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Geometry anisotropy and mechanical property isotropy in titanium foam fabricated by replica impregnation method

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ABSTRACT

Polyurethane (PU) foams have both geometry and mechanical property anisotropy. Metal foams, which are manufacturing by investment casting or melt deposition method and using PU foam as a template, also have mechanical property anisotropy. This work studied the mechanical properties in two directions of titanium foam with four different cell sizes fabricated using the replica impregnation method. The two directions are (1) the loading direction parallel to the foaming direction where the cells are elongated (EL direction) and (2) the loading direction perpendicular to the foaming direction where the cell are equiaxed (EQ direction). The results show that the compression responses for both EL and EQ directions are isotropy. Micrographs and X-ray micro-computed tomography show that the degree of geometry anisotropy is not strong enough to results in mechanical property anisotropy.

1. Introduction

Reticulated polyurethane (PU) foams are processed using reaction of chemicals, which are carried along a conveyer belt for continuous production. This is followed by the peeling of parallelepipedic PU foam blocks to obtain a periodic variation of the open-cell structure [1]. The chemical reaction causes foaming in the vertical direction, hence the cells are elongated in the foam rising direction and thus geometrically anisotropic. Mechanical property anisotropy is also confirmed by experimental and modelling of open-cell PU foam [2]. The compression strength and stiffness of PU foams loading in the foaming direction is higher than in the rolling direction or the transverse direction [3,4]. X-ray micro-computed tomography (μCT) of PU foam shows that cell anisotropy decreases with a higher apparent density [3,4]. In addition, mechanical property anisotropy decreases as the aspect ratio of cell decreases and becomes indifferent as the aspect ratio of cell is less than 1.2 for PU foam [3].

Metal foams can be manufactured by many methods. Open-cell aluminium foam (e.g. Duocel® and m.pore®) are produced using investment casting with PU foam as a template, while nickel foam (e.g. Incofoam®) uses melt deposition on PU foam [5]. Both metal foams have perfect replica of PU foam template, hence geometry and mechanical property anisotropy are expected to present and have been reported, for example, for aluminium foam [6,7] and for nickel foam [1,4]. The load bearing capability of aluminium and nickel foam loading in the direction parallel to the foaming direction is higher than those loading in the traversed direction [1,4,6,7].

For titanium foam, powder metallurgy is the common manufacturing process. Open-cell titanium foam with low to medium porosity can be produced by powder space holder technique [8–10]. Although the powder space holder might initially be relatively equiaxed, if the preforms are compacted or hot pressed, pores in metal foam will be elongated perpendicular to the compaction or pressing direction because the powder space holder became flatten [10,11]. This results in geometry anisotropy and effectively mechanical property anisotropy after sintering. For titanium foams fabricated using compaction with powder space holder technique, the titanium foams are slightly stronger perpendicular to the compaction direction and slightly weaker along the compaction axis [9]. The difference in mechanical property anisotropy increases as the degree of geometric anisotropy increases for metal foams [1,12]. On the other hand, if the performs are formed using metal injection moulding method, pores in metal foam will remain equiaxed [13].

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Titanium foam can also be fabricated by replica impregnation method. For this manufacturing method, a PU foam is used as a sacrificial template. PU foams are dipped in titanium slurry and subsequently burnt out. Titanium powders were then sintered. Titanium foams should replicate the structure of corresponding PU foams. There is no previous report on the geometry and mechanical property anisotropy of open-cell titanium foam fabricated by replica impregnation method.

Since PU foams have both geometry and mechanical property anisotropy, the objective of this work is to investigate if titanium foams retain both geometry and mechanical property anisotropy. Titanium foams with four different cell sizes were produced and monotonic and interrupted compression tests were carried out using titanium foams in two different loading directions.

2. Experimental procedures

2.1. Titanium foam preparation

Argon gas atomised commercially pure (CP) titanium powder was used in this work. From SEM observation, the powders were spherical [13]. Table 1, which shows the chemical composition of the CP titanium powder and traces of Fe, H, N, C and O were observed. Manufacturer's specification of powder size was $< 45\ \mu m$. From a powder size analysis, the measured average powder size was $22.94\ \mu m$ (D_{50}). The measured density of the powder was $4.49\ g/cm^3$. In this work, a thickening agent was Polyvinyl alcohols (PVA) and a dispersing agent was Dolapix. 4 wt% PVA in aqueous solution has the viscosity of 25–31 cP at 20 °C. Dolapix contains carboxylic acid solution with approximately 65% active matter.

To prepare titanium slurry, PVA and Dolapix, were dissolved in water using magnetic stirrer at 90 °C for 90 min and CP titanium powder was subsequently added and mixed at 90 °C for 10 min using an electronic mixer. The mixing ratio of titanium slurry was 75 wt% of titanium powder, 1.5 wt% of PVA, 1 wt% of Dolapix and balanced by water. The effect of each component on the rheology properties was previously studied and the mixing ratio used here is the optimum from previous investigation [14].

