

Assessment of the Ultrasonic Properties of Additive Manufactured Materials for Passive Components of Piezoelectric Transducers

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Abstract— The potential of additive manufacturing (AM) to revolutionize aspects of industrial production is widely recognized. AM can create objects with non-uniform properties by varying the ratio between deposited materials or altering the internal structure of the object. Amongst many possibilities, such AM objects could benefit the design and fabrication of different passive components of ultrasonic transducers, e.g. backing material, lenses and matching layers. The acoustic properties of AM objects produced using the Polyjet and Fused Deposition Methods were characterized. Initial results suggest that these technologies can easily produce objects with a wide range of tuned acoustic properties by varying either the internal structure or the material composition.

Keywords—*acoustic properties; additive manufacturing; material characterization; air-coupled ultrasound;*

I. INTRODUCTION

The explosion of interest in additive manufacturing (AM) has led to a wide variety of processes capable of producing objects using materials ranging from elastomers and polymers to metals. The layer-by-layer nature of many AM processes allows the production of low-volume, customised objects, which are not economically feasible with traditional manufacturing technologies. This has been greatly beneficial for the rapid production of custom-fitted medical implants, devices and tools including models for preoperative planning, medical prostheses, medical devices and even tissue itself [1].

The Fused Deposition Method (FDM), an extrusion-based AM process developed by Stratasys (Eden Prairie, MN, USA), was one of the earliest commercially widespread AM



Fig. 1. Left to right, respectively: Internal structure of solid, high density, and low density FDM cubes.

technologies. FDM today is relatively inexpensive and widely used. It works by heating a polymer filament, which is then pushed through a nozzle in a controlled manner. The heated polymer is passed over a platen such that the object is built up layer-by-layer [2]. Two extrusion nozzles are used, one that provides the support material and one for the model material. The most commonly used polymer is ABSplus, an updated form of ABS (acrylonitrile butadiene styrene).

The Polyjet process is an inkjet-based AM process developed by Objet (Rehovot, Israel). This technique works by printing thin films of ultraviolet (UV) curable photopolymers using arrays of nozzles. Again, the object is built up layer-by-layer. The Polyjet process has the advantage that it allows two different photopolymers to be printed together, in addition to the support material. Adjusting the relative amounts of the two photopolymers changes the material composition and allows tuning of properties such as elasticity and optical transparency.

TABLE I COMPOSITION OF POLYJET SAMPLES

Sample	% VeroWhite	% Tango Black
1	100	0
2	42.44	57.56
3	43.27	56.73
4	44.46	55.54
5	45.83	54.17
6	47.56	52.44
7	50.36	49.64
8	0	100

The effect of AM process parameters on mechanical properties of ABS structures produced by FDM, such as elasticity, mechanical strength and surface roughness, have been characterized with varying degrees of success. However, to the authors' knowledge, there has been no previous discussion of the acoustic properties of AM materials. The aim of this study is therefore to determine how the acoustic properties of AM materials vary as a function of processing parameters such as build density or material composition for FDM and Polyjet, respectively, with the ultimate aim that they may be used to fabricate passive components in ultrasonic transducers, including backing material, lenses and matching layers.

II. MATERIALS AND METHODS

A. AM Samples

FDM structures are built as either a completely filled solid or a shell with a 1 - 2 mm thick, solid external boundary surrounding an internal lattice structure. Shells enable reduced material usage and reduced deposition time while also ensuring that the object supports the required loads. The internal lattice structure can have hexagonal, triangular or rectangular configurations and these can be aligned at various orientations with respect to the x, y and z axes of the build platen. The density and orientation of this internal structure have been shown to affect the mechanical properties of FDM structures [3][4].

A series of cubes, with 25 mm length of side, of different build densities were produced using ABS-P430 polymer and a Stratasys μ Print SE FDM tool. The build densities produced are classed as Solid (S), High Density Sparse (H) and Low Density Sparse (L). As can be seen in Fig. 1, H and L objects have an internal, trapezoidal lattice structure.

All the internal shell dimensions were measured five times from half-built L and H cubes using a microscope (SZX10, Olympus, Tokyo, Japan) in conjunction with analysis software (analySIS.docu, Olympus, Tokyo, Japan). The thickness of the external wall surrounding the internal structure was measured to be $943.7 \pm 6.2 \mu\text{m}$. The thickness of the internal walls comprising the honeycomb structures was measured to be $392.5 \pm 10.3 \mu\text{m}$ and the length of the square L cavity is $1505.6 \pm 19.1 \mu\text{m}$. The dimensions of the rectangular H cavities varied, with the lengths in the range 218.8 - 382.9 μm and the widths in the range 235 - 344.2 μm . The pitches in the L and H cubes were $1968.5 \pm 4.7 \mu\text{m}$ and $779.7 \pm 6.6 \mu\text{m}$, respectively. The raster angle alternated between -45° and $+45^\circ$ on successive layers.

