Capacitance–Based Non-Destructive Testing of Three-Dimensionally Printed Polymer

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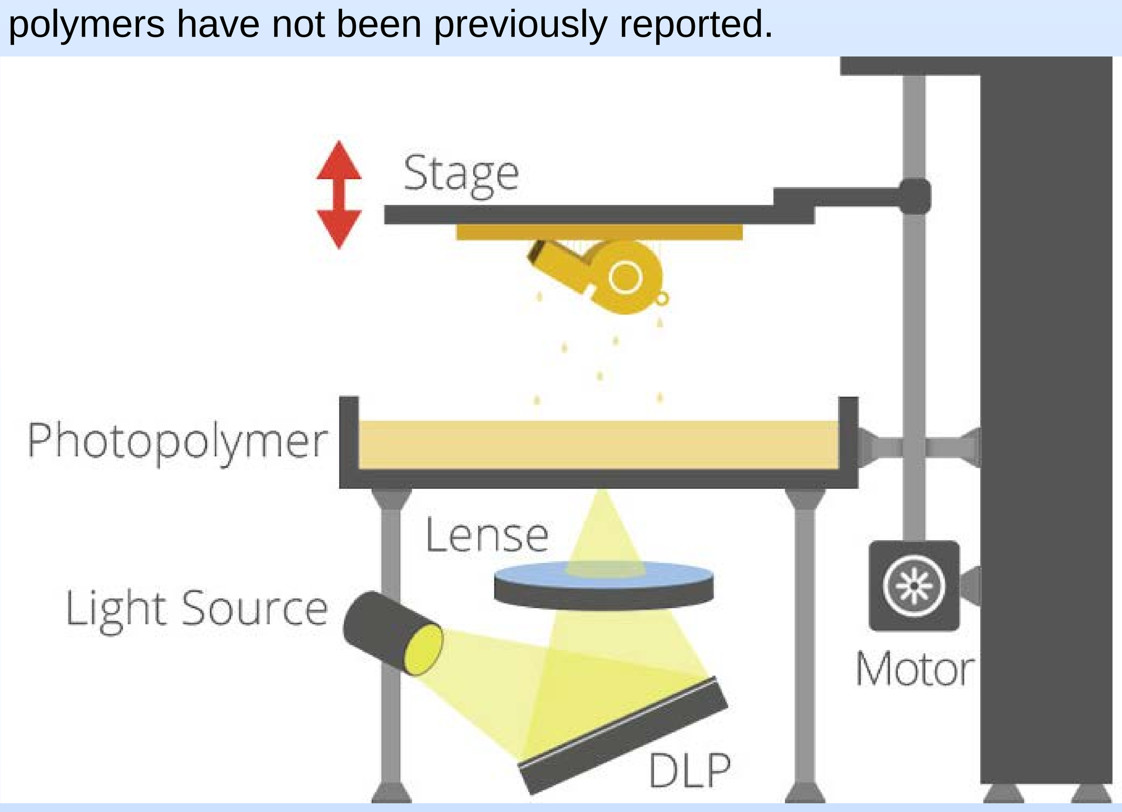
♦ Abstract

The effects of the printing conditions on the molecular structure (molecular alignment) of 3D printed polymer are reported for the first time, as shown by the electric permittivity perpendicular to the layers printed by bottom-up stereolithography, using a UV-curable acrylate ester resin. The relative permittivity (4.1-4.3) increases slightly with decreasing layer thickness (50-25 µm), due to the increased molecular alignment when the layer thickness decreases. All values are higher than the value (3.5) for the bulk polymer. The permittivity decreases with increasing curing time, due to the networking and the consequent decrease in molecular alignment. It decreases with increasing light intensity, due to the increase in the degree of curing. Increase in the resin age prior to printing increases the permittivity, due to the age hindering curing. The relative permittivity decreases with increasing aging time after printing, due to the post-curing; the decrease is more pronounced when the layer thickness is larger, because of the greater difficulty of curing a thicker layer and the consequent greater effect of post-curing. The low degree of molecular alignment obtained after 3 h of aging for a large layer thickness of 50 µm is similar to that of the bulk polymer, as indicated by the similarity in the relative permittivity. The technique reported here may be used for sensing the condition of 3D printed polymer structures without the use of attached or embedded sensors.