Reticulated PU foams as a sacrificial template was submerged into homogenisedly mixed titanium slurry. Four different cell sizes of PU foam, which were 25–40 ppi with an increment of 5 ppi, were used. 'ppi' is pore per inch and it is a unit for cell size measurement, which is commonly used in PU foam industry. In this work, polyester-based PU foam was used because it does not react with titanium powder during processing [15]. Subsequently, excess slurry was removed from PU foam coated with titanium slurry by compression. After at least 24 h air drying, PU foam coated with dried titanium powders, which is commonly called 'green titanium foam', was debound and sintered. The debinding condition was 600 °C for 2 h with the heating rate of 1 °C/min to remove any organic contents, i.e. PU foam, PVA and Dolapix. The sintering condition was 1150 °C for 2 h under high vacuum of less than 10^{-3} Pa.

2.2. Compression tests and characterisation

Compression samples have cylindrical shape with a diameter of 15 mm and a height of 18 mm. Compression samples were wire cut from sintered titanium foam in two direction perpendicular to each other as shown in Fig. 1, which are (1) the axial direction of a cylinder (the loading direction) parallel to the foaming direction and (2) the axial direction of a cylinder perpendicular to the foaming direction. It is noted that in the commercial production of PU foam, the vertical direction is a non-constraint direction, where the foam can rise due to chemical reaction. This vertical direction is called the foaming direction. As a result, reticulated cells will tend to be elongated in the foaming direction as shown in Fig. 2(b) and equiaxed perpendicular to the foaming direction as shown in Fig. 2(a). The first group of samples with the axial direction of a cylinder parallel to the forming direction had elongated cells bearing the compression force and this was named EL samples. The second group of samples with the axial direction of a cylinder perpendicular to the foaming direction had equiaxed cells bearing the compression force and this was named EQ samples. In addition to monotonic compression test, interrupted compression tests were also performed. At each 1 mm increment in displacement, the test was stop and the cross head was retreated so the cross head was reloaded for the next increment. EL and EQ samples were subjected to monotonic and interrupted compression tests with a constant speed of 1 mm/min and were repeated 4 times for each set of experiment.

Microstructures were investigated using three dimensional optical microscope (3D-OM) and scanning electron microscope (SEM). From 3D-OM micrographs, average cell sizes can be determined using image analysis software. It was done by in a similar way to that which the PU foam manufacturer uses to determine the cell diameter of PU foam. Details of the procedures can be found in [16]. Each average cell size was determined from at least 150 representative cells. In addition, an apparent density of titanium foam was determined as the averaged valued of density measured from mass divided by overall volume for each titanium foam sample. A relative density could then be determined from the ratio of an apparent density to the bulk density. For SEM analysis, the acceleration voltage was 10 kV, the working distance was 5–7 mm, and the emission current was $70\ \mu A$. Chemical compositions were also analysed using XRD. Small titanium particles were prepared by grinding the sintered titanium foams together with liquid nitrogen. The analysis parameters for 2θ–θ method XRD were 50 kV and 300 mA. A combustion technique was used to determined carbon and oxygen contents of sintered titanium foam.

Table 1
Chemical compositions of commercially pure titanium (wt%).

Fe	H	N	C	O	Ti
0.033	0.005	0.009	0.005	0.113	Balance

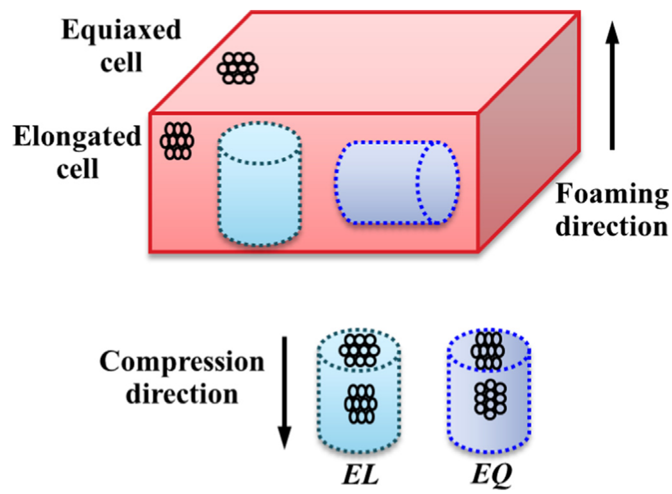

Fig. 1. A schematic diagram of titanium foam sample, which indicates the foaming direction of PU foam, where the compression samples were selected and the cell structure of titanium foam with respect to the compression direction.