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Reviewed Paper

INTERLAYER MECHANICAL PROPERTIES OF THERMOSET COMPONENTS PRODUCED BY MATERIAL EXTRUSION ADDITIVE MANUFACTURING

Jonathan Taulo Pedersen-Bjergaard[1], Mathias Michael Christensen[1], Marco Brander[1], Berin Seta[1], David Bue Pedersen[1], Jon Spangenberg[1]

[1]Department of Mechanical Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

Abstract

Material extrusion additive manufacturing (MEX-AM) with thermoset media is of interest as its unique material properties are advantageous for many applications. However, thermoset MEX-AM's resultant interlayer mechanical properties have not yet been fully ascertained. In this study, a robot arm and extrusion system are used to 3D print a two-component polyurethane with depositions of varying holding intervals between layers, to quantify the effect on interlayer-stiffness and –strength. The material is extruded through a 7 mm nozzle to fabricate 42 mm high walls with a width equal to a single strand. The bulk- and interlayer mechanical properties are measured through tensile testing of dogbone samples. The results indicate that the interlayer mechanical properties do not reduce as compared to the bulk behavior.

Introduction

Material extrusion additive manufacturing (MEX-AM) of thermosets is akin to the process of Fused Deposition Modelling (FDM), wherein a liquidized thermoplastic filament is deposited in a layer-by-layer fashion [1]. MEX-AM of thermosets employs the same strategy of selective material extrusion along a specified path but substitutes thermoplastic filament with a two-component thermosetting material, dispensed through a static mixer tube.

Traditional FDM, characterized as wet-on-solid printing [2], allows for high geometrical freedom due to limited material deformation, however, the bonding strength between layers is impacted, which can hinder the use within engineering applications [3]. With two-component thermosetting polymers the bonding mechanism is chemical, and it is characterized as a wet-on-semisolid process. The two components are usually comprised of an oligomer resin and a hardener that when mixed undergo an irreversible chemical reaction forming a highly cross-linked polymer [4]. The purpose of this study is to quantify the interlayer mechanical properties in MEX-AM with thermosets.

Methodology

The experimental setup consisted of a 6-axis ABB IRB 6620 robotic arm integrated to a 2-K-DOS dispensing system from Fritz Giebler. The dispensing toolhead was mounted to the tool flange of the robotic arm. The two polyurethane sub-components were printed via a static mixing nozzle. The experimental setup is shown in Figure 1.

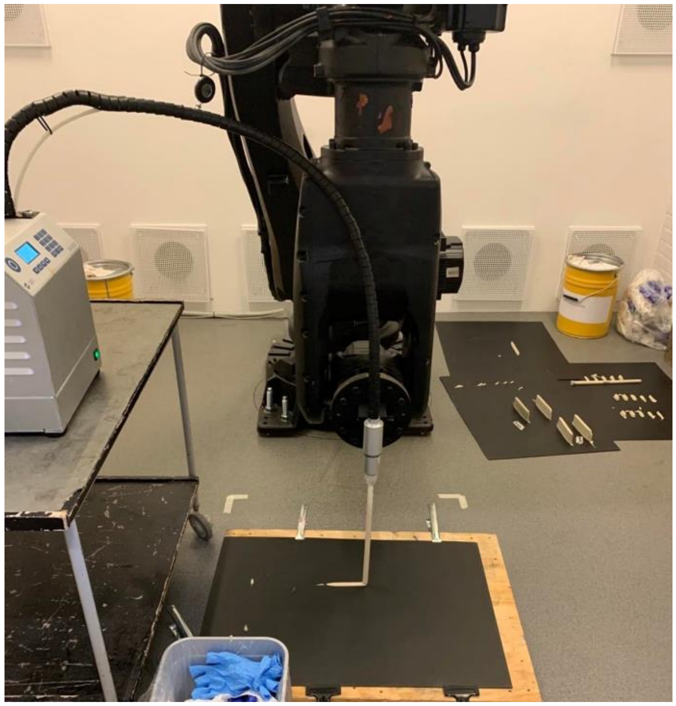

Figure 1 - Picture of the experimental setup. The dispensing system visible on the left is integrated with the industrial robotic arm and printing through a static mixing nozzle.