A series of Polyjet 50 mm diameter discs were also printed using an Objet Connex 500. The ratio of two proprietary materials was varied as detailed in Table I. The materials used were VeroWhite, a white rigid plastic, and Tango Black, a black elastomer. The layers comprising the discs were 16 μm thick according to the tool datasheet and all discs were solid, with no internal lattice structure.

B. Direct Measurements

The external dimensions of the FDM and Polyjet samples were measured using a caliper. The mass of each sample was measured using a precision lab balance (XT2220A, Precisa Gravimetrics, Dietikon, Switzerland). The density of the samples was calculated from these measurements.

C. Acoustic Measurements

A Panametrics 5077 pulser/receiver (GE Measurements and Control, Boston, MA, USA) was used for all the ultrasonic measurements. The pulser provides a semicycle of a square voltage signal to drive the transmitting transducer; the amplitude of this excitation signal was set to 100 V. The low pass filter was inactive and the high pass filter was set to 10 MHz. The pulser also provides a synchronous signal that was used to trigger the oscilloscope to record the data. The pulse repetition frequency was set to 200 Hz. Gain at reception was selected to maximize the signal to noise ratio (SNR) whilst avoiding saturation of the received signal by the oscilloscope.

A DPO 7054 500 MHz digital oscilloscope (Tektronix, Beaverton, OR, USA) was used to acquire and digitize the electrical signal generated by the receiving transducer. Signals were averaged 20 times to improve SNR. Vertical resolution was 8 bits, signal length 2000 sample, and the sampling frequency was 10 MS/s. The 7054 DPO is a Windows-based oscilloscope so it has an internal universal serial bus (USB) connection to an integrated PC and the digitized signals were stored on this PC for further calculations and analysis.

Two different configurations were used in the experiments: air-coupled for Polyjet cylinders and gel-coupled in the case of the FDM cubes. For air-coupled measurements, a pair of bespoke, wideband piezoelectric transducers (CSIC, Madrid, Spain) were employed, working in the frequency band 0.15 - 0.35 MHz [5]. Magnitude and phase spectra of the transmission coefficient for through transmission at normal incidence were obtained experimentally. Up to three thickness resonances appeared, depending on the sample, although none of them were first order, as can be seen in Fig. 2. This was taken into account before introducing the data into the algorithm used to solve the inverse problem. The analysis algorithm allows the user to obtain the acoustic properties along the thickness direction of each sample [6]. In order to do so, an acoustic model which considers each sample as a homogenous plate was applied. Values such as speed of sound, attenuation, density and impedance were calculated along the build direction of the discs i.e. along the z-axis [7].

In the gel-coupled configuration, two transducers with center frequency 0.25 MHz, were placed in direct contact with

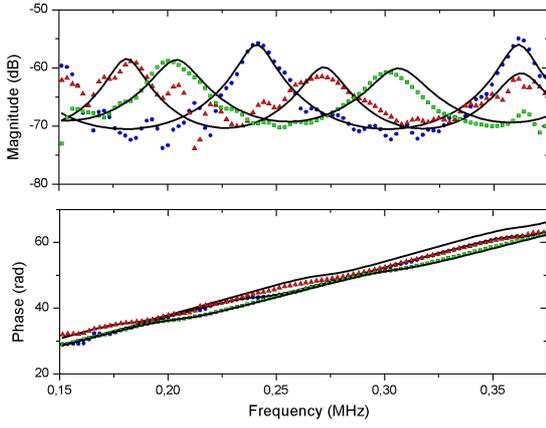


Fig. 2. Magnitude and phase spectra of the transmission coefficient of Polyjet samples. *Blue circles*: 100% VeroWhite; *Red triangles*: 100% Tango Black; *Green squares*: Sample 7 49.65% Tango Black. *Solid lines*: correspond to acoustic model fitting considering the whole sample as a homogeneous plate.

