Co-Printing Test Specimens as Surrogates for Complex Part Characterization

Mark Peyron, David Gill, Cecile Grubb, Zachary Zywiak, Severn Anderson, Adam Hoch
Western Washington University
Department of Engineering and Design
516 High St
Bellingham, WA 98225

ABSTRACT

Engineers at Western Washington University have been conducting research to develop, analyze, and produce novel materials, processes, and parts utilizing Fused Deposition Modeling (FDM). Throughout this research, there has been a repeated need to test and evaluate 3D FDM-printed parts. However, as the parts are required as a component of materials, product, or process development, it is inconvenient and time-consuming to create replicate parts solely for destructive mechanical testing. We have been investigating a method of "co-printing" of specimens (CoPS) specifically designed for important mechanical, thermal, and morphological characterization and testing. These small CoPS are intended to be representative of the printed parts, and thus need to printed under identical conditions (or as close as possible) to the printed part. As a part is being additively fabricated, there are interactions between adjacent roads and between adjacent layers. These interactions include mechanical, chemical, and thermal processes, each of which can alter localized material properties. The CoPS test specimen must contain sufficient numbers of layers to contain these interactions, but the specimen must also be small enough to build quickly to minimize any effects on the process of building the actual desired part. The test specimen should also be small enough to test easily without a lot of preparation. These challenges have been addressed in the development of CoPS for FDM. The CoPS presented here were designed for dynamic mechanical analysis (flexural and tensile), load-cell based testing (tensile and compression), microscopy (SEM and optical), pycnometry, and thermal testing, with the parts being created on commercially-available FDM printers.
We implemented a series of experiments to evaluate CoPS and report on the suitability of various types and sizes of CoPS for various applications and their advantages and disadvantages.

1. INTRODUCTION

1.1 FDM: from prototypes to production parts

Additive manufacturing using fused deposition modeling (FDM) printing has become more ubiquitous, less costly and ever more applications are being conceived of and developed by engineering workgroups, entrepreneurs, designers and hobbyists. The products of FDM printing have transitioned from prototypes to production parts, a transformation that is even noted in the terminology change from "rapid prototyping" to "3D Printing." The creativity and freedom offered by this technology still must satisfy the customer, who needs to know and count on the properties of the parts that are produced. One means of assuring part properties would be to fully monitor the build process with sensors sufficient to fully monitor and/or control the process such that defined properties can be assured. This strategy is, however, often cost prohibitive. Thus, another method must be utilized to assure the customer of the properties of the printed part.

One topic of printed part characterization that has received considerable attention is dimensional accuracy and reproducibility, especially with relatively complex parts (*e.g.*, [1]). However, a recently publish roadmap for additive manufacturing [2] identified an urgent need for better methods of assessing the quality, reliability and reproducibility of additively manufactured parts. Included in the recommendations is the need for localized property data over a variety of scales which retain information on actual processing history. This is important for part reliability, but also key to evaluating the potential for new materials.

A straightforward method is to simply print a part and destructively test it. The more complex and larger the part, the more costly and time-consuming it is to print, and the less likely that frequent destructive testing would be viewed as an attractive option for assuring quality in these production parts. Moreover, the part itself may be sufficiently complex in geometric structure that no areas of the part are usable for testing under standard specified testing protocol. Lastly, this method does not assure that the next or previous production part meets specifications, though this is generally assumed to be true. This assumption is especially tenuous when utilizing consumer-grade 3D printers that have little or no closed-loop feedback and process control.

A method that has often been employed is to print test specimens separately and infer part quality from the results of these quality test coupons. The literature is replete with papers that have successfully used these methods for identifying improvements in print planning (raster orientation, infill type and %, *etc*.) and to assess new printer filaments. [3, 4]

In this paper, we propose an alternative methodology, one in which small-scale test specimens are printed simultaneously with the actual production part. If methods for simultaneously printing quality test specimens that are representative of the actual, larger printed part could be identified, then the small test specimens could be tested destructively and the results applicable to the as-printed part. We call these specimens printed simultaneously with the production part co-printed specimens, or CoPS.