The samples were printed with 3.5mm layer heights to a total height of 42mm with a width of a single strand. Multiple samples were printed this way, each with different holding intervals between each layer. Table 1 shows the printing parameters of each sample.

Experiment	Holding time between layers	Note
1	-	Bulk material as cast
2	30 seconds	
3	60 seconds	
4	120 seconds	
5	240 seconds	

Table 1 – List of performed experiments with different holding times.

Experiments 2-5 were printed in the following steps. The static mixer tube was primed with material whereafter a strand of 150mm length was printed. Upon completion, the nozzle was moved away from the strand for the duration of the holding interval. The static mixer's volume was completely purged of the curing material prior to the application of the next layer. Upon completion of the holding time, the nozzle was returned to deposit the next strand. This process ensured that wet-on-wet or wet-on-semisolid printing conditions were upheld. The process was repeated until the desired height of 42mm was achieved. The variation in the holding interval between each layer is done to determine how partial solidification in already deposited layers affects mechanical properties and interlayer bonds.

The produced samples were left to cure for 24 hours before being processed for tensile testing. The strands were milled into an ISO 527-2:2012 type 1BB dogbone geometry. Ten specimens were produced from each strand and were milled perpendicularly to the printed layers as illustrated in Figure 2 to ensure multiple layer interfaces along the length of a dogbone. Tensile testing was performed on a *Mecmesin MultiTest 2.5-i* at a rate of 1mm/s with a sampling rate of 100Hz. The data was exported and post-processed using Python 3.8.3 to determine the tensile strength and Young's modulus of the specimens.

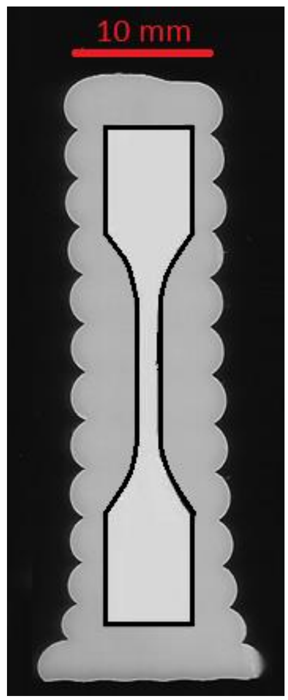

Figure 2 - Illustration of dogbone milling orientation within a printed sample.

In addition to the printed samples, experiment 1 established a baseline of bulk material by producing cast specimens for reference. The experiment was cast in a rectangular 150x14x42mm mould, roughly the same size as the printed samples to achieve a similar curing time. This sample was also allowed to cure for 24 hours before being post-processed in an identical manner to experiments 2-5.

Results and discussion

In this section, the interlayer mechanical properties of MEX-AM of two-component polyurethane are presented and discussed. Tensile testing was performed on 10 dogbones milled from each experiment in *Table 1* to establish statistically significant averages. Pictures of a dogbone specimen from experiment 2 during and after tensile testing are seen in Figure 3. Necking occurred in multiple places but as the test proceeded, the necking sites grew along the length of the specimen. Upon fracture, the multiple necking sites had become indistinguishable and the sample appeared to resemble a conventional dogbone, where necking only occurs in one site.

Figure 3 - Pictures of a dogbone from experiment 2 show necking in multiple places (left) and after break compared to an untested specimen (right).

This multiple necking phenomenon was observed in almost all the specimens from experiments 2-5. It is plausible that layer interfaces caused this behavior, as none of the specimens from experiment 1 were observed to neck in more than one place. The quantitative results from the tensile testing are shown with bar plots in Figure 4. The dark red bar represents the bulk material and standard deviations are shown with error bars.