♦ Introduction

Three-dimensional (3D) printing involves layer-by-layer deposition of a material and is powerful for the fabrication of objects with complex shapes. It is most commonly performed using polymers, which are much easier to process than metals or ceramics. A polymer consists of long molecules which tend to have a kinked conformation. The length of a molecule is typically large compared to the thickness of a printed layer. The effects of printing conditions on the molecular structure of 3D printed polymers have not been previously reported.



3D printing by stereolithography with bottom-up projection

http://www.3dprinting.lighting/wp-content/uploads/2015/02/3DPrinting.Lighting_Stereolithography_3DPrinting-Industry.jpeg

♦ Objectives

- To investigate the effects of the printing conditions on the molecular structure of a 3D printed polymer.
- The printing conditions addressed are:
  - Layer thickness
  - Curing time allowed per layer
  - Intensity in the ultraviolet (UV) curing of the polymer
  - Resin age prior to using the resin in printing
  - Aging time after completion of printing.

♦ Experimental methods

Materials

- UV cure resin containing acrylate ester (>60%) and photoinitiator.

Printing method

- Stereolithography with bottom-up projection system
- The light intensity is 750 mW, unless noted otherwise.
- The curing time for each layer is 15 s, unless noted otherwise.

Testing method

- The capacitance is measured using a precision RLC meter
- Electric field = 1.000 V/mm.
- Frequency = 100 Hz
- Specimen size : 25 mm x 25 mm

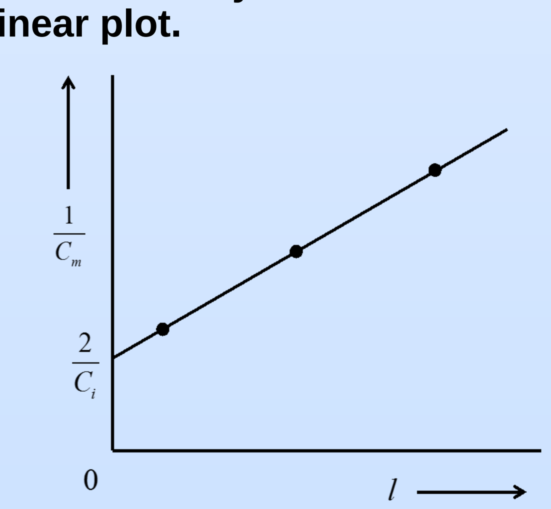
Origin of out-of-plane permittivity

- Polymer molecule s have permanent electric dipoles.
- In plane alignment of molecules gives rise to alignment of side groups in the out-of-plane direction., thus increasing the out-of-plane permittivity.

Out-of-plane permittivity measurement

- The specimen is sandwiched between two copper blocks which serve as electrical contacts (pressure = 3.46 kPa.)
- The contacts and specimen form a parallel-plate capacitor
- The printed multilayer and the two contact interfaces constitute three capacitors in series.
- The equation for capacitors in series gives
  $1/C_m = 1/C + 2/C_i$
  - C_m is the measured capacitance
  - C_i is the interfacial capacitance between the electric contacts and the specimen
  - C is the volumetric capacitance of the specimen and relates to the relative permittivity κ.
  - Plotting $1/C_m$ vs. the multilayer thickness L, the relative permittivity κ of the multilayer is obtained from the slope of the linear plot.

- C_i is obtained from the intercept of the line with the vertical axis at $L = 0$.
- The slope of the line is equal to $1/(\varepsilon_o \kappa A)$.
- ε_o is the permittivity of free space
- A is the area in the plane of the layers

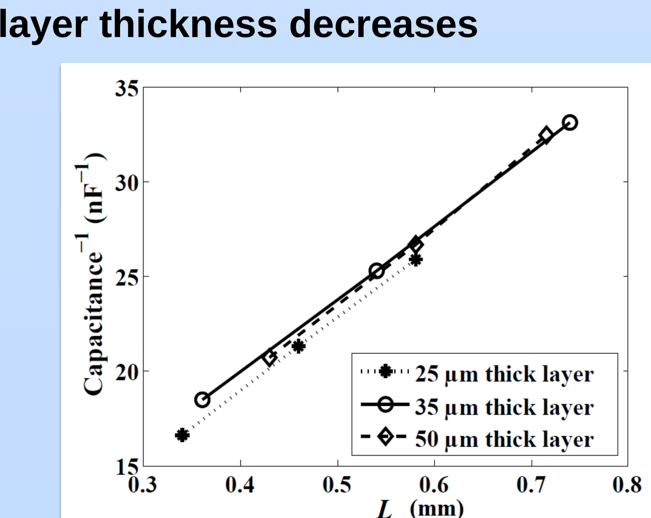


♦ Results and Discussion

Effect of layer thickness

- The permittivity increases slightly with decreasing layer thickness.
  - Due to the increased degree of in-plane alignment of the molecules when the layer thickness decreases
- Higher than the value of 3.5 for the bulk polymer
- The low value reflects the absence of molecular alignment.

