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Acoustic Patterning for 3D Embedded Electrically Conductive Wire in Stereolithography

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Abstract

In this paper, we reported a new approach for particle assembly with acoustic tweezer during three-dimensional (3D) printing for the fabrication of embedded conductive wire with 3D structures. A hexagon shaped acoustic tweezer was incorporated with Digital Light Processing (DLP) based stereolithography (SLA) printer to pattern conductive lines via aligning and condensing conductive nanoparticles. The effect of filler content on electrical resistivity and pattern thickness were studied for copper, magnetite nanoparticles, and carbon nanofiber reinforced nanocomposite samples. The obtained data was later used to produce examples of conductive 3D microstructures and embedded electronic components by using the suggested method.

Keywords

3D Printing; Acoustic Alignment; Stereolithography; Embedded Wire; Nanocomposite; Particle Assembly

INTRODUCTION

3D printing or additive manufacturing (AM) technology is a process of manufacturing complex three dimensional (3D) structures from a digital file with various materials. Being stored as digital CAD files allows easy customizations and adjustments. Software uses cross-sections of a digital file to generate layers with finite thickness and additional layers are deposited to build the object one layer at a time [1, 2]. Recently, AM has advanced to be more affordable, very useful and widespread in manufacturing finished products. Therefore, the research attention has shifted on more sophisticated products and systems, with applications across varied industries such as, medical [3], electronics [2, 4, 5], and composites [6, 7].

Fuse deposition modeling (FDM) method is becoming fairly popular as a result of its low cost and reliability compared to the other approaches. However, its material constraints to deposit, relatively poor resolution and mechanical properties of the finished products limit

the suitability of the method for practices especially for high strength applications [8]. Additive of nano- or microscale reinforcement of fiber or particles into the extruded material enhances the performance of the finished product and can deliver extra functions, such as electrical conductivity [2, 4–6, 9]. FDM is a slower process compared to stereolithography (SLA) and does not provide desired surface finish. Inkjet printing, which is relatively young adaptation of AM, can provide better speed and surface finish. However existence of particles increases the probability of clogging in the extruding or inkjet heads which are already prone to clogging. Therefore, alternative options for spatial control of fiber or particulate positions can address some issues of existing methods.

A variety of methods for particle manipulation and patterning in suspension have been used in recent years. Particle manipulation and fiber alignment have been demonstrated with flow-induced alignment [6], magnetic alignment [10], dielectrophoresis [11], and acoustic field [12]. The use of flow-induced alignment requires a flow through nozzle which is prone to clogging [13], while magnetic alignment and dielectrophoresis require particles to have necessary magnetic or electric properties to be aligned. On the other hand acoustic alignment provides better control over the distribution and orientation of particulates without too many material and engineering limitations. In this paper, we introduced a method to use acoustic alignment of nanoparticles to produce 3d printed parts with embedded conductive micro structures. Acoustic forces have been used to generate micro scale structures during SLA 3d printing by Llewellyn-Jones et. al [12]. They used a modified top down laser based SLA printer to produce 1mm thick single layer composite samples in order to investigate improvement in strength. In contrast, we developed a bottom up Digital Light Processing (DLP) based SLA printer to produce multiple layered pieces with embedded conductive microstructures. A hexagon shaped acoustic tweezer was designed to spatially position and manipulate the particles. Conductivity of microstructures was investigated for different particle materials and a method of curing partial regions of aligned pattern was applied to generate embedded, multilayered, complex conductive microstructures.

Method and Experimental Setup

Design concept

We designed and manufactured our DLP based SLA 3d printer which consists of DLP projector, optical system, platform, and acoustic tweezer (see Fig. 1a). The DLP based projector was used as the source of light to cure photocurable resin inside the acoustic tweezer. The optical system reduced the size of projected image and pixel size. The reduced pixel size, which corresponds with SLA resolution, was set to 20 μ m. The platform is connected to a linear stage. The linear stage has 2.5 μ m minimum step length and was used to set layer thickness. 3d printer was incorporated with the hexagon shaped acoustic tweezer to align micro- or nano- particulates and generates microstructures. A hexagon shaped acoustic tweezer, which is shown in Fig. 1b, was made by assembly of glass pieces. The width which refers the distance between parallel sides of the inner cavity was design to be 50mm. The six piezo plate actuators (Steiner & Martins Inc) were placed in the inner walls of the tweezer. The signal was generated by arbitrary waveform generator (HP Agilent 33250A) and then amplified to actuate piezo plates. The signal was generated at resonant

frequency of $f = 2.33 \text{ MHz}$ with the amplitude of $V_{pp} = 100 \text{ V}$. Actuated piezo plates created bulk acoustic waves (BAWs) in the media to align the particulates in desired microstructure. The photocurable resin with low viscosity was chosen as a media for less acoustic attenuation. The specified actuation signal corresponds with $600 \mu\text{m}$ wavelength in the resin.

