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FEASIBILITY STUDY OF PRINTING ACOUSTIC METAMATERIALS USING EXTRSUION FREEFORMING METHOD

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ABSTRACT
Metamaterial is a new field of research in engineered material which lately becomes object of interest due to its unique properties not found in natural objects. Properties such as bandgaps, wave guiding, cloaking and diffuser have been attractive research topics. In this paper, feasibility of using solvent-based extrusion freeforming is explored to print high density ceramic lattices for acoustic metamaterials application. An extrusion-based 3D printer was design and set up for low temperature printing of zirconia lattice structures. An experimental procedure was used to investigate the formation of bandgaps for the 3D printed woodpile sonic structures. This enables the transmission spectrum of the sonic structures to be obtained experimentally.

INTRODUCTION

The concept of metamaterial was first realized when Veselago (1968) brought forward the idea of what would happen if permittivity and permeability of a material are simultaneously negative. He further predicted that substance that has both negative permeability and permittivity could have a negative refractive index thus a different property not observable in nature. This idea however remains as it was until the 1990s when interest on this new branch of engineered material resurfaced again. Initial developments were mainly focussed on electromagnetic and optical wave applications. While the concept of metamaterial is the same in acoustic term its development is still comparatively new with many researches and experimental still being pursued. Although this new material is still relatively new a clear proper definition is required to distinguish it from other materials. There have been many researches concentrated on acoustic metamaterial with a two dimensional (2D) lattice system. On the other hand there are very few researches that discussed on those of a three dimensional (3D) structure. Among the 3D lattices woodpile structure is the simplest of all. As a matter of reference in photonic crystals the woodpile lattice is one of the most popular 3D lattice structures (Wu and Cheng, 2011). This is due to its simple design that uses rods or gratings arranged periodically to form a layer and then stacked orthogonally with another layer.
The application of additive manufacturing (AM) processes and in particular that of paste extrusion method in fabrication of woodpile sonic structures has never been reported. The works of Wu and Chen (2012), and Soliveres et al. (2009) described before were based on hand assembled structure. The fabrication of a sonic woodpile acoustic metamaterial requires a design input which specifies the geometry of the intended structure to be constructed. This specification determines amongst others the expected bandgap performance of the structure. The primary objective of this study was to explore possibility of solvent-based extrusion freeforming process to print acoustic metamaterials with desirable geometry.

MATERIALS AND METHODS

Solvent-based extrusion freeforming equipment was designed and set up for lattice structure fabrication. Figure 1 illustrates the experimental device set up for low temperature extrusion

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freeforming of high density bioceramic lattice structures. The device possesses four main features including three X, Y, and Z axis and a paste extrusion head.

