Additive manufacture of impedance matching layers for air-coupled ultrasonic transducers

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***Abstract*— A key problem in designing an efficient ultrasonic transducer for operating in a low acoustic impedance medium such as air is the large impedance mismatch between the active piezoceramic material and the load medium. While acoustic matching layers can be added to the face of the piezoceramic, the associated manufacturing difficulties and reliability can impact upon the cost and longevity of the resultant transducer. This paper presents some preliminary investigations conducted using an additive manufacturing technique, to develop a new material system for matching layer fabrication for air-coupled ultrasonic transducers. Results to date are very encouraging, and could result in a robust, reproducible, economical and improved fabrication method for air-coupled transducers.**

Keywords — impedance matching; air-coupled ultrasonic transducers; 3D printing, additive manufacture, micro-stereolithography.

I. Introduction

Air-coupled ultrasonic transducers are used in many application areas, including gas flow measurement [1-2] and non-contact inspection of materials such as paper, foam, and composites [3-6]. In a conventional ultrasonic transducer assembly, often comprising of a thickness mode piezoelectric transduction element, the impedance mismatch between the active piezoelectric element and the load medium limits the efficiency of the transducer. In the case of air-coupled ultrasonic applications, this acoustic impedance mismatch is significant (~30MRayl:400Rayl typically) and makes the device usable only in a narrow frequency bandwidth and at very low efficiency. Passive impedance matching layers are often used in such cases, between the active piezoelectric element and the load medium, to reduce this impedance mismatch. However, this is again not straightforward for an air-coupled application, due to a variety of reasons, primarily:

- Materials with suitable acoustic properties are not readily available for matching layer fabrication.
- Matching layers are usually very attenuative (as layers are typically heterogeneous).
- Matching layers are often difficult and/or hazardous to manufacture.

Typically about 40-50% bandwidth can be achieved using a single, quarter wavelength matching layer and about 70% bandwidth for a double matching layer configuration [7]. Use of a graded multiple matching layers [8] could potentially further improve the operational bandwidth. However, such graded matching layers are seldom used in practical applications, mainly due to manufacturing difficulties.

In this paper, we adopt an advanced additive manufacturing technique, known as micro-stereolithography (µSL) [9] and develop a new µSL material system to produce matching layers for use in air-coupled ultrasonic transducers. The technique would potentially eliminate (or at-least minimize significantly) any post processing required in a typical matching layer fabrication process. For example, consider a glue-less transducer assembly process, where the layer could be fabricated directly on the surface of the active piezoelectric element. This is a significant benefit not only to improve the energy transfer into the load medium, but also in improving the reliability of the complete transducer fabrication process, as faults in the matching layer bond line are often one of the main modes of failure in an ultrasonic transducer.

II. Materials and Methods

A. Additive manufacturing apparatus

Stereolithography is an additive layer manufacture process that utilizes a photo-curable polymer resin material to produce three-dimensional (3D) objects. µSL is capable of fabricating components with micrometer scale feature sizes. The µSL apparatus used in this investigation (illustrated in Figure 1) is a custom built system employing an inverted method of fabrication whereby the uncured, liquid photopolymer is held in a tray with an optically transparent base and a silicone layer on its uppermost surface. The tray is mounted above a structured light source which is used to photo-polymerize the resin at addressable locations on the two-dimensional (2D) focal plane of the source. The light source used in the µSL system contains an LED digital light projector (DLP) with a digital micro-mirror device, capable of outputting 1088 by 612 pixel 2D plane in a single exposure.

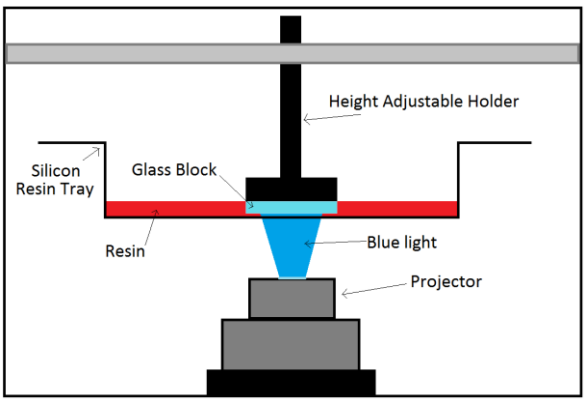

Figure 1: A schematic diagram of the µSL set-up.

B. *µSL material development*

Conventional ultrasonic transducer assembly typically consists of: An active layer (usually a piezoelectric ceramic/composite substrate) used to generate the ultrasound; a backing layer to help damp the mechanical ring-down of the transducer; and matching layer(s) to aid better transmittance into and from the load medium. While a wide range of device configurations are possible, a simple piezoceramic disc (PZ27 - Ferroperm, Denmark), with a nominal resonance frequency of approximately 200 kHz, was selected for this feasibility study. While using a composite active layer could be advantageous for operation in low acoustic impedance load media [10]), within this feasibility study only a plain PZT ceramic substrate is considered.

