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A new numerical modelling method for deformation behaviour of metallic porous materials using X-ray computed microtomography

M. Doroszko*, A. Seweryn

Department of Mechanics and Applied Computer Science, Faculty of Mechanical Engineering, Bialystok University of Technology, 45C Wiejska, Bialystok 15-351, Poland

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ABSTRACT

Microtomographic devices have limited imaging accuracy and are often insufficient for proper mapping of small details of real objects (e.g. elements of material mesostructures). This paper describes a new method developed to compensate the effect of X-ray computed microtomography (micro-CT) inaccuracy in numerical modelling of the deformation process of porous sintered 316 L steel. The method involves modification of microtomographic images where the pore shapes are separated. The modification consists of the reconstruction of fissures and small pores omitted by micro-CT scanning due to the limited accuracy of the measuring device. It enables proper modelling of the tensile deformation process of porous materials. In addition, the proposed approach is compared to methods described in the available literature. As a result of numerical calculations, stress and strain distributions were obtained in deformed sintered 316 L steel. Based on the results, macroscopic stress-strain curves were received. Maximum principal stress distributions obtained by the proposed calculation model, indicated specific locations, where the stress reached a critical value, and fracture initiation occurred. These are bridges with small cross sections and notches in the shape of pores. Based on calculation results, the influence of the deformation mechanism of the material porous mesostructures on their properties at the macroscale is described.

1. Introduction

Metallic cellular materials have reached development maturity in terms of stability of the production process, mechanical properties and costs required for industrial applications [1]. They are characterised by mechanical properties that makes them suitable for a wide range applications in industry. They are used mainly in the aerospace, automotive and medical industries [2]. A porous 316L stainless steel is applicable, *inter alia*, for the production of biomedical implants [3]. Metallic porous biomaterial, which is produced by powder metallurgy (sintering), reaches Young's modulus values similar to bone, thereby providing improved biocompatibility [4]. An important factor for bone growth is also appropriately adjusting the stiffness and strength of the implant to the bone preservation [5]. The next advantage of the porous material, as compared to the solid, is the ability for bone tissue ingrowth inside of implants, which thereby forms a durable bone-implant connection and does not allow for the loosening of implants [6].

Modelling and simulation methods have made significant contributions to the understanding of the mechanical properties of cellular materials in connection with their structure [7]. Determination of the relationship between structure and properties of cellular materials is difficult due to complex three-dimensional structure [8].

One major problem in modelling of the deformation process of porous materials is reconstruction of the real spatial shape of the porous mesostructure. Often these are complex shapes characterised by high heterogeneity. For this reason, it takes many attempts to recreate them. Methods available in the literature can be divided into two approaches. One of them assumes an as great as possible simplification of the cell geometry. In this case, the use of appropriate boundary conditions (symmetric, periodic boundary conditions) allows for the determination of the material behaviour under load on a macroscopic scale based on analysis of the representative cell [9]. This is frequently also applied as a multi-scale approach using homogenisation [10,11]. This results in relatively simple calculation models. Cecot and Oleksy [10] studied the high order finite element method (FEM) applied to the multigrid based homogenisation. Furthermore, Romanowicz [11] predicted the failure behaviour of angle-ply laminates under tensile loading from the mesoscale models. The second, more complicated and comprehensive approach, consists of an as accurate as possible

* Corresponding author.
E-mail addresses: m.doroszko@pb.edu.pl (M. Doroszko), a.seweryn@pb.edu.pl (A. Seweryn).

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reproduction of the real morphology of the pores. These methods can be divided into two groups. In the first one the mapped shape is made on the basis of the obtained porosity distribution; then, by applying the appropriate calculation procedure representative geometric models are generated. Recently geometric models were created based on: fractal analysis [12], Voronoi tessellations [13], distance and level set functions [14], modified phase-recovery algorithms [15] and set up of morphology parameters [16]. The work of Pérez et al. [12] presented a fractal finite element model in order to analyse the effect of the porosity on the elastic compressive behaviour of metallic foams. Xiao and Yin [13] used geometries based on Voronoi tessellation to build simple random porous structures and characterised the porosity-permeability relations of these geometries. Methodology for generation of representative volume elements (RVEs) for cellular materials based on distance and level set functions was presented by Sonon et al. [14]. Hasanabadi et al. [15] developed a new method for the three-dimensional reconstruction of a microstructure from limited statistical information provided by cross sections. Zieliński [16] proposed a relatively simple method for a random generation of periodic microstructures representative of open cell foams with spherical pores dedicated for sound absorption. Despite the wide range of opportunities offered by these methods, the most accurate representation of the real shape of heterogeneous mesostructures are obtained by the methods belonging to the second group. Their essence is to recreate the shape based on cross sectional images of the studied materials. One of the approaches is the serial sectioning method [17]. Chan O′Keeffe et al. [17] employed the serial sectioning method to microstructural reconstructions of steel crack tip and implemented into a large-scale simulation for ductile fracture analysis. The method consists of recording the images of the material cross sections, usually by using various kinds of microscopes. After recording the image the sample layer is ground and the next surface information is acquired. The number of made sequences depends the number of cross sections from which the cell structure will be recreated. Taking into account the time consuming nature and the difficulties related to making further images, the method has limited application. For this reason, the most commonly used method of mapping heterogeneous shapes of the cellular materials is method based on computed microtomography. In recent years, research was conducted on numerical modelling of mechanical properties based on microtomographic images of various porous materials. Mostly these were metallic cellular materials: aluminium [18], nickel foam [19], porous titanium [20], metallic syntactic foams [21], Advanced Pore Morphology (APM) foam [22] and sintered metal fibres [23]. Veyhl et al. [18] investigated the macroscopic mechanical properties of closed-cell Alporas® foam and open-cell M-Pore® sponge. The compression behaviour of a Ni-foam under various strain rates, employing the exact foam geometry based on micro-CT, was presented by Michailidis [19]. In their paper, Fiedler et al. [20] described finite element modelling combined with microtomography in order to accurately capture the complex geometry of a porous titania scaffold coated by poly(D,L-lactic acid). Mechanical anisotropy of the compressive properties of aluminium perlite syntactic foam was described by Sulong et al. [21]. Sulong et al. [22] also investigated the mechanical properties of APM foam under quasi-static and dynamic compressive loading. In the work of Veyhl et al. [23], the authors studied compressive behaviour of a sintered metallic fibre structure with different relative densities. In addition, attempts were made to model other heterogeneous structures, such as: thermal barrier coatings under tensile load [24], bone loss around failing implants [25] and fracture modelling of concrete [26].