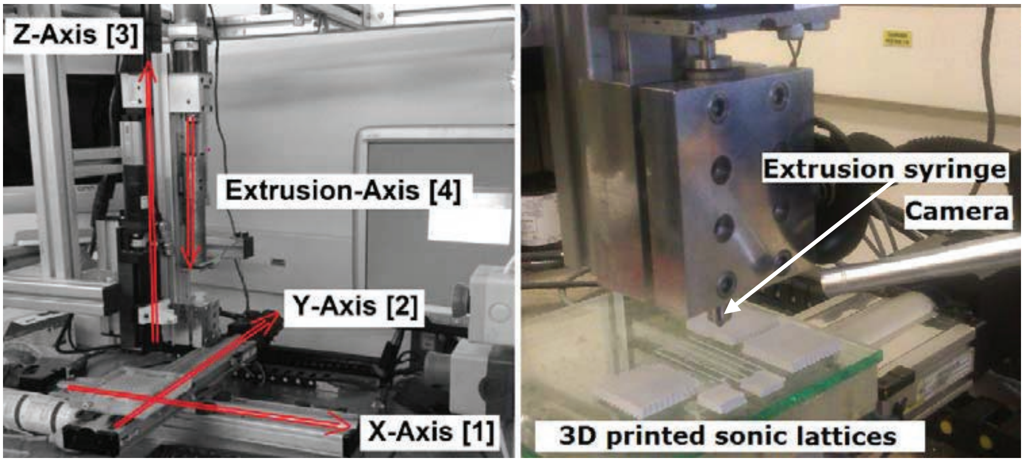

Figure 1. Experimental set up of the extrusion freeforming device

The materials used in this experiment were as follows: (i) Zirconia powder (HSY-3, Daichii Kingenso, Japan) with density of 5.68 g/cm³; (ii) poly(vinyl butyral) (PVB, Grade BN18, Whacker Chemicals, UK) with density of 1100 kgm-3; (iii) poly(ethylene glycol) (PEG, MWt = 600, Whacker Chemicals, UK) with density of 1127 kgm-3; (iv) propan-2-ol (Fisher Scientific, UK) with density of 789 kgm-3. The overall solvent-based extrusion freeforming process steps are: 1) preparation of paste, 2) 3D printing of paste and 3) post-processing including drying, debinding and sintering. Thermoplastic binder, polyvinylbutyral (PVB), and plasticizer, polyethyleneglycol (PEG) (MWt = 600) with the ratio of 75 wt.% PVB and 25 wt.% PEG, are fully dissolved in the solvent, propan-2-ol and then bioceramic is added (a ceramic/polymer mixture with 60 vol.% of ceramic based on the dried paste) to the solution and is stirred for 2 hours to achieve a well-dispersed solution. Next, excess solvent needs to be evaporated via blowing heated air until a viscous bioceramic paste is left. Bioceramic paste is loaded into a stainless steel syringe and extruded through nozzle. After printing, the lattice structure needs to be dried (normally leave at room temperature for 8 hours) to remove excess solvent. Finally, the lattice is put in oven for debinding and sintering. The debinding and sintering (at 1400^{o}C) stages beget micropores in printed filaments within a lattice structure with computer-controlled macroporosity. Two different acoustic woodpile designs were investigated: normal, and a shifted rods arrangement (Figure 2).
An experimental procedure was used to investigate the formation of bandgaps for the 3D printed woodpile sonic structures. This enables the transmission spectrum of the sonic structures to be obtained experimentally. The setup used for the experiment was based on the widely accepted ultrasonic immersion transmission technique described by Liu et al (2000). A block diagram of the arrangement used in the experiment is shown in Figure 3. A numerical analysis and theoretical model were performed using the finite element method (FEM) package offered by COMSOL 4.3a (details have not been discussed in this paper) to compare with experimental results. Measurements were made of the transmitted signals in water without and with the sonic crystal in place. The first measurement with just water served as the reference signal and was used to

normalise the subsequent measurement with the sonic crystal in place. Experimental measurement was then made for a few 3D printed woodpile sonic structures.

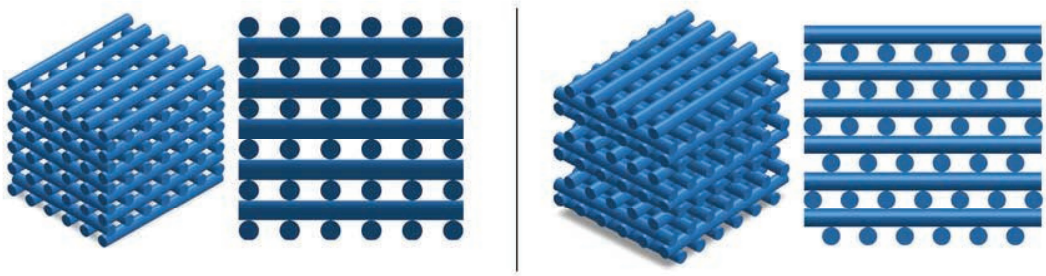

Figure 2. Different acoustic woodpile designs: normal acoustic woodpile (left), and woodpile structure with a shifted rods arrangement (right)

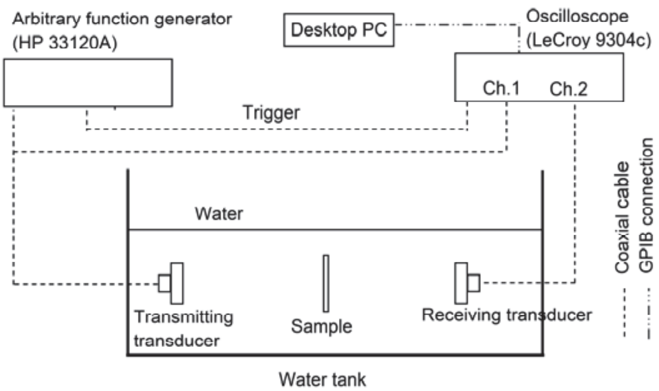

Figure 3. A block diagram showing the experimental arrangement

For the experiments a 2.25 MHz transducer was used as the transmitter and a 1 MHz transducer as the receiver. The frequency chosen was 1.6 MHz which corresponds to the frequency inside the expected bandgap region and a reference measurement with just water was made. To ensure there was no air trapped between the sonic crystal rods, vacuum pump was used to suck air out. Using a fine nylon thread the sample was suspended between the transducers and another measurement was made.