1.2 Co-printing principles defined

Though establishing a universal plan for printing quality-assurance specimens is not possible given the different parts, part functions, printers, thermal, temporal and spatial inhomogeneities, we seek to identify a cohesive set of principles for co-printing, and to give specific examples of how they can be employed. CoPS are inherently adaptable to new circumstances and new CoPS can be created as part and material characterization needs arise. The general principles of co-printing are:

- CoPS should be spatially distributed in the *xy* print bed as well as the *z* axis to permit investigation of part variabilities (dimensions, mechanical properties, voids, *etc*.).
- CoPS should be thermally representative of the printed part with thermal effects of the bed, support material, and unsupported material represented in the test specimen.
- CoPS should be temporally representative of the part, so that the time lag between layers (which greatly affects layer adhesion and properties) in the part matches that of the CoPS.
- CoPS should be able to assess part-to-part variability and within-part variability. For long print times, the latter must be shown to be within part specifications.
- The volume of the CoPS should be small relative to the production part volume so that the added time for co-printing does not adversely affect the quality of the printed part. This places an upper limit on the number and size of the CoPS.

- The CoPS themselves should be sized so that they can be used to produce reliable test results. This may result in specimen dimensions that differ from standards such as ASTM thermoplastic standards.

1.3 Comparison of co-printing with other strategies

Table 1 lists advantages and disadvantages of various methods for performing quality assurance testing for FDM printed parts. These range from doing no testing to performing non-destructive testing to planning and creating customized co-printed test specimens. The biggest limitation to co-printing is expected to be related to the volume of the CoPS (V_{CoPS}) relative to that of the production part (V_{PART}). If $V_{\mathrm{PART}} >> V_{\mathrm{CoPS}}$, then the added time between layers required for co-printing is relatively insignificant, and the effect on the actual part is expected to be minimal.

Table 1. Comparison of strategies for testing of FDM printed parts and test specimens.

Print Testing Strategy	Advantages	Disadvantages
NT: No testing (no co-print; no QA/QC tests)	• Least initial time & initial cost	• Part failure not attributable to specific causes • Part not qualified for its application
DT: Destructive testing of actual part; no co-printing	• Part failure directly evaluated	• Costly print time for producing full additional parts • Geometry may preclude testing • Variability between prints not assessed
NDT: Non-destructive testing of actual part; no co-printing	• Information obtained on as-printed part, usually from some imaging technology (X-ray tomography of ultrasound)	• Costly instrumentation • Image-only data does not provide mechanical or other properties
SPP: No co-print with part, only separate pre- or post-print of specimens	• Non-destructive for actual part • Some spatial and temporal factors investigated	• Not representative of as-printed part • Qualities of printed part inferred, not measured contemporaneously
BDA: Test specimens printed before, during and after part printing	• Non-destructive for actual part • Some spatial and temporal factors could be investigated • Replicate test data available if temporal effects ignored	• Pre- & post-printed specimens not representative of as-printed part • Tool path may interfere with during and post-print specimen location unless printed far from the part
CoPS *xy*: Test specimens co-printed as satellites around the printed part on bed surface (*xy*)	• Non-destructive for actual part • CoPS representative of as-printed part if height-matched to actual part	• Influence of layers near bed could be significant • Extensive co-printing adds print time that could affect part quality
CoPS *xyz*: Test specimens co-printed as satellites around part (*xy*) & stacked in *z* direction with support between	• Non-destructive for actual part • CoPS representative of the printed part • Influence of bed can be controlled through support layers near bed • Temporal, spatial & thermal effects investigated	• Extensive co-printing adds print time that could affect part quality achievable without co-printing • Additional print time may significantly change printing economics

