Regular Metal Foams produced by Expandable Polystyrene Technology

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Abstract

A new process for the production of a regular metal foam using polystyrene foaming technology has been developed. This technique includes a spray coating process of polystyrene spheres with a metal powder slurry. Filled in a mould the cavity between green spheres is eliminated by expansion of the polystyrene core and all green spheres transform into a polyhedron shaped structure. The subsequent heat treatment includes the debinding and sintering. Various metals and alloys can be applied for this technology.

The new regular metal foams are characterised by high homogeneity, whereas all cells are similar polyhedron with a homogeneous wall thickness in a very close tolerance. A low structural density down to 0.3 g/cm³ (for steel) can be achieved. This new structures have a very high stiffness per weight ratio.

The paper presents details of the technology and estimations of the mechanical properties of the cellular structure.

Introduction

Many natural structures are designed for highest specific strength and stiffness (bone, bamboo, …). Material is only used where it is needed for the optimum of strength and weight. Weight reduction can be attained by the presence of pores. To learn from nature and copy the principles of material design is one the main interest for metallic cellular structures.

Honeycombs and metal foams are examples for metal structures with high porosity. A good review of cellular metals and their production methods is given by various authors [1-3].

A classification of cellular metals by physical condition of the source material (solid, liquid, vapour) followed by classifying the condition of materials in the process and processing details is given by Banhart [1] and Wadley [2]. Four techniques starting from solid phase with metal powders are specified.

- Hollow sphere structures made of hollow metal powders
- Ultramet (template coating and sintering)
- Alulight (foaming process by particle decomposition)
- LCD-panel (gas entrapment after consolidation and hot rolling)

To the above-named processes the technologies for metal-hollow-spheres (MHS), MHS-structures and closed cell structures shall be added. These technologies are developed by Fraunhofer-Institute IFAM-Dresden and are based on a spray-coating process of an organic substrate followed by a debinding and sintering procedure [4]. Because of the powder-metallurgical-based technology many metals and alloys can be handled. Parameters and characteristics of cells and cell-walls can be tailor made. The cell-size can be changed between 0.5 mm – 10 mm, the wall thickness between 10 µm – 1000 µm. The morphology of the cell-wall-surface can be influenced by the powder, the coating procedure and sintering parameters. Independent of material a relative density of 0.03 can be obtained. The important properties are:

- low density,
- diversity in material
- deformation behaviour,
- high specific strength and stiffness (steel, steel-sandwiches),
- corrosion resistant (stainless steel) also at higher temperature (up to 1000°C),
- high temperature strength (steel, molybdenum, tungsten),
- sound absorption,
- good flowability through the MHS-structures,
- high electric conductivity (cupper),
- thermal insulation,

Many potential combinations of properties are possible. The properties of MHS and MHS-structures are well investigated [5-7]. Investigation of the new closed-cell-structures is under development.

Basics and Technology of the new regular closed cell structure

Polystyrene foam parts as packing is known and widely used. Expandable polystyrene spheres (EPS) are made by pre-expansion process of polystyrene granules. The granules are produced by polymerisation of styrene. To achieve the final shape of packing-parts the pre-expanded EPS is expanded in special tools. It is fundamental that EPS contains pentane, which is needed for expansion and dissipates in the foaming process.

EPS is a mass-product and used as substrate for production of hollow spheres [4, 7]. For the production of the regular closed cell structures the technologies for MHS and for EPS-foam-parts are combined.

Compared to the hollow-sphere-technology [4] for the new technology EPS-spheres with residual pentane are used as substrate. The metal-powder-suspension containing the organic binder and metal-powder is sprayed on the styrofoam spheres. Coated spheres are dried during the same unit operation by counter flow heated air in fluidized bed and the green spheres are received [4, 8].

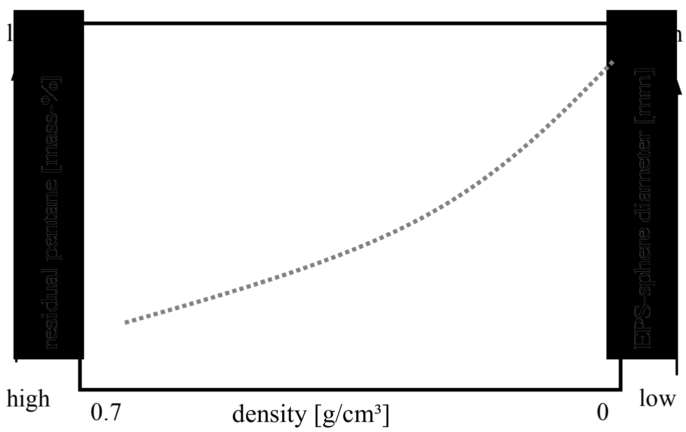

Fig. 1 Interdependence of diameter, density and residual pentane of EPS-sphere

The basic requirement for the new technology is that residual pentane, density and diameter of spheres are interdependent (fig. 1). If density decreases diameter increases and residual pentane decreases.

