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Forging of metallic foams to reproduce biomechanical components

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Abstract

In this study an analysis of the forging process of a simple-shaped metallic foam billet was carried out using both experimental trials and mathematical models in order to obtain a 3D geometry of the complex form.

In particular, the deforming behaviour of a metallic foam and the development of density gradients were investigated through a series of experimental forging tests in order to produce a selected portion of a hip prosthesis. This type of replacement for human bone was chosen as object of study due to its elevated commercial demand and its particularly complex 3D shape. A commercial finite element code (Deform 3D®), with an accurate rheology of the material, was utilized to model the foam behaviour during the forging process. The code for the rheology of the material is considered using a model valid for porous materials which also includes a measure of local density. The usefulness of the model used was verified by the comparison of the predicted results (the force necessary for the completion of the forging process and the final shape obtained) and the experimental evidence.

Keywords: Aluminium foams; Hip prosthesis; Forging

1. Introduction

Metallic foams represent one of the most interesting materials introduced to the manufacturing field in the last years. Their lightness, good degree of insulation and elevated mechanical strength are the keys to their success in the near future even though some problems will have to be overcome, such as high production costs, manufacturing complexity (especially in the production of particular shapes) and lack of know-how for secondary applications such as for panels or billets.

However, due to their unique properties, metallic foams could be useful in a number of potential applications including filters, heat exchangers and energy absorbers [1–3].

A range of alloys used in the engineering field, such as aluminium, iron, nickel, copper and titanium can be foamed to obtain a relative density – to a minimum of 3% – thanks to a variety of manufacturing technologies [1,4].

Among the above-mentioned materials, aluminium foams are of current interest in many industrial applications [5–8] and, they have recently gained popularity in transport (aerospace, ship building, etc.) and biomedical industries [5], and also in the construction of sports facilities, due to their effective cost, high specific stiffness and good resistance to corrosion.

Several studies on metallic foams were recently presented and published in various conference proceedings [9–14].

Some papers focus on the mechanical properties of both cellular materials and metallic foams [15–18]. Other papers describe aspects related to production and the possible applications of such materials [19,20].

Vice versa, a few studies were carried out to investigate either the behaviour of metal foams following plastic deformation processes [21,22] or the estimated ability of a model which the finite element shows as far as the study of secondary operations for this type of material [23–28] is concerned; in any case, different approaches to describe the behaviour of metallic foams by the finite element method (FEM) have been proposed.

In particular, Hujcko and Faria [29] used a visco-elastic model, simplified for finite elements (FE) to represent the mechanical behaviour of cellular materials.

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Moreover, several authors [30,31] have used models for the foam from a micro-structural point of view. More specifically, the "multiple cell FE" model was analyzed using the explicit LS-DYNA FE code and the Belytschko–Tsay shell elements with reduced integration, hourglass control and self-contact option.

However, there is a considerable lack of knowledge in the characterization of the macroscopic behaviour of foams, especially when 3D complex shapes are considered.

For this reason, the aim of the present study is to investigate the effectiveness of mathematical modelling when compared to experimental evidence; to do this, a portion of a commercial hip prosthesis was considered to carry out both the estimation of the registered punch load and the final shape of the forged component.

Such comparative variables were obtained through an experimental analysis of the forging process. Furthermore, the change in density at different time intervals of the process was investigated to obtain a complex forged shape.

2. Industrial case study: hip orthopaedic prosthesis

Since the first known case of total hip replacement in Germany (1938), numerous implants have been designed and introduced into the orthopaedic prosthesis market.

Usually, they are mainly made of titanium and its alloys due to their lower Young's modulus, higher biocompatibility and better resistance to corrosion [32].

Nevertheless, there are several unresolved technical problems associated with the use of titanium as an implant material. In particular, the bioinert characteristic of its protective surface oxide does not readily form a strong interface with surrounding tissue.

Furthermore, the relatively high stiffness of titanium, compared to the surrounding human bone, can lead to stress-shielding problems and subsequent implant malfunction/loosening [33].