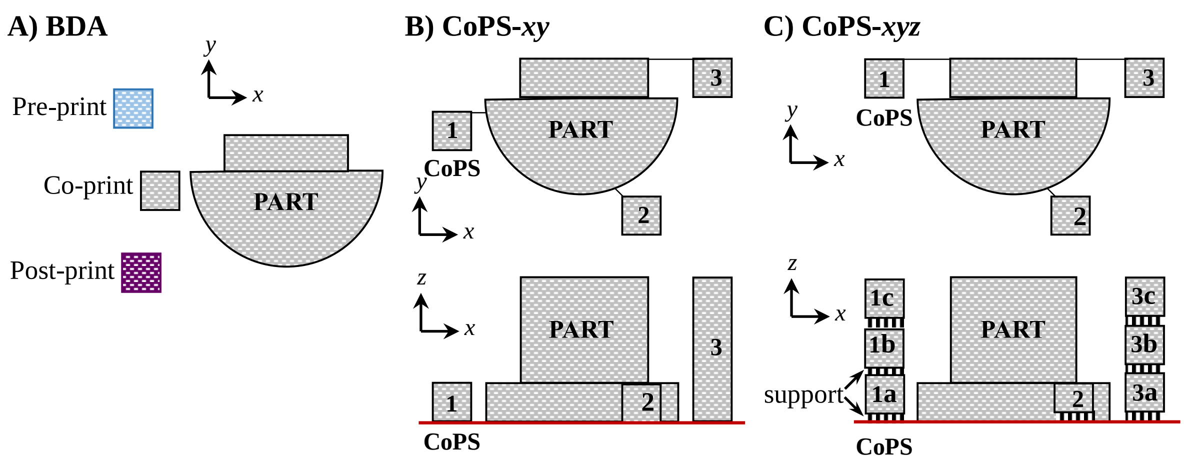

Figure 1. Comparison of co-print strategies. **A**) BDA: Test specimens spaced relatively far from the part and printed before, during and after the part print. **B**) CoPS-*xy*: Co-printed specimens, spaced very closely to the part in the *xy* plane and locally height-matched. **C**) CoPS-*xyz*: Co-printed specimens arranged very near the part (*xy*), but separated from the printer bed and each other by low-infill, removable support that creates a "stack" to represent vertical variability.

2. EXPERIMENTATION

2.1 Printers, print planning and filaments

The study described in this paper was conducted utilizing two different printers at Western Washington University. The DSC samples and CoPS *xyz* were printed using a F306 printer produced by Fusion3 Design (Greensboro, NC, USA). The F306 printing utilized 1.75 mm ABS polymer from MakeShaper (Sanford, NC, USA) printed on a glass bed using a glue stick to aid polymer/glass adhesion. Process planning utilized Simplify3D software, and printer settings including 245 °C nozzle temperature, 110 °C bed temperature, 4500 mm/min printing speed, 100 % rectilinear infill, and skirt. The 0.350 mm diameter nozzle was set to deposit roads with a width of 0.450 mm and layer thickness of 0.200 mm. The CoPS-*xyz* parts used 30% density serpentine support with a raft. Different DSC samples were made, but the samples made above the bed utilizing support required a 60 % support density and 1.50 mm support pillar resolution because of the small size of the parts. The F306 has an enclosure that is not temperature controlled, but reaches an equilibrium of approximately 38 °C near the build level during printing like that listed above. The parts for the CoPS-*xy* satellite test used a LulzBot TAZ-5 printer (Aleph Object, Inc, Loveland, CO, USA). The specimens were printed using 3.0 mm HIPS on the PEI print bed with 250 °C nozzle temperature and a 110 °C bed temperature. Process planning was performed using Cura LulzBot Edition (David Braam and Ultimaker).

2.2 Pycnometry

Polymer infill in CoPS was measured using liquid pycnometery with a Hubbard-Carmack capillary-stoppered specific gravity bottle (25 mL capacity; Sigma Aldrich). The procedure was based on ASTM standard D70. [5] Eq. 1 shows the measured values used in this method.

$$\frac{\rho_S}{\rho_W} = \frac{S}{W - N} \quad [1]$$

ρ_s and ρ_w are the density of printed sample and pure water at the temperature of the measurement, respectively. *S*, *W* and *N* are the masses (g) of the dry specimen, pycnometer vessel with water and vessel with water and specimen, respectively. The infill fraction of the CoPS is ρ_s/ρ_0, where the void-free filament density is ρ_0. Degassed deionized water was used for all measurements. Printed specimens with volumes of 1 – 5 cm^3 were tested. All samples were dried at 30°C under vacuum prior to measurement, and the specimen mass before and after immersion in water was measured to check for water infiltration into the sample. More than 60 samples have been measured using this technique; the precision achieved for % infill was less than ±1 percentage point.

2.3 Differential scanning calorimetry (DSC)

Calorimetry measurements were performed using a TA Instruments DSC Q200 instrument. Both specific heat capacity [6] and thermal conductivity have been measured, the latter using modulated DSC. [7, 8] Modulated DSC requires variable height specimens to induce a thermal lag, from which thermal conductivity is measured. Variable thickness (0.3 – 4 mm) circular diameter (4 mm) specimens were printed with ABS filament to illustrate such small specimens as potential CoPS. Sample diameters were chosen so that they fit within the hermetic aluminum DSC pans. The modulation conditions were a 40 °C baseline with a ± 1.0 °C modulation with an oscillation period of 80 s.