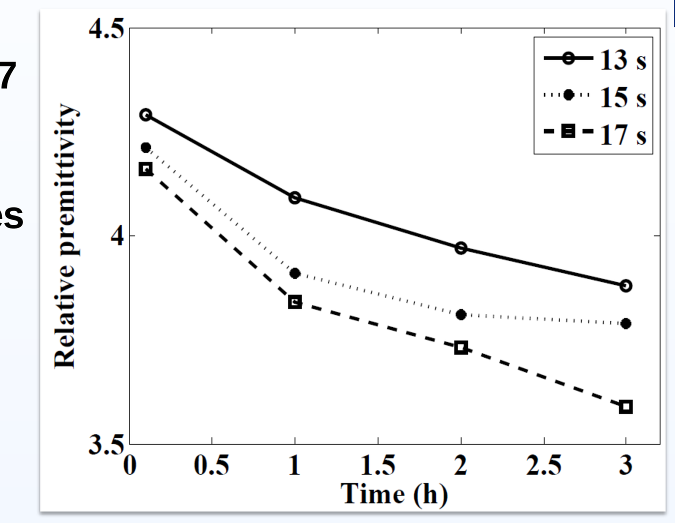
κ for 25 µm = 4.29
κ for 35 µm = 4.19
κ for 50 µm = 4.10



Effect of curing time

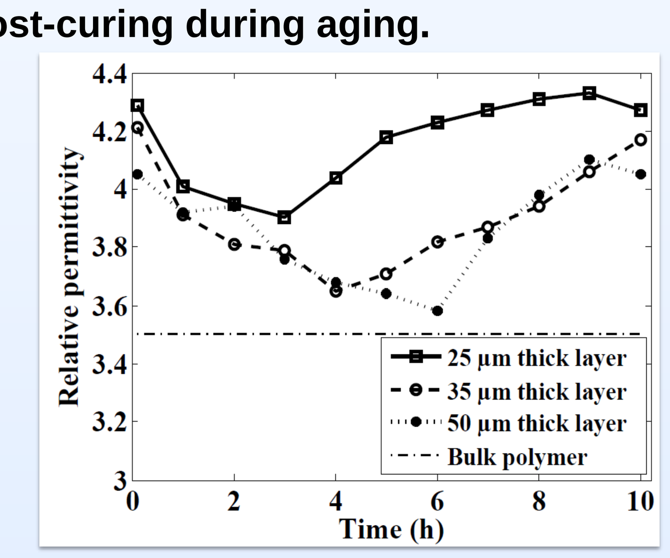
The curing time per layer is changed from 13 s to 15 s and to 17 s to print a multilayer with 35 µm layer thickness.

- The relative permittivity decreases with increasing curing time.
  - This is attributed to the networking and the consequent decrease in the degree of molecular alignment that accompanies curing.



Effects of aging time after printing

- The relative permittivity decreases with increasing aging time.
  - This is attributed to the post-curing during aging.
- The decrease of the relative permittivity is more pronounced when the layer thickness is larger.
- For layer thickness 50 µm, the relative permittivity decreases upon aging to 3.6.
  - Slightly higher than the bulk polymer
  - Due to the greater difficulty of curing a thicker layer and the effect of post-curing