For this reason, the introduction of titanium foams as implant material could be an important improvement since the pores present in the material produces a substantial reduction in stiffness; as a general rule, stiffness decreases with the square of relative density [34,35].

From this point of view, it would be very useful to investigate "crush density" changes during a process of flowage.

The actual intention is to obtain a prosthesis characterized by a Young's modulus close to that of human bone in order to avoid the currently diffused problem of implant loosening, which tends to slide off the bones.

A suitable density gradient of the manufactured part can be obtained by using a proper "forging" process during which the initial volume and the density of the billet varies according to the matrix shape and its progression [36]. Thus, an innovative approach can be developed by using foams as materials instead of solids to manufacture biomechanical parts that have the same density and stiffness of natural bones.

The optimal materials to be used are obviously titanium alloys or stainless steel. Unfortunately, foams obtained from such materials have been unavailable up to now on the worldwide market, although there are several studies oriented towards the production of titanium foams [4]. This study was carried out using aluminium foam even if, as reported above, this alloy is not biocompatible and will never be used to produce bone replacements. However, the flowage mechanism allows for the acquisition of a more general methodology that, in the future, could be extended to other materials more suitable for implant manufacturing for humans.

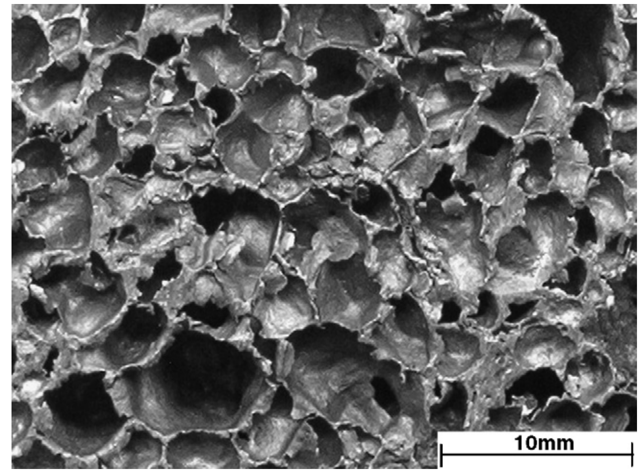

Fig. 1. The structure of the worked aluminium foam.

More in detail, for the present study an Aluligh® foam was selected. It is an Al6061-O foam containing 1% magnesium and 0.6% silicon (UNI AlMg1Si0.6); this material is available in cylinders with a relative density ranging from 0.1 to 0.4. Pores have several shapes with different sizes, which are generally closed, having an equivalent diameter from 0.5 to 5 mm (Fig. 1).

3. Investigated problem and experimental equipment

The hip implant is characterized by highly varied mass distribution along its axis, as can be seen in Fig. 2.

The portion of the prosthesis investigated was selected according to the research on fatigue failure of hip–bone implant

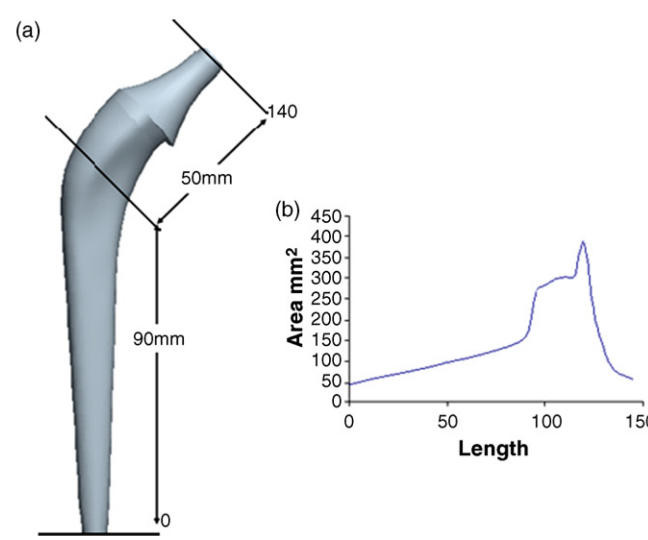

Fig. 2. (a) Commercial hip; (b) material distribution along the hip axis.