Photo-curable resins for µSL generally comprise of a diacrylate functionalized oligomer, acrylate functionalized cross linker and a photo initiator (PI). For the work presented here, a general oligomer and cross linker were chosen, namely polyethylene glycol diacrylate (PEG) and dipentaerythritol penta-/hexa-acrylate (DPPHA), respectively. The PI selected was bis(.eta.5-2,4-cyclopentadien-1-yl)bis[2, 6-difluoro-3-(1H-pyrrol-1-yl)phenyl]titanium - a titanocene with activity in the visible spectral region. For maximum ultrasonic energy transfer into the gas medium, the optimum acoustic impedance needed for the matching layer is very low. The theoretical optimum is typically between 0.02-0.8MRayl for practical applications – as it is generally considered to be the geometric mean of the acoustic impedance of the load medium and the piezoceramic used. In order to reduce the acoustic impedance of the µSL matching layers, glass micro balloon filler (material properties listed in Table 1) was added to the photo-curable resin. This enables us to produce a robust matching layer, whose acoustic impedance is easier to engineer and is closer to the optimum impedance needed, compared to an unloaded polymer layer.

Table 1: Micro balloon filler material properties

Parameter	Typical Value
Density	0.125 g/cc
Isostatic crush strength	250 psi
Effective particle diameter	120 microns

C. *Additive manufacturing method*

The process begins by lowering the "build platform", down towards the upper surface of the resin tray. A thin gap is left between the two surfaces, confining a precisely defined thickness (typically a few hundred µm) of liquid resin. The DLP source is then used to expose a pattern representing a single cross-section along the z-axis of a 3D model onto the layer of liquid resin. The exposed regions of the resin solidify, while the unexposed regions remain uncured. After exposure, the build platform is raised along with the cured layer of resin adhered to it. After a short wait period to allow the liquid resin in the tray to re-level, the platform is lowered until another layer of resin is confined between the previously cured layer and the silicone of the resin tray. Another layer is exposed and cured onto the previous layer before raising the platform. These steps are then repeated until the entire model has been fabricated. After manufacture, the model is rinsed with solvent to remove any traces of uncured resin.

III. MATCHING LAYER FABRICATION

A. *Additive manufacture trials*

Initially, tests were carried out to determine maximum curable layer thickness in the µSL setup described earlier. As received PEG and DPPHA were mixed in a 1:1 by volume ratio using a magnetic mixer for approximately 30 minutes, until the mixture was homogenous. PI was then added and the mixture was mixed again for homogeneity. Small samples were first produced for calibration and exposure time test purposes. The samples were each 0.5mm side length and separated from each other by ~0.1mm. Exposure time was then varied from 3 seconds to 60 seconds and the resultant thicknesses of the squares can be seen in Figure 2. As expected, when the exposure time increases, the thickness of the cured polymer monolith also increases until the light can no longer penetrate the material and no more material is cured. The maximum curable thickness was found to be around 510 microns.

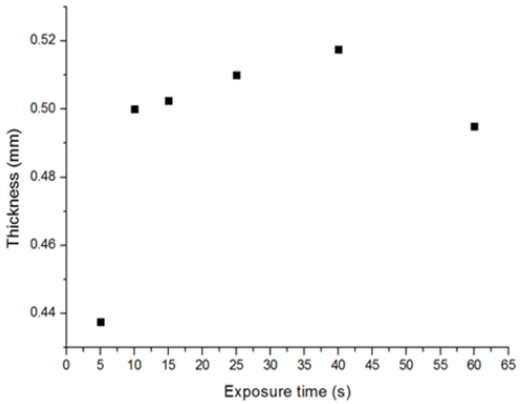

Figure 2: Measured single resin layer thickness as a function of exposure time.

Incorporation of scattering media such as the micro-particle fillers used here can affect light propagation in polymer systems, thus exposure time measurements were repeated on the micro-balloon filled resin to obtain an optimum exposure time. Another batch of resin was mixed, this time adding micro-balloon fillers to the mixture. These were added slowly, allowing proper mixing to occur, up to a mass ratio of 1:32 (filler: resin). Squares of the same size as used previously (0.5mm) were produced using this resin and examined under an optical microscope. It was observed that the micro-balloons were more prominent on the top of each sample than the bottom and this was thought to be due to the micro-balloons floating in the resin. As a method of retarding any floating of the balloons, the resin component ratio was biased to be more viscous with a volume ratio of PEG-DPPHA stock of 1:3 (DPPHA being the more viscous component). This alternative mixture was used with different filler: resin mass ratios. For each filler-resin ratio, squares for various exposure times were produced and examined under a microscope. The resultant exposure time comparisons can be seen in Figure 3.