2.4 A Co-printing case study: CoPS-*xy* satellite specimens

Layer to layer adhesion has been reported by many authors as being a principal source of mechanical failure and reduction in the bulk (apparent) material properties of FDM produced parts. [9] One proposed strategy for providing test specimens that best match the layer to layer properties of a part is the co-printing of satellite specimens. These specimens are not printed at the same *xy* location of the design part, but are printed very near to the part in regions of the print bed that are assumed or measured to have similar temperature. The satellite parts are printed at the same time as the design part providing temporal similarity in layer to layer deposition times. If the satellite parts are of analogous size to the design part, the proposed test components should provide representative thermal histories as well as contain similar defects for any anomalies that occurred during the printing process. However, if the satellite parts are too big, they will have an adverse effect on the design part by increasing the layer to layer time significantly.

A test was conducted to evaluate the utilization of satellite specimens for process evaluation. This is only a first try at using co-printing and the part itself was not integral to the analysis. The satellite parts for this test, shown in Figure 2, were designed as compression test towers with design dimensions of 12.7 mm x 12.7 mm x 25.4 mm. The design part for this build was a ring with 50 mm outer diameter, 6.35 mm wall thickness, and 25.4 mm height, and was surrounded on 4 sides by compression test specimens arrayed every 90°. The design part's volume was 22,700 mm^3 and the 4 compression specimens surrounding each design part had a combined volume of 16,700 mm^3 making the total build increase by 73 %. The selection of the type and dimensions of each test specimen should match the goals of the project. In this case, the team was already utilizing compression test specimens of this size for other research, so continuing this size would allow any measured data from this test to be possibly be leveraged for use in other experiments as well. These compression specimen dimensions were used in an effort to reduce any edge effects that might occur from the border walls, hopefully providing a good measurement of the bulk deposited material. However, the 73 % increase in overall material volume owing to co-printing seems somewhat excessive and this test could well have been completed with fewer specimen towers. While the 4 towers held the promise of measuring additional position-dependent information, utilizing 3 towers would have only increased the build volume by 55 % which might well be more50 mm di reasonable while still providing good spacing around the design part. Because of utilizing 4 test towers, the authors chose to emphasize positional identity with the design part at the expense of temporal identity.

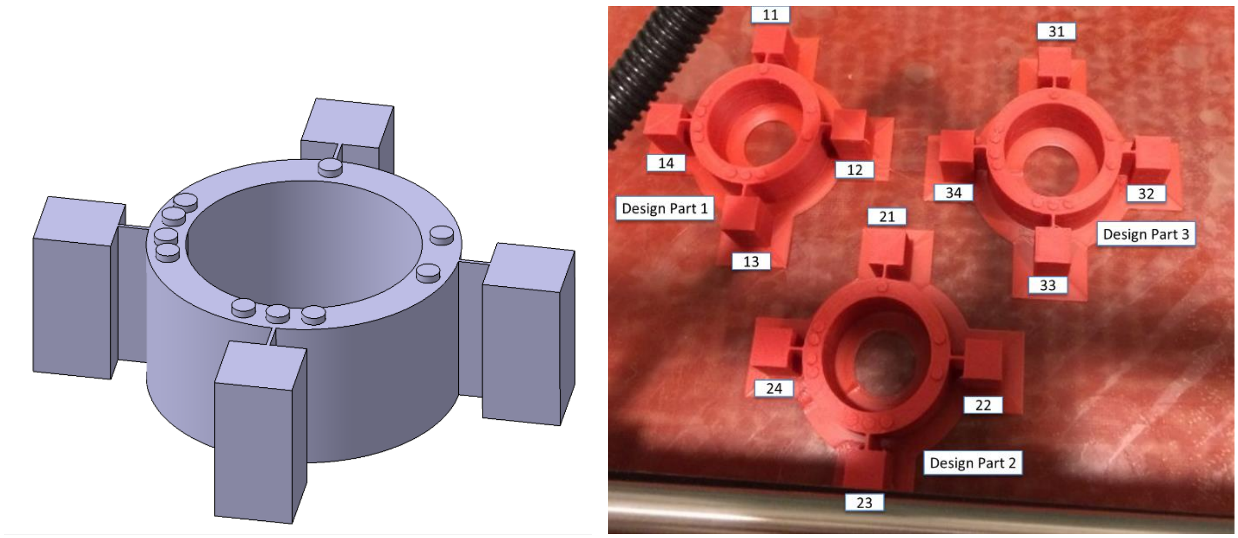

Figure 2. Model of design part with 4 co-printed compression specimens (left) and 3 completed parts shown on the print bed as built (right). For each specimen, the first number denotes the design part number and the second number denotes sample number.