Acoustic alignment

In the acoustic tweezer, two opposite corresponding piezo plates were actuated to create a standing BAW. In a standing BAW, the acoustic radiation forces are maximized and these forces drive the particles to the closest node or anti-node of the standing BAW. This action is mainly depended on location, size, compressibility, and density of the particles. The primary acoustic radiation force on a single particle with a radius much smaller than the wavelength suspended in an inviscid fluid can be derived as [14];

$$F_{PRF} = -\frac{2\pi V_p E_{ac}}{\lambda} \phi \sin\left(\frac{4\pi x}{\lambda}\right) \quad (1)$$

$$\phi = \frac{5\rho_p - 2\rho_f}{2\rho_p + \rho_f} - \frac{\beta_p}{\beta_f} \quad (2)$$

$$E_{ac} = \frac{p_a^2 \beta_f}{4} \quad (3)$$

where, V_p is the volume of the particle, E_{ac} is the acoustic energy density, ϕ is contrast factor, p_a is acoustic pressure, λ is the wavelength, β_p is compressibility of the particle, β_f is compressibility of the liquid, ρ_p is the density of the particle, and ρ_f is the density of the fluid. When acoustic contrast factor ϕ is positive, particle are driven towards the node and this is the case for every material chosen for this study.

In the designed acoustic tweezer, the particulates are mainly subjected to primary radiation force and gravity. Use of low viscosity resin, reduces the undesired drag force which works against primary radiation force. Fig. 2 shows a schematic demonstration of one dimensional (1D) acoustic alignment only with acoustic force and together with gravity. As it is demonstrated, particles are accumulated at the bottom as a line along the nodal planes of the acoustic field and continuous lines equally spaced by $\lambda/2$ is produced.

Fabrication of Specimens

Magnetite nanoparticles (from Alpha Chemicals) with outer diameter (OD) of 300nm, copper nanoparticles (from US-nano) with OD of 300 nm, and carbon nanofibers (from US-nano) with OD of 200–600 nm and length of 5–50 μm used as reinforcement and the source of the conductivity. Nanoparticles and nanofibers were added into low viscosity

photocurable resin with weight fractions ranging from 0.0–9.0wt% to produce suspension for the process. Fig. 3 shows the diagram of the 3D printing process for the fabrication. First, prepared suspension was filled in the acoustic tweezer. Then particles were mechanically dispersed inside the container and aligned in the preferred direction by actuating the piezo plates. After the alignment, necessary parts of the pattern were solidified by light projection from DLP projector. After that, particles were mechanically dispersed and remaining parts of the layer were solidified without any alignment. The same steps were repeated for every layer. Finally, the printed piece was removed from the platform and post-cured. The postcuring process was performed 30 mm beneath a UV lamp inside a UV light oven. The fabricated pieces were placed under the lamp and were cured for 60 minutes.

RESULTS

First we used fabrication method to produce 1D patterning of continuous lines in one layer sample with dimensions of $10 \times 10 \times 0.5$ mm. Samples were produced with different weight fractions of carbon nanofiber, copper and magnetite nanoparticle reinforcements to measure conductivity of produced patterns. Three different opposed piezo plate pair options were used for horizontal, 60° , and 120° alignments of line patterns (see Fig. 4). Conductivity on x–y plane was provided by those individual patterned lines.

Acoustic field with 2.33 MHz frequency and ~ 1400 m/s speed of sound in the photocurable media corresponds with ~ 600 μm wavelength. Therefore, nodal planes of the field equally spaced by $\lambda/2 \approx 300 \mu\text{m}$. This value corresponds with average ~ 300 μm distance between lines of the pattern shown in Fig. 5. By acoustic focusing, particles were accumulated at the nodal planes to shape conductive lines. This results with transparency on the other parts of the layer. Samples with conductive line patterns were used to evaluate the resistivity of patterns based on material and percentages of nanoparticulates. Figure 5 shows microscope images of patterned unidirectional conductive lines. While Fig. 5a shows the sample with aligned magnetite nanoparticles, Fig. 5b, 5c, and 5d show the microscope images of unidirectionally patterned reinforced magnetite, carbon nanofiber, and copper nanoparticles, respectively.