RESULTS AND DISCUSSION

Table 1 depicts weight loss and average shrinkage percentage for three pore-size 3D printed zirconia sonic lattices after sintering, respectively. The quality of produced lattices depended largely on paste viscosity and the subsequent paste extrusion settings. Figure 4 shows lattices with different pore sizes typical case of optimal paste consistency and printer settings. The rheology of the paste when loaded into the extrusion syringe affects the formability of the filament that is extruded during the print procedure; A paste with too low viscosity (less zirconia content) would result in a filament that is less able to hold its shape, and more likely to deform upon settling on the build plate.

Table 1. Average shrinkage percentages for each of the three pore-size groups after sintering excluding values outside the 0-25% range, which were considered to be anomalous

Designed pore size (μm)	Filament shrinkage (%)	Pore shrinkage (%)	Height shrinkage (%)	Dimensions shrinkage (%)		Weight loss (%)
70	9.4	10.3	11.9	10.5	10.7	13.2
200	11.9	11.8	12.7	10.4	10.7	13.2
310	9.7	13.0	10.3	11.2	11.1	13.2
Average	10.3	11.7	11.9	10.7	10.8	13.2

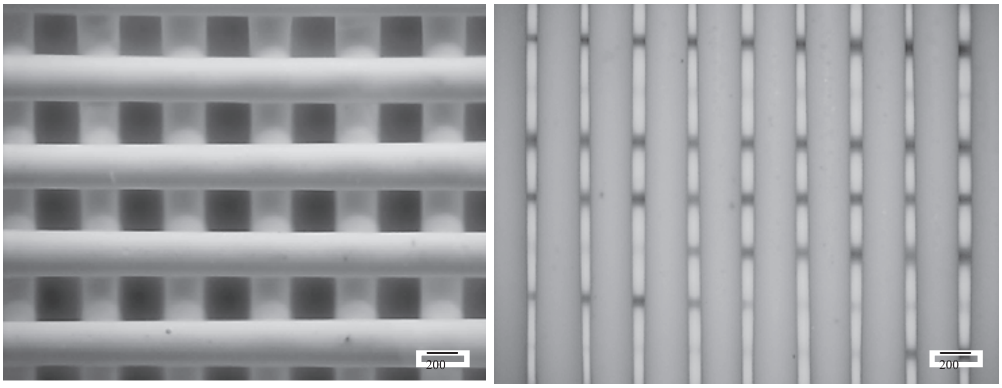

Figure 4. Microscopic images of sintered zirconia lattices with 300 and 70 microns pores

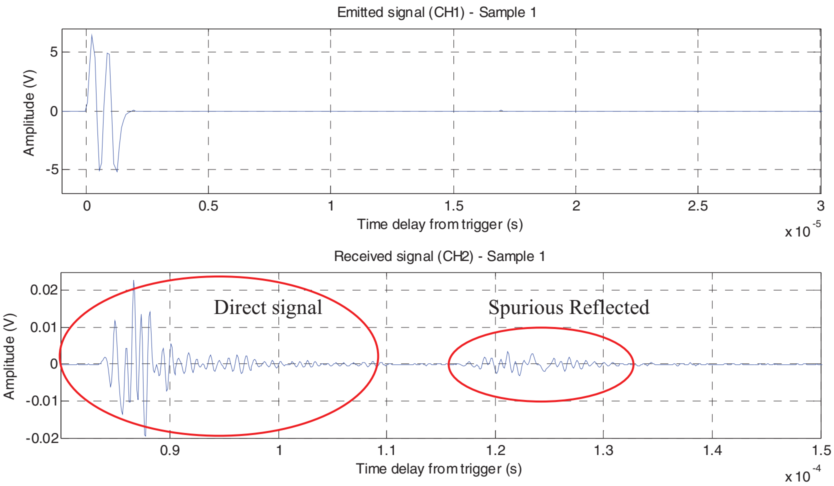

Figure 5. The applied and received signals for the measurement of the zirconia sample showing the direct arrival and a spurious reflection

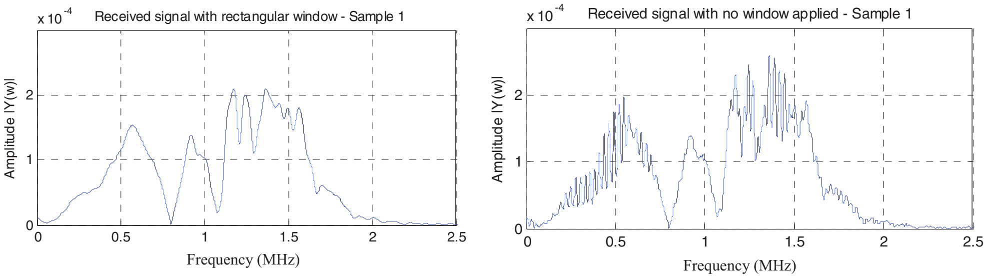

Figure 6. Frequency spectrum of the received signal with no window (right) and rectangular window applied for the Sample (left)