The measuring device, a micro-CT, has limited accuracy of cross sectional mapping. This results in a lack of information about the geometric shape of details smaller than the pixel size obtained during the measurement. In the case of investigated porous material, sintered 316L steel, these are small pores and fissures caused by powder compression. A lack of mapping of these elements results in over-

Table 1
Chemical composition [%] of the used solid 316 L and 316 L compliant with AISI standard [32].

Material	C	Mn	Si	Cr	Ni	P	S	Mo
Used 316L	≤0.03	≤2	≤0.75	16.5	11	≤0.04	≤0.03	2.1
AISI 316L	0.03	2	1	16–18	10–14	0.045	0.03	2–3

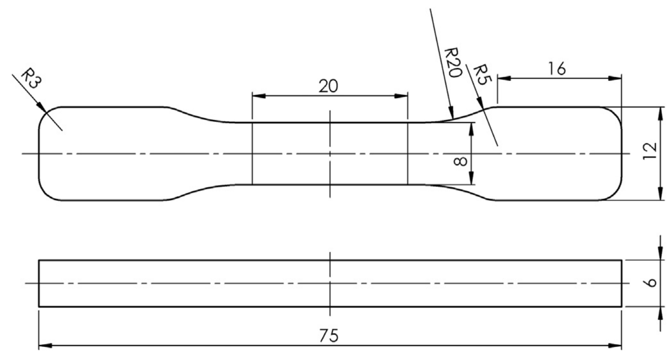

Fig. 1. Specimen intended for tensile testing.

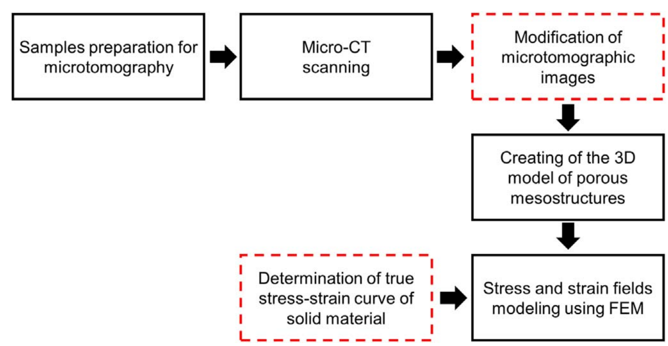

Fig. 2. Modified procedure of numerical modelling of deformation process of porous mesostructures created on the basis of microtomographic images. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

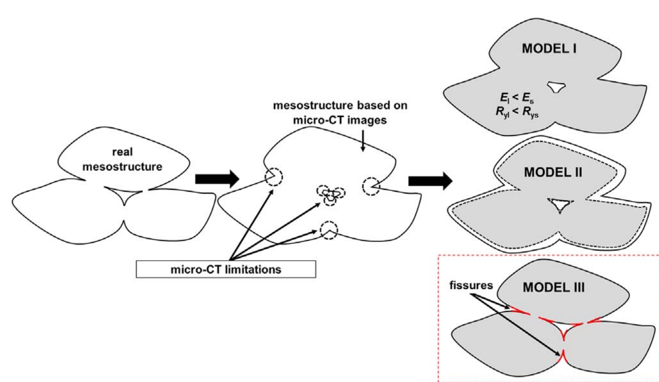

Fig. 3. Schematic comparison of the modelling methods used in this work.

estimation of the nominal stress (averaged) obtained as a result of numerical calculations [27]. In order to achieve optimal quality of tomograms it is necessary to properly configure micro-CT working parameters for a given material [28]. The main factors influencing on the mapping accuracy of the porosity shape are: density and size of the samples and configuration of the micro-CT device (i.e. power of the X-ray source and detector resolution).

Attempts were made to reduce the effect of micro-CT inaccuracy in order to decrease the macroscopic stress value [23,29]. In their work, Veyhl et al. [23] decreased Young's modulus and yield strength, which