The resistivity of carbon fiber changes from $12 \mu\Omega\cdot\text{cm}$ to $10^4 \mu\Omega\cdot\text{cm}$ based on manufacturing method and temperature, while the resistivity of copper is $1.6 \mu\Omega\cdot\text{cm}$ in its bulk form. Those good electrical properties were used to fabricate embedded conductive wires during SLA 3d printing. The change of electrical resistivity of the photocurable resin after the addition of nanoparticle with and without acoustic focusing was investigated. Results for resistivity of the patterned lines and unpatterned samples are demonstrated in Fig. 6. Filler content of particulates refers to the percentages of reinforcement in the acoustic tweezer before acoustic alignment. Resistivity of the sample without any additive was $2.5 \times 10^{14} \Omega\cdot\text{cm}$ and it decreased to $3.6 \times 10^{12} \Omega\cdot\text{cm}$, $3.5 \times 10^{13} \Omega\cdot\text{cm}$, and $2.28 \times 10^{14} \Omega\cdot\text{cm}$ with 9wt% copper nanoparticles, 1.75wt% carbon nanofiber, and 5.5wt% magnetite nanoparticles, respectively. Due to very low concentration of particles, the addition of particles has very limited effect on conductivity without acoustic focusing. On the other hand, the resistivity of patterned samples are 13–15 orders of magnitudes lower than the resistivity of unpatterned sample as a result of acoustic focusing. Resistivity of the samples with acoustic patterning decreased to

16.3 $\mu\Omega\cdot\text{cm}$, 349.6 $\mu\Omega\cdot\text{cm}$, and 14340 $\mu\Omega\cdot\text{cm}$ with 9wt% copper nanoparticles, 1.75wt% carbon nanofiber, and 5.5wt% magnetite nanoparticles, respectively. This substantial change was achieved by accumulation of nanoparticles at nodal planes of acoustic field and later allowing particles to settle out of the resin with gravity. Similar results were achieved based on fit-to-flow method and inkjet printing with silver nanoparticles [15, 16]. However similar studies with FDM based conductive material fabrication has lower particle concentration to prevent clogging of the nozzle. Low concentration of particles results with higher resistivity values around 1–10 $\Omega\cdot\text{cm}$ [2, 17].

While electrical conductivity on x–y plane was obtained by acoustic alignment, electrical conductivity on z direction was obtained by overlapping patterned layers. The height of the pattern depends on the particle concentration. Sufficient particle concentration was used to obtain pattern height same with the layer thickness to overlap the interlayer microstructures. Fig. 7a shows relation between particle weight concentration in acoustic tweezer and pattern height for different particle materials. Fig. 7b, c show pattern cross-section with 50 μm and 100 μm height in 200 μm cured layer, with 0.65wt% and 2wt% magnetite nanoparticles. Unfortunately, those patterns cannot conduct electricity towards next layer. In order to achieve that goal, we reduced the layer thickness to 100 μm and repeat the process with 4wt % copper nanoparticles. The result shown in Fig 7d has 100 μm layer thickness.

The SLA printing of 3D embedded conductive structure with acoustic alignment is based on stacking layers which consists of aligned and nonaligned parts. By designing the projected images for each layer, contacts between patterns of different layers were provided. An embedded zig-zag stitch wire pattern is demonstrated in Fig. 8(a) as an example of a complex 3D structure and 3D illustration of the same structure is shown in Fig. 8(b). The zig-zag stitch pattern is consisting of two 100 μm thick conductive wires and it was fabricated with 8 layers which are also shown in Fig. 8. Contact between interlayer patterns, shown through optical and SEM images of a cross-sectional cut in Fig. 9(a,b), is found to be the source of the conductivity in z direction. The conductivity provided by microstructure and interlayer contact is demonstrated with basic LED circuit in Fig. 9(c). Acoustic alignment provides high concentration of the particles at the nodal planes of the acoustic field. High concentration results with direct contact between particles, therefore conductivity of the pattern is produced. High concentration and direct contact of the nanoparticles are demonstrated in Fig. 9(d) with high resolution SEM image.

