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Digital material laboratory: Wave propagation effects in open-cell aluminium foams

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A B S T R A C T

This paper is concerned with numerical wave propagation effects in highly porous media using digitized images of aluminium foam. Starting point is a virtual material laboratory approach. The aluminium foam microstructure is imaged by 3D X-ray tomography. Effective velocities for the fluid-saturated media are derived by dynamic wave propagation simulations. We apply a displacement-stress rotated staggered finite-difference grid technique to solve the elastodynamic wave equation. The used setup is similar to laboratory ultrasound measurements and computed results are in agreement with our experimental data. Theoretical investigations allow to quantify the influence of the interaction of foam and fluid during wave propagation. Together with simulations using an artificial dense foam we are able to determine the tortuosity of aluminium foam.

1. Introduction

Digital material methodology combines modern microscopic imaging with advanced numerical simulations of the physical properties of materials. One goal is to complement physical laboratory investigations for a deeper understanding of relevant physical processes. Large-scale numerical modeling of elastic wave propagation directly from the microstructure of the porous material is integral to this technology.

In this paper, we numerically consider a highly porous, open-cell aluminium foam. Such a man-made material is suitable for various applications in mechanics and engineering, e.g. as light-weight construction elements, mechanical filters or chemical catalysers. Besides its own applicability, open-cell aluminium foam has certain mechanical properties (porosity, intrinsic permeability, tortuosity etc.) which are similar to various cellular materials such as trabecular bone or polyurethane foam. Thus, various results of the present investigation can be transferred directly e.g. to the non-invasive diagnostics of cancellous bone.

Open-cell aluminium foam can be fabricated using open-cell polymer foam as template structure which is replaced by aluminium during a casting process. The resulting aluminium skeleton is built up as an irregular polyhedral network accounting for high porosity and effective hydraulic permeability, cf. Fig. 1.

In order to investigate the complex wave propagation phenomena in this material, we split the considerations in three parts. First, we explain our applied digital material workflow. The specific workflow is put into context with other known approaches. Second, we discuss and present a specific numerical setup to investigate highly porous media using finite-difference wave simulations on a microscale. Third, we present and evaluate the results for aluminium foam. These

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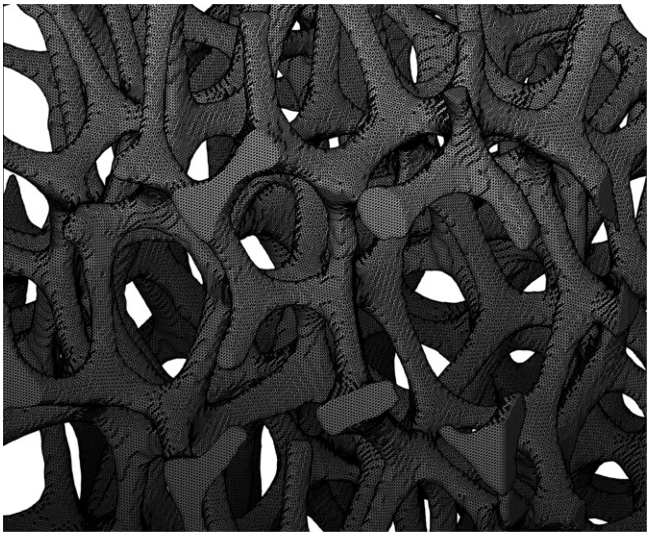

Fig. 1. Irregular polyhedral network of the investigated open-cell aluminium foam. Detail from a CT reconstruction.

numerical results, which contain the physical processes on the pore scale, allow us to understand observations on a much larger scale (i.e. the sample scale).

2. Characterization of the material

For the present study, we analyze a 10 ppi AlSi7Mg foam (m.pore GmbH, Dresden, Germany). For quasi-static loading conditions, this material exhibits a linear-elastic range followed by a pronounced plateau stress in the stress–strain relation (Gibson & Ashby, 1997; Nieh, Higashi, & Wadsworth, 2000). Already for moderate compressive stresses, single layers of the skeleton start to fail which leads to a subsequent collapse of the entire structure. However, this paper will focus on sound and ultrasound propagation effects with small amplitudes and we restrict ourselves on purely elastic material properties. The bulk properties of aluminium forming the porous skeleton can be characterized with standard testing methods. The mechanical properties of the ligaments (Young's modulus, Poisson's ratio, density) are known from quasi-static experiments (Jang, Kraynik, & Kyriakides, 2008), cf. Table 1.

In Fig. 2, a typical pore of the investigated foam is depicted. The morphological properties discussed in this section are derived from the depicted single pore cell, which we consider to be representative for all cells. Stochastical considerations are not included in this paper. Due to gravity effects during the processing of the polymer template, an intrinsic anisotropy of the structure can be observed. The cells are elongated in z direction by the anisotropy factor $\tau = 1.25$. Note that, within this contribution, all mechanical and numerical experiments are carried out with respect to this elongated z direction. We measure the cell size to account 7.3 mm in z direction and 5.8 mm in x and y direction, respectively. Furthermore, we find a typical ligament length of 2.0 mm. In Fig. 3, the cross sections of one ligament are depicted. Again, the depicted ligament is considered to be representative for all ligaments within the specimen without further stochastical considerations. One

Table 1
Modeling parameters and numerically estimated properties of the digitized aluminium sample shown in Fig. 5.

Used modeling parameters	
Young's modulus of aluminium	$E^s = 70.0$ GPa
Poisson number of aluminium	$\nu^s = 0.33$
Effective (true) density of aluminium	$\rho^{sR} = 2700$ kg/m^3
Bulk modulus of pore fluid	$K^f = 1.48$ GPa
Effective (true) density of pore fluid	$\rho^{fR} = 1000$ kg/m^3
Sample size (grid points)	$400 \times 400 \times 400$
Grid spacing	$\Delta h = 60.331$ µm
Sample thickness	$d = 400 \times 60.331$ µm = 0.0241 m
Porosity	$\phi = 0.923$ (from CT data)
Pore geometry	see Fig. 2
Dominant frequency of used wavelet	$f_{dom} = 24$ kHz
Dominant wavelength@1480 m/s	$\lambda_{dom} = 0.061$ m ≈ 2.6 d