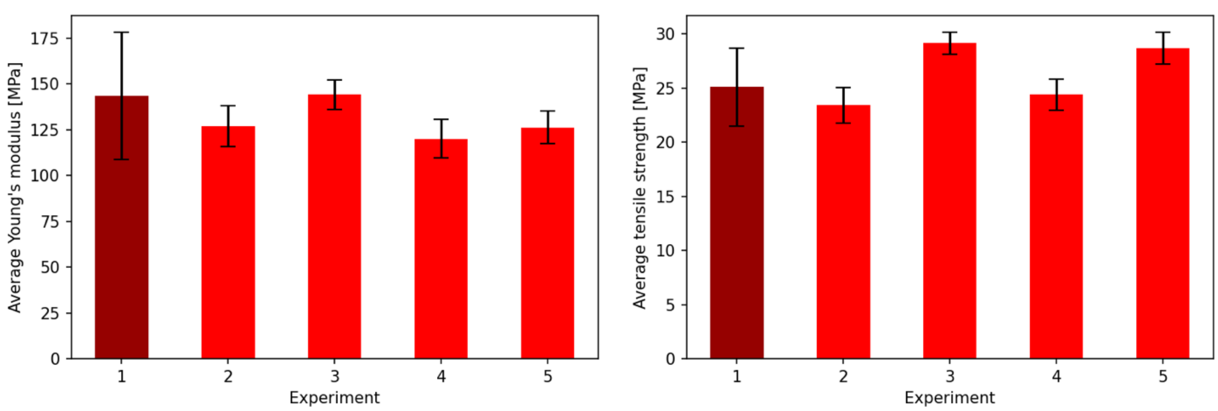

Figure 4 - Average Young's modulus and tensile strength of experiments 1-5.

The results show no significant difference between the interlayer mechanical properties of 3D printed specimens and those of the bulk material. The results also show that the interlayer mechanical properties are irrespective of the 0-240s holding interval between layer deposition of the utilized material. Such results agree with recent finding by Mahmoudi et al. [5], where the authors report on the isotropic behavior and strong interlayer bonds that are independent on the printing direction. On the other hand, Uitz et al. [6] concluded, in regards to tensile strength, that elongation at break has some degree of anisotropy.

The standard deviations are generally low, conducive to the properties being reliable, however the results from experiment 1 exhibit significantly larger standard deviations. This is attributed to the tensile testing being a manually performed process that requires repetitive precision. The specimens milled from experiment 1 were the first to be tested and therefore the repetitive loading process into the machine was not as well established as for the later tests.

There is a notable difference between some of the tensile strengths. This study does not investigate this further and instead attributes it to statistical uncertainty. This is a preliminary study meant to explore the general tendencies of the mechanical properties of two-component thermosets manufactured using MEX-AM. As such, further studies should be conducted to verify the results and look into whether there is a reason for this difference or if it is in fact a product of statistical uncertainty.

The material used for this study exhibits varying mechanical properties that are dependent on the temperature at which it cures. As the curing is exothermic, experiment 1 was cast in a mould of the same size as the remaining experiments to get the same amount of heat generation, however, the mould could influence the cooling rate of the material. The way of casting reference samples may be re-evaluated. In addition, this study should be repeated with different two-component thermoset media/materials to validate the results.

The results presented in this study point to a number of potential applications of the technology. Due to good interlayer mechanical properties, two-component thermosetting polymers could be used for engineering applications, especially for components that require the geometrical freedom provided by MEX-AM. It also shows potential within big-area additive manufacturing, as the speed of the pumps and motion system are the primary limitations. Thermoplastics are not as suited for this, as it requires very rapid heating of large amounts of material.

Conclusion

This study concludes that material extrusion additive manufacturing of two-component thermosets produces good interlayer mechanical properties and can result in almost isotropic behavior. This differs from most other AM processes and could potentially be used for a wider range of engineering purposes than parts produced by traditional thermoplastic FDM. While the interlayer mechanical properties are good, there are still artifacts of the MEX-AM process as the 3D printed dogbones experienced necking in multiple places. Finally, the study should be repeated with a variety of two-component thermosets in order to validate the results.

Acknowledgement

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