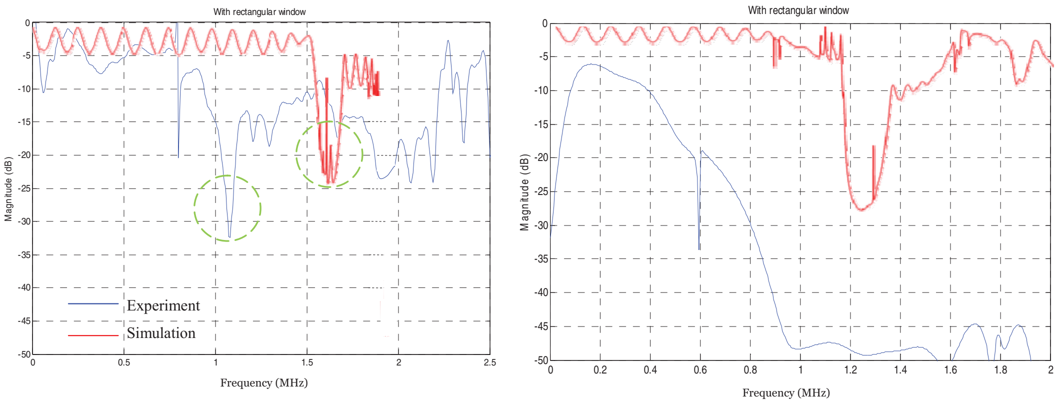

Figure 7. a) Transfer function of the normal designed zirconia sample with rectangular window applied b) transfer function of the shifted rods designed alumina sample with rectangular window

The transmitted and received signals with a typical normal designed 3D printed sample with averages lattice constant of 885 µm and rod diameter of 427 µm with a filling ratio of 38% is shown in Figure 5. A rectangular window was then applied to the signal received between 83 µs and 110 µs. The frequency spectrum of the non-windowed and windowed received signals is shown in Figure 6. These signals were then normalised to that with just water and the transfer functions obtained are shown in Figure 7 for the normal designed 3D printed sample and a typical woodpile structure with a shifted rods arrangement with averages lattice constant of 1.66mm and rod diameter of 550 µm with a filling ratio of 27% printed from Alumina. From the transfer function plots in Figure 7a, two main observations can be made. The first observation is related to absorption. It is evident from the plots that the amplitudes of the received signals are remarkably smaller than the theoretical ones. Besides loss due to reflection, this suggests that some of the wave energy has been absorbed by the sample. It is worth noting that the energy absorbed by the water medium has been taken into account during the normalisation process. The reason for this observed difference could be due to both microporosity of filaments (debinding and sintering process beget this), and the process of the zirconia paste preparation itself. As the zirconia suspension need to be constantly stirred to evaporate the propan-2-ol solvent it was possible that small air bubbles got trapped in the mixture and eventually formed the 'porosity' when the structure harden. Another possible reason for the absorption is due to micro air bubbles trapped on the structure surface itself which did not get completely removed during the application of vacuum. Another observation that can be made is that related to bandgap. From the transfer function plots in Figure 7 a noticeable sharp dip can be observed at frequency just above 1 MHz with a width of approximately 70 kHz. Since the shape of this dip is clearly defined and not just a spike and also considering that the applied signal was particularly strong in this region, this attenuation could be due to formation of bandgap. It however occurred at different frequency range than the theoretical one. This difference could be due to the inconsistency in the dimension of the woodpile structure (in particular warpage) as observed during the fabrication process in some samples. Microporosity of filaments and lattice inaccuracy had more effect on the alumina sample with shifted rods as soon in Figure 7b.

CONCLUSIONS

A solvent-based extrusion freeforming device was design and set up for low temperature printing of zirconia lattice structures. The results proved that extrusion freeforming is an efficient approach to make high density bioceramic lattice structure suitable for acoustic metamaterials application. Paste rheology is an important factor and printing parameters need to be adjusted property to achieve highly uniform lattice structures. Micropororsity and inaccuracy of the sonic lattices could result in a remarkable difference in transfer function plots determined by experiments and theoretical calculation.

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