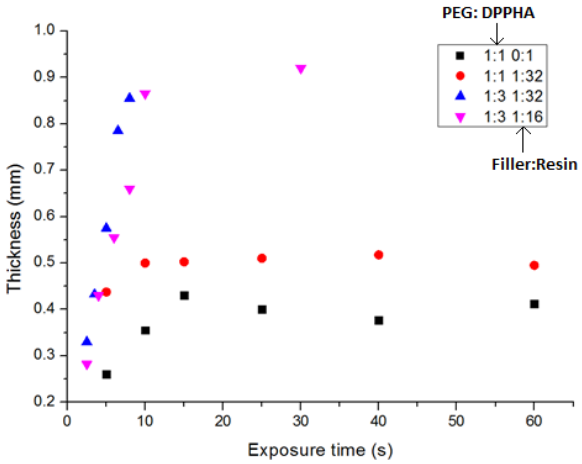

Figure 3: Measured single resin layer thickness as a function of exposure time for varying resin component and filler: resin ratios.

In order to maximize matching layer efficiency, a large fraction of micro-balloons is advantageous, so as to lower the acoustic impedance of the layer and bring it closer to the theoretical optimum. In an attempt to find an upper limit of filler volume fraction, micro-balloons were added to the mixture in increasing quantities until the resin was no longer curable. As more micro-balloons were added, the resin became more viscous, so the resin component ratio was returned to 1:1 (filler: resin). The maximum filler: resin ratio that still allowed the resin to be used successfully was, by mass, 1:6. Using this optimized resin, matching layer additive manufacture was attempted. The DLP source was set to use a circular exposure of diameter 10mm (to match the PZT ceramic footprint used) and the resin added to the resin tray. Using the apparatus in Figure 1, the glass block was lowered into the resin, leaving a gap between glass and tray of ~200microns. The optimum exposure for the mixture (8 sec) was used to build-up a matching layer (approx. 3mm thick).

B. Non-destructive testing of µSL matching layers:

In order to study the matching layers fabricated using the µSL technique, a series of tests were carried out using micro-focus X-ray computed tomography (µ-CT). Samples were imaged non-destructively using an XT H 320 LC X-ray system (Nikon Metrology, UK), employing a Perkin Elmer 1621 EHS detector panel (Perkin Elmer, Germany). Individual matching layers were scanned using a 200kV maximum X-ray energy, 3W beam power, 4s exposure per projection and 12dB analogue detector gain with no beam filtration. A ×40 geometric magnification factor was used, yielding a reconstructed voxel size of 5µm. The 3D volume of the matching layers was reconstructed using *CTPro* (Nikon Metrology, UK), using a simple ramp back-projection filter with no beam hardening correction. Volumes were analyzed within *Volume Graphics Studio Max 2.2* (Volume Graphics GmbH, Germany), facilitating visual inspection of features, dimensional measurement and quantitative defect characterization, such as porosity analysis. It was noted from the volume rendered µ-CT radiograph that a clear, polymer rich boundary region is visible between each µSL layers. While this could have an undesirable effect to function effectively as a matching layer, the effect is anticipated to be minimal due to the heterogeneous nature of the finished matching layer substrate. It was observed that the layer porosity is consistent at about 28% and the boundary porosity seems to change throughout the sample, varying between 18 and 24%. It should be noted that the boundary position is defined manually during post processing and hence could be a source of some small inaccuracies here. Sample µ-CT radiograph scan slice is presented in Figure 4.

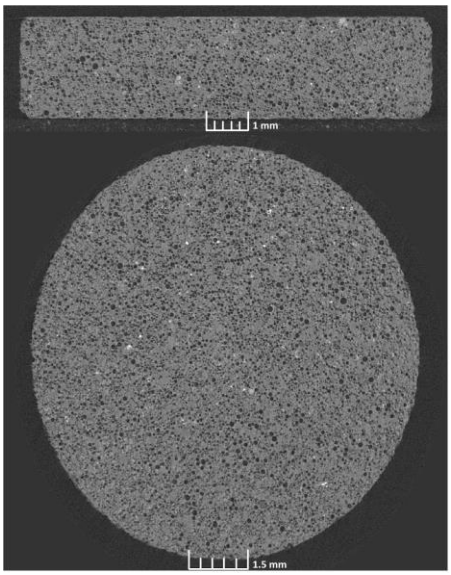

Figure 4: µ-CT radiograph image of a prototype µSL matching layer - (top) slice across thickness and (bottom) across the radiating face of the matching layer.

C. Transducer characterisation:

A series of transducers with µSL matching layers described in the earlier sections were fabricated and their behavior was analyzed experimentally in the lab. Figure 5 shows some of the devices made during this trial directly printed onto the PZT ceramic as part of the µSL process.