The CoPS were tied to the main part with thin walls with the intent that the printer would continue to deposit material as it transitioned from the design part to the test specimen so that the specimen would not contain additional extruder starts and stops that might affect results. The risk of this method is that the design part will be affected cosmetically or structurally by the connection points of these thin webs. A decision must be made for each case that utilizes knowledge of the purpose and function of the design part.

Each of the design towers was separated from the design part and individually tested. Compression testing was performed using an MTS Insight universal tester using aluminum platens; the compression speed was 0.05 in/min, as per ASTM D695.

3. RESULTS

Selected examples of co-printing and a description of results are presented below.

3.1 Co-print case study: compression data

The CoPS-*xy* case study compression towers were tested individually with the post-test specimens shown in Figure 3.

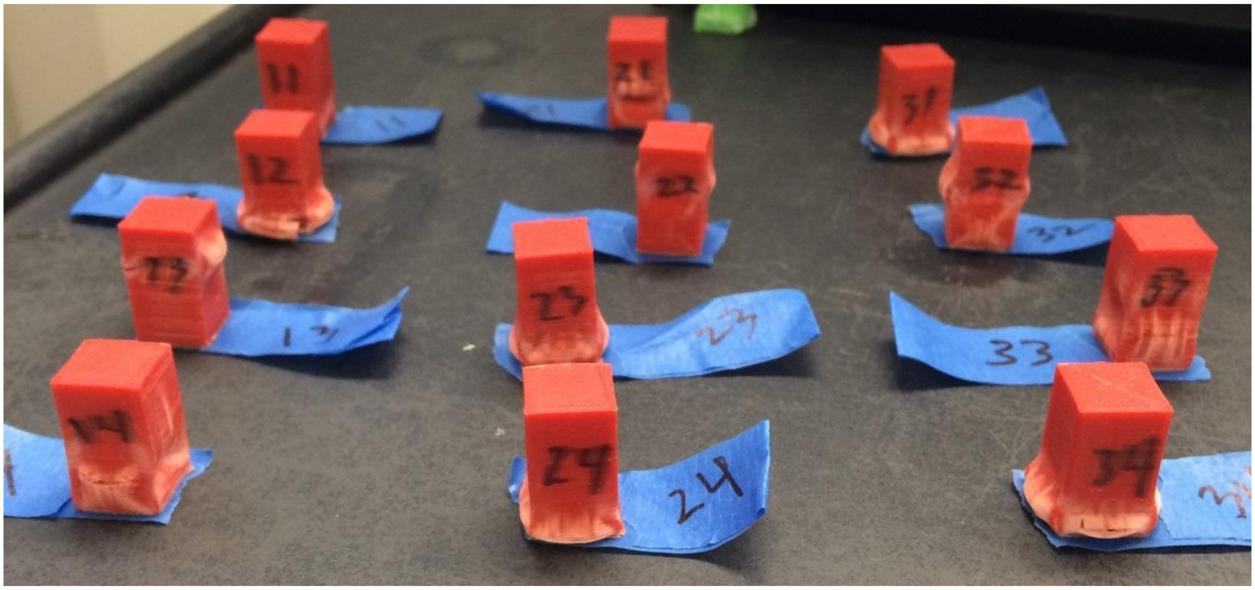

Figure 3. CoPS-*xy* satellite compression test samples after testing showing orthogonal double barreling and possibly compression instability due to work softening.

By appearance, the specimens failed primarily due to double barreling (specimen labeled 13, 21, 22, 32, 33) or by yielding that may be suggestive of compressive instability due to work softening (seen in all other samples flared at one end).[10] The double barreling samples had one barrel oriented along one part axis and the other barrel occurring in the orthogonal axis (*e.g.*, if top barrels along *X* axis then the bottom barrels in the *Y* axis). There is no statistically significant correlation between the build position of the test specimen (around the diameter of the part) and the failure mechanism or peak stress achieved. In fact, all of the samples shared similar maximum compression stress achieved within one standard deviation. The size of the parts in *X* and *Y* was also very similar with only 2 parts lying outside the band of 1 standard deviation. With there being no statistically significant variation in maximum compression stress, there was also no significant correlation to the spatial position of the 3 design parts on the bed or of the spatial distribution of the CoPS towers around the design parts. This was the desired outcome as the design parts were grouped relatively close together on an area of the bed expected to have very uniform temperature. However, the lack of variability in the CoPS would give a design engineer some level of assurance that the actual parts contained uniform properties across the dimension of the part.