The developed method is capable of producing embedded electronic component such as; electromagnetic coil, resistor, or strain sensor. An electromagnetic coil fabricated through the developed method is demonstrated in Fig. 10. A 100 μm thick wire is produced with 12 layers and wrapped around a core cavity. The core cavity is left empty for future assembly of a magnetic core. Total height of the piece is around 1.2 mm and it consists of 12 layers with 100 μm thickness. Similar patterns can also serve as a resistor, but the pattern needs to be designed carefully to minimize undesired inductance.

CONCLUSIONS

A new approach to fabricate embedded conductive wires and electronic components based on acoustic alignment of conductive nanoparticles was illustrated. DLP based SLA 3d printer with hexagon shaped acoustic tweezer was used for the approach. First, hexagon shaped acoustic tweezer was demonstrated to effectively align the particles into horizontal, 60°, and 120° patterns. Then, produced anisotropically conductive and transparent patterns were tested for electrical resistivity based on particle materials and filler contents.

Results show that patterned copper particles exhibits less electrical resistivity compared with carbon nanofiber and magnetite particles. Magnetite nanoparticles show ~1000 times higher electrical resistivity compared with copper nanoparticles. Despite the higher electrical resistivity, magnetite nanoparticles can still be important material for patterning magnetic microstructures. The relation between particle concentration and pattern height was also demonstrated due to its importance for the conductivity on z direction. Finally, zig-zag stitch pattern as a complex 3D form and electromagnetic coil pattern as an embedded electronic component were presented as examples of the developed method. Conductive structures of those examples were produced with 100 µm thickness.

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Fig. 1. Setup of DLP based SLA 3D printer incorporated with the hexagon shaped acoustic tweezer; (a) 3d schematic of 3d printer setup, (b) the hexagon acoustic tweezer with placed piezo plate actuators.

Fig. 2.
Schematic of particle alignment in an acoustic field with only acoustic force and with acoustic force and gravity

Fig. 3.
Flow diagram of the 3D printing process

Fig. 4. Different unidirectional pattern combinations used and their schematic acoustic tweezer setting demonstrations ; (a) horizontal, (b) acoustic tweezer setting for horizontal alignment, (c) 60°, (d) acoustic tweezer setting for 60° alignment, (e) 120°, (f) acoustic tweezer setting for 120° alignment.

Fig. 5.

Images of patterned unidirectional conductive lines: (a) Unidirectionally patterned magnetite sample with dimensions of $10 \times 10 \times 0.5$ mm; Images of (b) Magnetite, (c) carbon nanofiber, (d) copper reinforcements which aligned into unidirectional lines under microscope (scale bar: $500 \mu\text{m}$). In each sample, lines of the pattern have an average distance of $300 \mu\text{m}$ at the operating frequency of 2.33 MHz .

Fig. 6.

Resistivity of patterned and unpatterned samples as a function of nanoparticle weight concentration in the acoustic tweezer; (a) resistivity as a function of carbon nanofiber concentration, (b) resistivity as a function of copper nanoparticle concentration (c) resistivity as a function of magnetite nanoparticle concentration

Fig. 7.

Effects of particle weight percentage on pattern height and shape; (a) relation between particle concentration and generated pattern height for different nano particles, (b) cross section of aligned pattern with 50 μm height in 200 μm layer (scale bar: 50 μm), (c) cross section of aligned pattern with 100 μm height in 200 μm layer (scale bar: 50 μm), (d) Cross-section of aligned pattern with 100 μm thickness, pattern is conductive in z direction (scale bar: 100 μm).

Fig. 8. Embedded zig-zag stitch pattern. (a) The pattern consists of 8 layers to produce 2 separate conductive wires in complex 3D freeform (scale bar: 1 mm), (b) 3D illustration of the zig-zag stitch pattern. The wires are 100 μm thick in average. Layer 1, 8 are 200 μm and Layer 2–7 are 100 μm thick.

Fig. 9. Conductivity of embedded zig-zag stitch pattern; (a) cross-sectional cut of printed piece to demonstrate interlayer microstructure contact (scale bar: 100 μm), (b) SEM image of cross-sectional cut of printed piece, (c) demonstration of conductivity in a simple LED circuit, (d) High resolution SEM image of copper nanoparticles in the conductive pattern.

Fig. 10.

Embedded electromagnetic coil pattern. (a) The pattern consists of 12 layers to produce a wire coil surrounding magnetic core cavity (scale bar: 1 mm). (b) 3D illustration of the electromagnet pattern. The wire is 100 μm thick in average. The coil can be produced longer by repeating layers 2–8 until desired length.