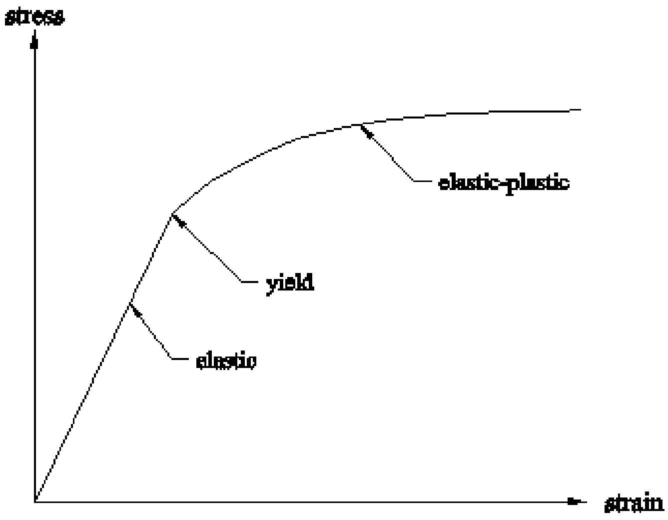

Figure 3.1 Typical stress-strain curve for metals.

The basic theory for this analysis is the Hooke's law which is given by

$$\sigma = E.\varepsilon \qquad (3.1)$$

Hooke's Law is only effective in elastic region. From the typical stress-strain diagram such as in Figure 3.1, elasticity exists along the straight line before a curve starts to develop. The point where the curve starts to occur is known as the initial yield stress where $\sigma = \Re$. The region after yield is the elastic-plastic region.

3.2 Porosity

Porosity is simply the ratio of the porous area to total area of a structure. Porosity is given by the formula

$$\text{Porosity} = \frac{A_n}{ab} \qquad (3.2)$$

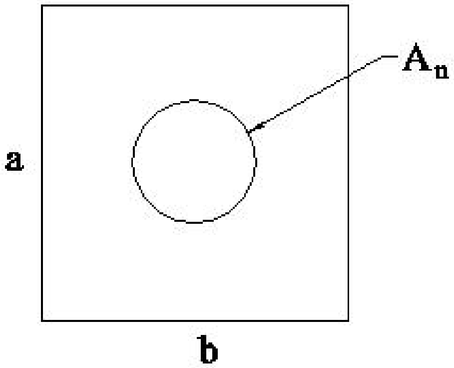

Figure 3.2 Simple porosity definition.

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