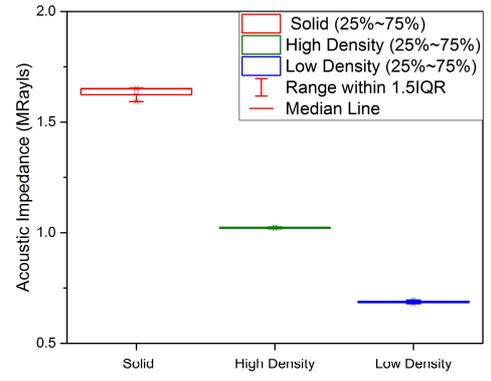
each other using gel coupling. The pulser-receiver then provided a transmission pulse and the received signal was stored in the DPO 7054 oscilloscope. The transducers were then separated, each sample was placed between them, and the time delay between the transmitted and received signals was obtained. The time delay through the cube was obtained using both acquired signals and the ultrasound velocity was calculated from this time delay and the measured sample thickness. This was repeated along each axis of the cube in order to determine both potential anisotropy and dispersion of the ultrasonic waves. The ultrasonic propagation speed was then used to estimate the elastic properties of the FDM objects. As the wavelength is much larger than the cell diameter, the following equation was used:

$$v = ((k + 4G/3) / \rho)^{1/2} \quad (1)$$

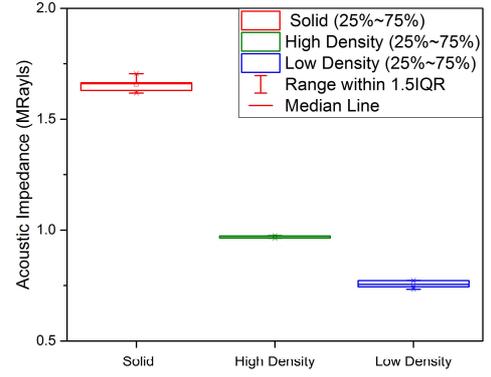
where v is the ultrasonic propagation speed measured by time delay, ρ is the measured volumetric density, and k and G are the bulk and shear moduli, respectively.

III. RESULTS

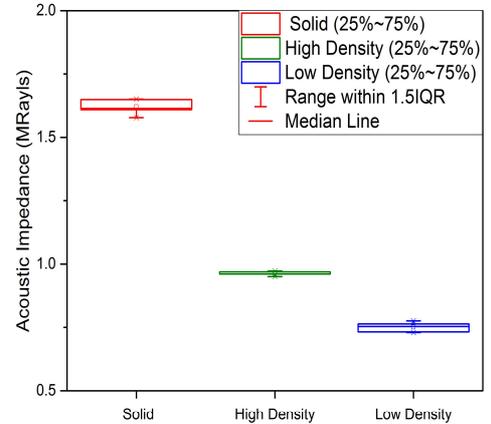
As shown in Fig. 3, the acoustic impedance of the FDM cubes varies up to 58%, from 0.68 MRayl to 1.63 MRayl, along z axis, according to the build density. Anisotropy is expected between the speed of ultrasound measured along the build direction and along axes perpendicular to it. According to Fig. 4, these differences are greater as the build density decreases, with 10% increased speed of ultrasound normal to layer deposition compared to the parallel direction. The lack of variation with build plane is due to the fact that the cross-sectional structure of the cube is similar over the x - x and y - z planes, with the ultrasonic wave travelling perpendicular to the build direction i.e. the z -axis of the lattice structure. However, the acoustic impedance measured along the build axis of the object i.e. over the x - y plane, differs as the ultrasonic waves



(A): along X axis



(B): along Y axis



(C): along Z axis

Fig. 3. Variation of acoustic impedance with build density and axial orientation

pass parallel to the lattice structure. This can be best observed when considering the results from the low density cube.

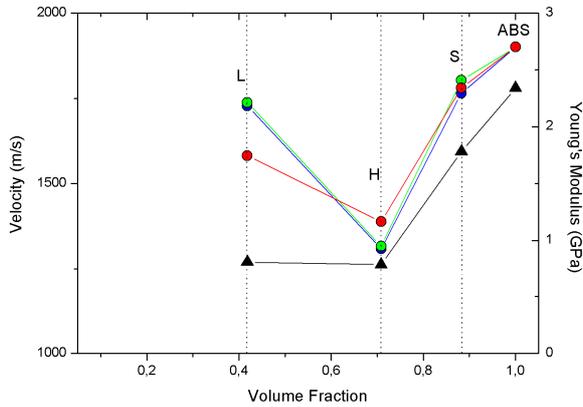


Fig. 4. Volume fraction vs Velocity as a function of axial orientation and Young's modulus. Blue circles: along x axis; Green circles: along y axis; Red circles: along z axis; Black triangles: Young's Modulus.