The next planned experiment is to qualify the co-printing method using a carefully designed part consisting of a grouping of different compression test specimens printed with different scale factors and with different starting and finishing heights above the print bed. This “design part” will then be appropriately surrounded with satellite CoPS-*xy* selected to provide data for parts printed with representative temporal and thermal histories and at representative print bed spacings.

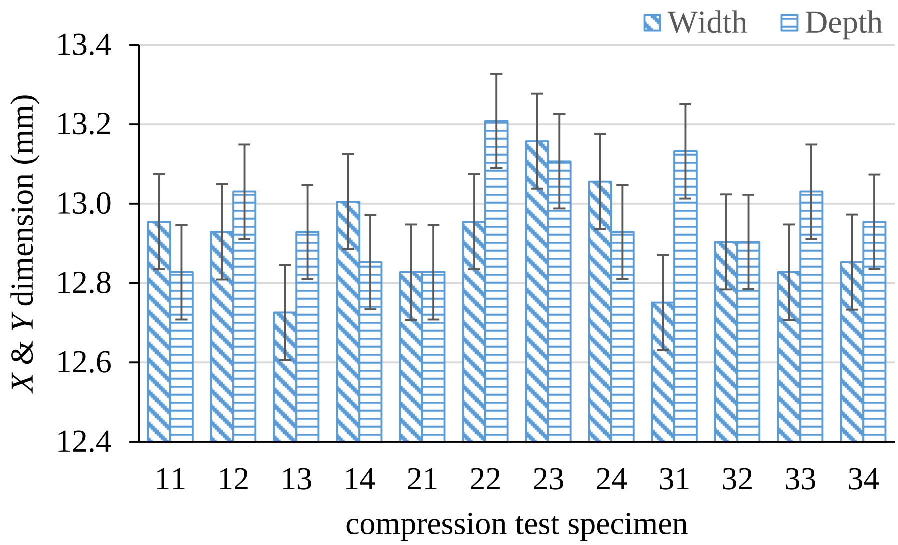

Figure 4. Comparison of *X* (width) & *Y* (depth) dimensional stability. Error bars represent ±1 standard deviation for the data.

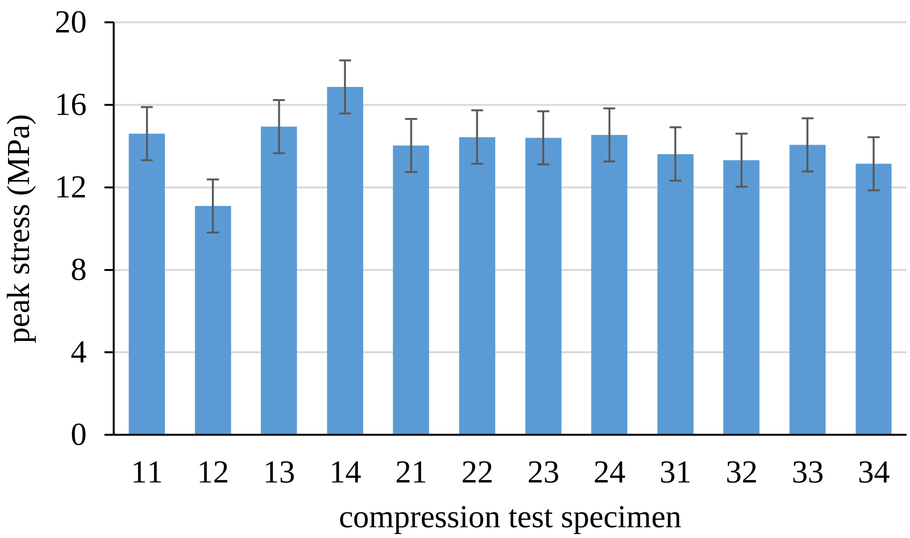

Figure 5. The compression test showed no significant variation between the towers built at 4 locations around each of the 3 design parts.

3.2 Pycnometry

Pycnometry is an example of a test method for which the optimum specimen size may be determined by the characterization method, but the influence on the production part must always be considered. The 25 mL pycnometer used (see Figure 6) has a wide mouth, and samples up to a diameter of about 17.5 mm and height of 25 mm can fit inside. The best precision is achieved with the maximum displaced liquid (*i.e.*, the largest specimen). On the other hand such a relatively large CoPS might constitute a significant volume relative to the production part. Thus a compromise might be necessary. The production part quality must not be compromised by too extensive of co-printing, so the actual CoPS size might have to be smaller than would otherwise be optimal. For larger production parts, this compromise may not be necessary. This application illustrates that the appropriateness of CoPS must be determined on a part-by-part basis.