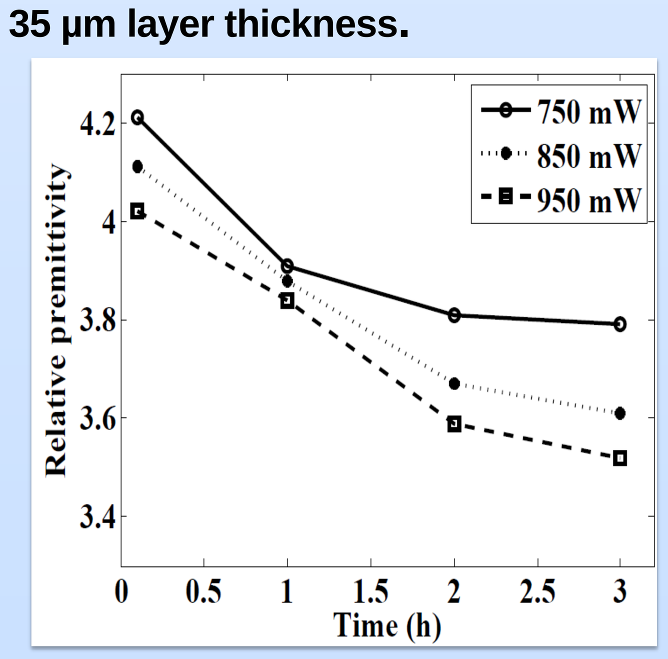


Multilayers with three different layer thicknesses, i.e., 25 µm, 35 µm and 50 µm, are analyzed

- As the layer thickness decreases, the relative permittivity takes less aging time to attain a minimum.
- The relative permittivity rises upon further aging after attaining the minimum.
  - Probably due to the stress relaxation
  - Supported by the uncurling of the specimen.

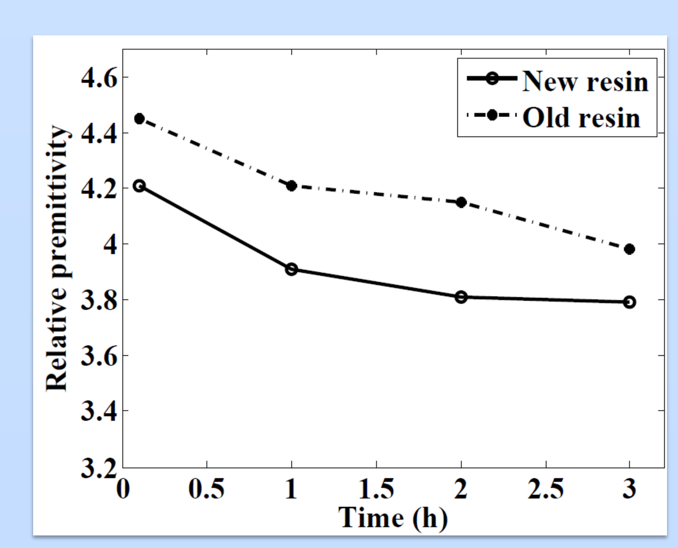
Effect of light intensity

- The light intensity is increased from 750 to 850 mW and to 950 mW to print a multilayer with 35 µm layer thickness.
- The relative permittivity decreases with increasing light intensity.
  - Attributed to the increase in the degree of curing.
  - Consistent with the effect of curing time per layer



Effect of resin age

- Resin age is the time elapse between resin purchase and printing.
- The new resin is 2 months old whereas, the old resin is 2 years old
- The relative permittivity increases with increasing resin age.



- This is attributed to the hindrance to curing due to the age.
- Less curing gives rise to higher permittivity.

♦ Conclusions

- This paper provides the first report of the effects of printing conditions on the molecular structure of 3D printed polymer.
- The effects are shown by unprecedented out-of-plane electric permittivity measurement.
- The permittivity increases slightly with decreasing layer thickness, probably due to the increased degree of alignment of the molecules when the layer thickness decreases.
- All these values are considerably higher than the value of 3.5 for the bulk polymer.
- The permittivity decreases with increasing curing time, due to the networking and the consequent decrease in the degree of molecular alignment.
- The permittivity decreases with increasing light intensity, due to the increase in the degree of curing with increasing light intensity.
- Increase in the resin age from 2 months to 2 years increases the relative permittivity, due to the hindrance to curing by the age of the resin.
- The permittivity decreases with increasing aging time after printing, due to the post-curing that occurs during aging. The decrease is more pronounced when the layer thickness is larger, because of the greater difficulty of curing a thicker layer and the consequent greater effect of post-curing.
- The low degree of molecular alignment obtained after 3 h of aging for a large layer thickness of 50 µm is similar to that of the bulk polymer, as indicated by the similarity in the relative permittivity.
- The capacitance measurement behind permittivity measurement may be exploited for the monitoring of the 3-D printing process without the use of attached or embedded sensors.

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♦ Forthcoming publication

Naga B. Gundrati, Patatri Chakraborty, Chi Zhou and D.D.L. Chung. First report of the effects of printing conditions on the molecular structure of three-dimensionally printed polymer. Submitted.