This result can be further explained by Fig. 4., which shows the relationship between volume fraction (ratio of sample density to bulk ABS density) and longitudinal velocity through the sample along the x, y and z axes, where the positive z-axis is the build direction. Different regions of mechanical behavior can be distinguished in this graph. In Zone I, as the cube goes from high density to low density, the velocity of sound increases while the density decreases. In this region, changes in stiffness are not pronounced when compared to the other two zones. In Zone II, the velocity of the sound decreases when going from a solid FDM cube to a high density cube. The drop in velocity can be attributed to a decrease in the stiffness as a consequence of the shift from a solid internal structure to the lattice structure. The changes in Zone III, going from bulk ABS to a solid printed ABS cube, can be attributed to differences between ABS and the proprietary ABS-P430 used to produce the cubes, as well as to the fundamental limits of the FDM process in producing a solid cube layer-by-layer. The results show that changing the object's internal structure can optimize the acoustic properties of an AM object.

Results shown in Fig. 5 demonstrate that alteration of the composition ratio between VeroWhite and Tango Black allows the acoustic impedance to be tuned with little change in density. Further work is needed to fully characterize the relationship between acoustic properties and composition ratio of these two polymers. The potential benefit of AM techniques such as FDM and Polyjet for the fabrication of passive acoustic components is illustrated by the wide range of acoustic impedances that can be generated using these techniques.

IV. CONCLUSIONS

The acoustic impedance of the solid FDM cube did not match that of bulk ABS material. This may be due either to differences between ABS and the proprietary ABSplus material supplied by Stratasys or to processing parameters such as the effect of heating on the polymer properties during extrusion and the layer-by-layer nature of the AM process. FDM using ABSplus was capable of producing acoustic impedances in the range 0.68 - 1.65 MRayl by varying the volume fraction from 0.42 to 0.88. Likewise, the discs produced using the Polyjet

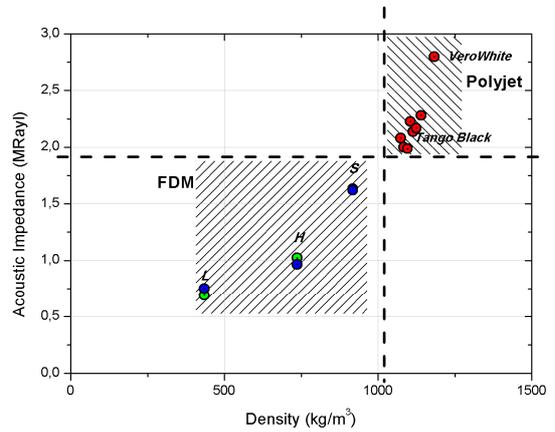


Fig. 5. Variation of acoustic impedance with density. Green circles: acoustic impedance of FDM cubes along build direction; Blue circles: acoustic impedance of FDM cubes normal to build direction; Red circles: acoustic impedance in thickness direction of Polyjet samples with different content of Tango Black/VeroWhite.

process had acoustic impedances in the range 1.9 - 2.8 MRayl by adjusting the composition according to the relative proportions of the two photo-curable polymers.

This demonstrates that the acoustic properties of materials can be tuned using AM processes through either changes to the internal structure or alteration of the polymer properties. This may be particularly useful when engineering passive components of ultrasonic transducers to meet both acoustic matching and mechanical design specifications.

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REFERENCES

- [1] J. Giannatsis and V. Dedoussis, "Additive fabrication technologies applied to medicine and health care: a review," *Int. J. Adv. Manuf. Technol.*, vol. 40, no. 1, pp. 116–127, Jan. 2009.
- [2] I. Gibson, D. W. Rosen, and B. Stucker, *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. Springer, 2009.
- [3] H. Eiliat and R. J. Urbanic, "Using Genetic Algorithms to Optimize the Build Orientation for Fused Deposition Modeled Components Containing Internal Reinforcement Structures," in *Volume 2B: Advanced Manufacturing*, 2014, p. V02BT02A027.
- [4] L. Villalpando and J. Urbanic, "Parametric Internal Matrix Structures for Components Built by Fused Deposition Modelling," in *Enabling Manufacturing Competitiveness and Economic Sustainability*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 287–292.
- [5] T.E.G. Álvarez-Arenas, "Acoustic impedance matching of piezoelectric transducers to the air," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 51, no. 5, pp. 624–633, May 2004.
- [6] M.D. Fariñas and T.E.G. Álvarez-Arenas, "Ultrasonic assessment of the elastic functional design of component tissues of Phormium tenax leaves.," *J. Mech. Behav. Biomed. Mater.*, vol. 39, pp. 304–15, Nov. 2014.
- [7] T.E.G. Álvarez-Arenas, "Simultaneous determination of the ultrasound velocity and the thickness of solid plates from the analysis of thickness resonances using air-coupled ultrasound.," *Ultrasonics*, vol. 50, no. 2, pp. 104–9, Feb. 2010.