Using the mentioned dependence of parameters it is possible to control residual pentane and thereby the power of expansion. Starting from a random close packing of coated spheres in a mould and activating the foaming process the closed cell structure will be built up by removing the interspaces between the spheres. The polystyrene core expands and green spheres transform into polyhedrons. The subsequent heat treatment includes the debinding and sintering.

Description of Structure

After the expansion process of all single spheres in the mould every sphere builds one cell which is a polyhedron or polyhedron-like. Number of faces of each polyhedron is determined by adjacent spheres. The coating has to tolerate up to 50% of permanent elongation. Only a special developed metal-powder-suspension is able to achieve these requirements. Cell walls evolve from the coatings of contiguous green-spheres. Thickness of green-cell-walls is twice as much as the sphere-coating and has homogeneous thickness over all. Cell-dimension may be controlled by EPS-substrate selection. Spheres in the range of 1 mm up to 6 mm in diameter are available. The statistical spread of cell-volume depends on the statistical spread of substrate-diameter.

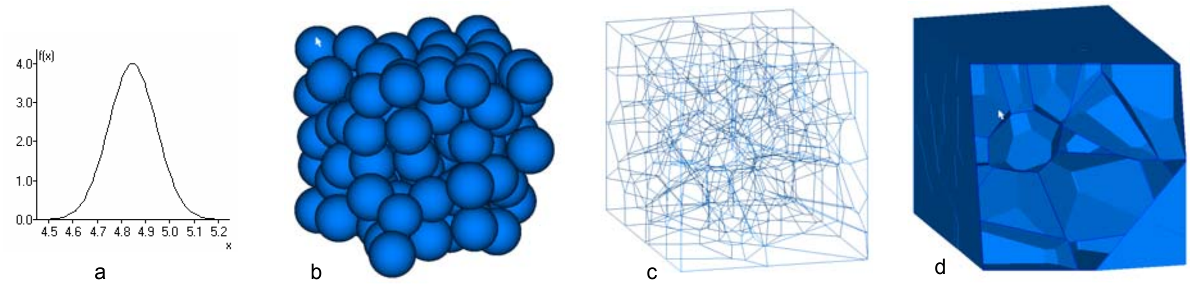

Fig. 2 Gaussian distribution (a) of the spheres in a virtual box (b), description of the Voronoi polyhedron (c, d) (figures a-d [9])

Green-spheres can fill the cavity of tool approximately with 63% of volume. If all spheres expand at the same time, with the same expansion power and rate and if expansion stops when surfaces of spheres come into contact the structure of cells is exactly that of voronoi polyhedron. Thereby an exactly mathematical description of macroscopic structure exists and modelling of properties should be possible.

It is important to observe properties of the green spheres like packing order, properties of coating (thickness, ductility, elasticity) and thermal field in the cavity to achieve an accurate closed-cell-structure.