Figure 5: µSL matching layers manufactured directly onto active PZT ceramics.

Since the operating frequency of the prototype devices used here are low (~200 kHz), a standard microphone air calibration setup was employed to test these prototype devices, first. These tests were carried out for both the transducer devices fabricated with µSL matching layers and some conventional devices for comparison purposes. The devices under test were driven by a standard pulser-receiver unit (Olympus 5077PR) and the acoustic pressure measurements were taken using a microphone (Bruel & Kjaer, UK) at a fixed distance of around 3cm from the front face of the transducer. This is in the far field of the transducer, and at the same time

is reasonably close to the radiating face which avoids any significant attenuation of the transmitted ultrasonic signal.

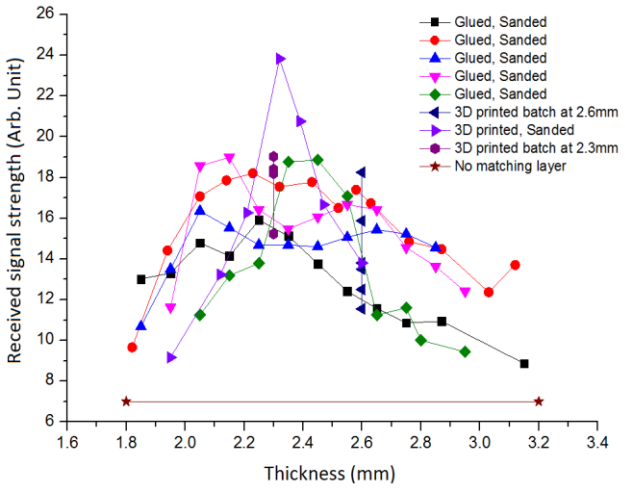

Figure 6: Performance evaluation summary of matching layers fabricated using µSL technique.

The speed of sound in the matching layer was determined experimentally first and was found to be approximately 1865 m/s, and consequently the optimum quarter wavelength (QWL) matching layer thickness for the filled matching layer is expected to be 2.3±0.1mm for the specific PZT device considered in this paper. However, there is a possibility that this might vary slightly, due to the specific composition of each matching layer produced. Consequently, some matching layers were built slightly larger and were machined thinner to take the microphone measurements at a few thicknesses around the theoretical optimum QWL value. The performance evaluation summary result from the microphone measurement is presented in Figure 6. It is clear from the results that the µSL matching layer performance is comparable to conventional (glued and thinned) samples – with the added advantage of very little raw material consumption and no post processing procedure involvement.

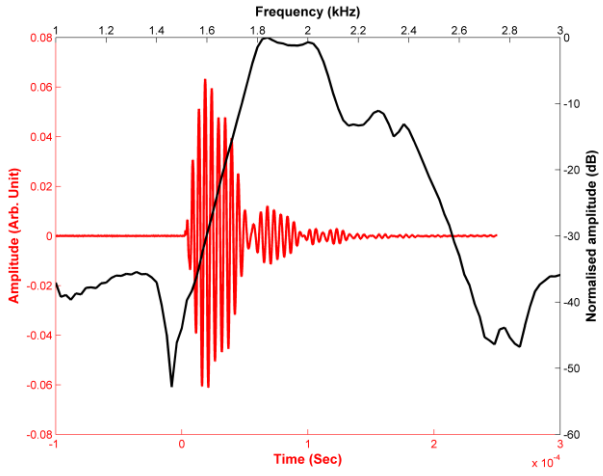

Figure 7: Surface dilation characteristics measured using a laser interferometer experimental setup for directly printed µSL (approximately 2.3mm thick).

A transducer with directly printed µSL matching layer (~2.3mm thick) was chosen for further analysis. The front face dilation characteristics of the devices were studied using a laser interferometer (Polytec OFV-5000). The transducers were excited with a single cycle, 10Vpp Sine wave, generated using a function generator (Tektronix AFG3021B) and the front face displacement measured by the laser interferometer positioned at the mid-point of the radiating front face of the transducer. Figure 7 presents the measured front face displacement data from transducers with µSL matching layer printed directly onto the PZT ceramic. Results indicate clearly that the transducer prototype built with directly printed µSL matching layer produces consistent devices, with characteristic behavior similar to devices produced with conventional matching layers adhesively bonded to the piezoelectric element.

IV. Concluding Remarks

This paper presents some preliminary investigations conducted into using µSL for matching layer fabrication and the results to date are encouraging. Even though the materials used in the µSL process were not optimized from an acoustic propagation point of view, the resultant device behavior was found to be consistently comparable or better (both in terms of sensitivity and bandwidth). Further work on this topic is ongoing and will include optimizing the resin used in µSL process to further improve the matching layer properties and the process of manufacturing of complex matching layer structures with graded impedance profile.

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