Figure 6. Pycnometer containing a cylindrical FDM printed specimen.

Liquid pycnometry is potentially non-destructive, provided that during the brief time that the specimen is submerged in water, little water is taken up by the sample. This requires that specimens are wrapped with a single road with good layer-to-layer adhesion. Also, commercial pycnometers are quite small and may not fit the larger design part, thus requiring the use of CoPS to evaluate the build quality. The specimen may be re-dried in a vacuum oven and subjected to further tests, but there is some risk that even a small amount of water absorption could alter some of the mechanical properties. Using the re-dried pycnometry specimens subsequently for microscopy (optical or SEM) is a viable alternative to obtain additional part characterization without additional co-print times. Gas pycnometry is a technique that also can be used to measure void content, but requires specialized instrumentation.

3.3 Differential scanning calorimetry

In contrast to the size limitations with certain CoPS, other types of test specimens may be affected by thermal and spatial variations within the print envelope. This is illustrated with small DSC specimens. For certain applications, such as printed injection molds, heat transfer is a key property, but part voids and build design significantly influence thermal conductivity. This is an example of the need for test specimens to match the as-printed part properties. In this case, modulated DSC was used to measure thermal conductivity in printed ABS parts (100 % rectangular infill). The measured thermal conductivity was 0.40 $W \cdot m^{-1} \cdot K^{-1}$, which is somewhat higher than published data for ABS (0.19 – 0.36 $W \cdot m^{-1} \cdot K^{-1}$).[11] The heated bed of a FDM printer introduces long-lasting thermal effects on properties in layers adjacent to the bed.[12] One way to reduce this effect is to separate the specimen from the print bed, as illustrated in Figure 7.

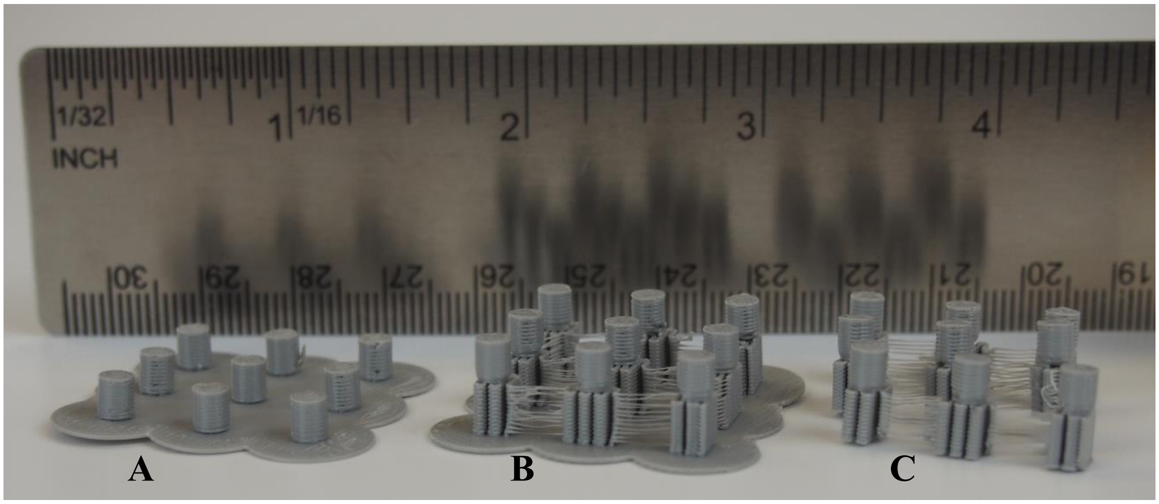

Figure 7. Cylindrical modulated DSC specimens (4 mm diameter X 4 mm height). **A**) Replicate specimens printed on a single-layer raft. **B**) Specimens printed on a raft then separated from the print bed by support material to insulate the specimens from the thermal effects of the heated bed. **C**) Same as B, but no initial raft layer (note the strands between the support stacks). In B) & C), the supported specimens are easily separated from the low density support layer.

3.4 Identified test specimens

Research into new materials is inhibited by the inability to readily untangle material property influences from thermal and temporal inhomogeneities in the printer envelop, reliability and performance of the printer and print planning and design factors. Indeed, each printed part could be thought of as a new material. In order to characterize important material and part properties, we have printed many types of specimens, many of them are relatively small and suitable as CoPS. An example is shown in Figure 8.