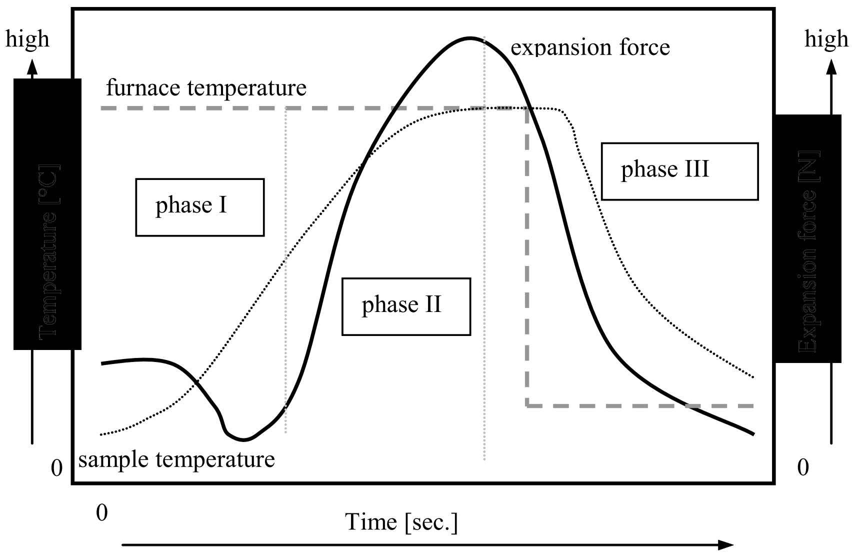

Fig. 3 Temperature time and expansion force of the foaming process in principle

Experiments

Examinations are carried out on coated and uncoated pre-expanded sieved EPS-spheres. Constituents of the metal-powder-suspension are polyvinylalcohol, dispersing and defoaming agent as well as the 316L-powder or carbonyl-iron powder.
The pre-expansion of substrate will be controlled by time under a given float rate and temperature. If time increases sphere diameter increases too. Every fraction in diameter has a characteristic density and as mentioned above a defined residual pentane proportion.
Evaluating the expansion behaviour of EPS is of basic interest to control the expansion-process of green spheres.
EPS-spheres or green spheres were filled into the tool. The expansion process of the EPS was activated by tempering in a furnace. Temperature was measured in the furnace at the sample surface and at the centre of the sample. The power of expansion was measured in one dimension by using a resistor sensitive to pressure (fig. 3). After removing the green foamed-parts from the tool the accuracy to reproduce the shape of the tool on the foamed-parts has to be characterised. Debinding of all samples is done under argon-hydrogen atmosphere. The styrofoam core and the binder are burned out during pyrolysis. All samples are sintered under hydrogen (316L: 1250°C, carbonyl-iron: 1120°C).

Results

As shown in figure 3 there are 3 steps within the foaming process. Phase I is a reduction of force because of substrate-softening as a result of increasing temperature. Phase II is the foaming procedure where temperature continues to rise and the measured foaming force increases. The Phase III is the cool-down phase where temperature and force decrease.
The foaming of substrate ends spontaneously after exceeding the maximum in force. This is the point in time where cooling have to start to stabilize cells and cell-walls and prevent collapse of cells.
To achieve high accuracy in replication of tool-shape the proportion of residual pentane is important.

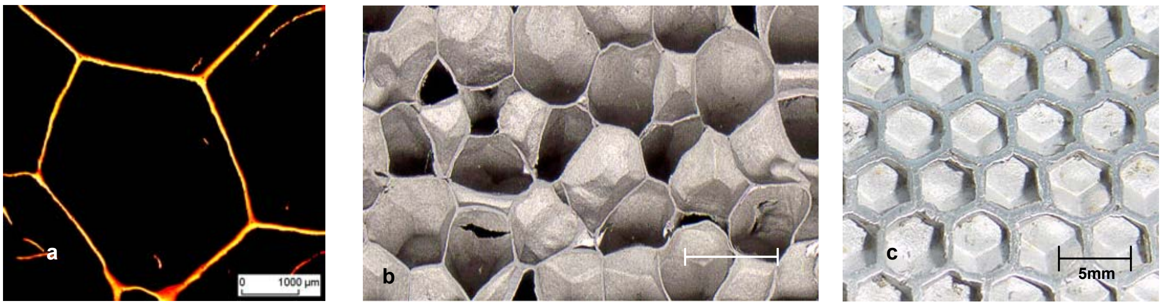

Fig. 4 Sintered closed cell structures: micrograph of single cell 316L (a), disorders structure 316L (b) and ordered structure low carbon steel (c)

The main parameters of the substrate are density and order of sphere-packing, proportion of residual pentane, input of energy, and properties of the coating.
Measuring of foaming force is important to observe and control the foaming procedure.
Experiments with coated substrate show two main problems:

- The shape of the tool was not accurately reproduced by the foamed substrate because of expansion force was too low. Substrate with higher proportion of pentane should be used.
- There were defects in cell walls observed. This was because of inhomogeneity in substrate. Selection of EPS and exact controlling of coating procedure are main factors to diminish these defects.

Fig 4a shows a micrograph of a single cell. Microporosity of cell walls is in general lower than 10 vol. %, but lower than 5 % can be reached as well. The ordered (Fig. 4c) and disordered (Fig 4b) structures can be produced in laboratory scale.