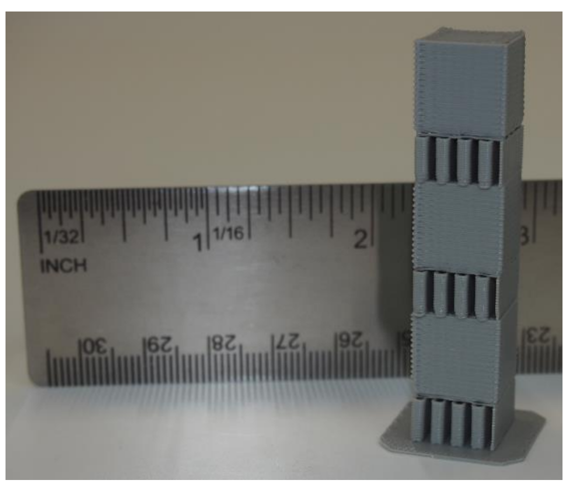

Figure 8. Illustration of stacked specimen for assessing influence of temporal and vertical (z) spatial effect in the print envelope. This specimen can be used for measuring infill by pycnometry, for compression testing and for microscopy.

A number of the specimens that we have used in research are identified in Table 2. The table lists some common sizes and build orientations that we have investigated. This compilation represents only what we have investigated so far. Co-printed specimens can, in general, be developed for many other tests, provided that they do not adversely affect the production part properties. Some obvious test specimens are omitted from Table 2, including tensile bars and impact specimens. Standard sizes of these specimens are deemed to be too large for most co-printing applications. An exception might be for smaller load cells and impact testers or for very large print envelopes.

Table 2. Co-printed specimens identified for various characterization tests

Void characterization (liquid pycnometry) • Cylindrical (diameter X height): 10 – 17 mm X 10 – 25 mm build info: *z* (height) • cuboid (length X width X height): 10 – 17 mm X 10 – 17 mm X 10 – 25.4 mm build info: 1) *x* (width), *y* (length), *z* (thickness) or 2) *x* (width), *y* (thickness), *z* (length)
Compression testing (universal testing apparatus) • cuboid (length X width X height): 12.7 – 17.8 mm X 12.7 – 17.8 mm X 12.7 – 25.4 mm build info: 1) *x* (width), *y* (length), *z* (height) or 2) *x* (width), *y* (thickness), *z* (length) • cylindrical (diameter X height): 10 – 17 mm X 10 – 25 mm
Flexural testing (dynamic mechanical analysis, DMA single and dual cantilever fixture) • rectangular (width X thickness X length): 10.0 – 12.7 mm X 1.5 – 3.0 mm X 30 – 60 mm build info: 1) *x* (width), *y* (length), *z* (thickness) or 2) *x* (width), *y* (thickness), *z* (length)
Microscopic characterization (optical & electron microscopes; sectioned along length) • cuboid (length X width X height): 5 mm X 5 mm X 5 – 60 mm build info: 1) *z* (height) • cylindrical (diameter X height): 5 mm X 5 – 60 mm build info: 1) *z* (height)
Thermal conductivity and specific heat capacity (DSC specimen) • Squat cylinder (diameter X thickness): 4 mm X 0.5 – 5 mm • build info: 1) *z* (thickness)
Tensile and thermal testing* (DMA tensile fixture) • filament (diameter X length): 1.75 – 3.00 mm X 25 – 30 mm * not a printed sample, but a segment of the printer filament

4. CONCLUSIONS

Presented is the concept of using co-printed specimens to provide part manufacturers with assurance of part properties representing the entire build process without the need to perform destructive testing on production parts. The CoPS concept provides a framework for the placement, sizing, and design of test specimens for different testing needs that are representative of the designed part while not significantly influencing or degrading the printing of the design part.

Strategies were presented to appropriately define CoPS geometry and location practices that are representative of the thermal, temporal, or spatial aspects of the part. While no single CoPS can be completely effective at matching all three aspects, a carefully considered and designed part can address the aspects that are of greatest importance to the design part.

Several example CoPS geometries were presented because different part functions and geometries require different tests to confirm part performance. These specimens demonstrate the adaptability of the CoPS concept and some of the decisions that must be made during CoPS implementation. The samples are designed for dynamic mechanical analysis (flexural and tensile), load-cell based testing (tensile and compression), microscopy (SEM and optical), pycnometry, and thermal testing.

Finally, a case study was presented using compression CoPS to represent the properties of a design part. The case study showed minimal spatial variation in compression results giving confidence to the manufacturer and designer that the designed parts will share similar properties, especially relating to compression.

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