Mechanical properties of the regular closed cell structures

In the following all presented results are investigated at disordered MHS-structures where cell arrangement is stochastic. Mechanical properties of MHS-structures and also for the closed cell structures are mainly influenced by

- material of cell-walls
- ratio of wall-thickness (d_w) and sphere diameter (D) (cell-volume)
- microporosity of cell-walls
- fraction of open porosity between spheres (MHS-structures)

The MHS-structures show a homogeneous plateau up to high value of compression-strain in stress-strain-curves of compression tests. Further on an isotropic deformation behaviour was scientifically proven [5, 7]. Strength of cellular materials depends mainly on structural density. For MHS-structures it is possible to increase the density for a constant ratio d_w/D by decreasing the volume of open porosity between the spheres. This can be obtained by additional compression of the same green spheres. Thereby the contact between spheres growth and plane contact areas are built and density increases (fig. 5). Another important effect of this structural modification is the change in stress-strain-curves as shown in fig. 5a.

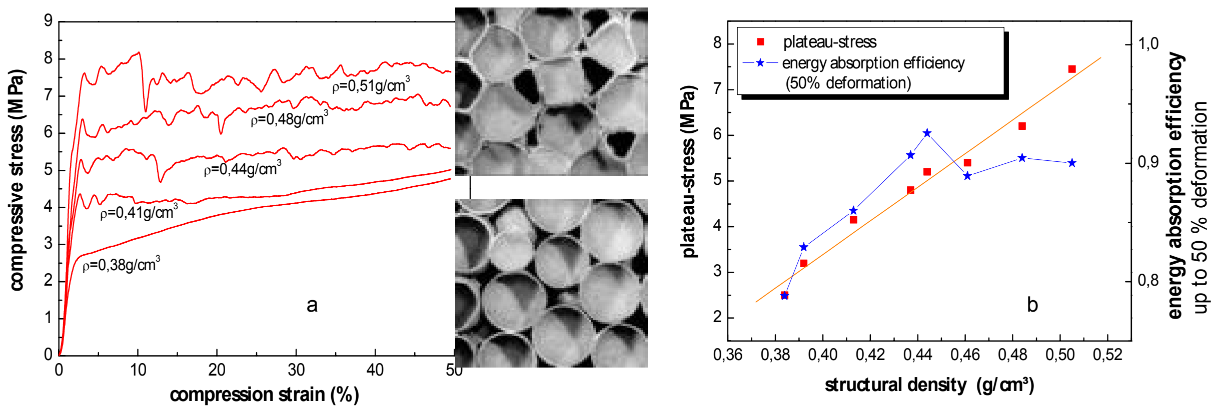

Fig. 5 Compressive stress-strain-diagram (a), plateau-stress and energy absorption efficiency (b) for different MHS-structures made of the same green spheres; sintered low carbon steel.

With increasing density the plateau-stress and discontinuity in stress-strain-curve are increasing. The energy absorption efficiency shows a maximum for a density of 0.45 g/cm³ and a value of 93% is obtained (fig. 5b). The mentioned discontinuity in stress-strain-curves supposed a change in deformation mechanism. On MHS-structures with point contacts between spheres bending of sphere walls is overbalanced however reducing open porosity between spheres (plan contact areas between cells) buckling of the cell walls (plan areas) becomes more important. For closed cell structures the buckling predominates. Buckling occurs at higher value of stress than bending of sphere walls hence elastic modulus increases and for the closed cell structures highest values can be achieved. It should be mentioned that honeycombs have the highest specific strength and stiffness only in two dimensions but the presented closed cell structures have three-dimensional honeycombs and hence properties are isotropic.

It is difficult to estimate the elastic modulus because it is not only depending on material and pore volume but rather on cell-design. Many models for calculation of elastic modulus for cellular and porous materials are known [10] and it is under current examination to verify models for this new closed cell structures.

Summary and conclusion

A successful production of the new regular closed cell structures by polystyrene expansion technology was demonstrated. Description and modelling is possible by adapting Voronoi polyhedrons. The experiments at MHS-structures show the influence of cell structure on mechanical properties. For the closed cell structures higher values in strength and elastic-modulus are expected than for MHS-structures. The presented closed cell structures have three-dimensional honeycomb-like-cells and hence properties are isotropic and exhibit high specific strength and stiffness.

Cell volume, cell-wall thickness, micro-porosity of cell walls, surface roughness and material determine the structural density and properties of the structure. If choosing the parameters carefully many properties can be adjusted and high values in strength and stiffness are obtainable.

The developed powder metallurgical process for the described regular metal foam can be applied to most of the metals and alloys.

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