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Evaluation of Thermography Inspection Procedures for Characterization of Water Degradation in Polymer 3D Printed FDM Parts

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ABSTRACT

Due to the nature of FDM 3D printed polymer parts, they easily absorb water. Thermography can help characterize the level of water absorption based off a few different parameters, but the material state is highly dynamic and dependent on surrounding environment. The challenge for experimental test specimens is that water can continue to absorb into different portions of the part and dry in others. This makes it difficult to effectively identify and determine parameters for characterizing water degradation. This paper reports the initial evaluations of a procedure for thermography inspections that involves freezing 3D printed FDM parts as a means to stabilizing an absorption state. Placing specimens in a freezer has shown potential to stabilize an absorption state without significantly altering data.
Keywords: Flash Thermography, 3D printing, Additive Manufacturing, Water degradation, Polymer aging

1. INTRODUCTION

FDM (fused deposition modeling) additive manufactured (AM) parts are now used in many functional use applications beyond the traditional prototype design purposes of the past. However, these functional printed parts experience unique environmental aging mechanisms that are different from traditional polymer fabricated parts. All polymers can experience various thermal, UV, chemical, and other aging degradations from environmental exposures [1], but FDM printed parts have more porosity, surface roughness, and complex internal cavities that provide additional aging considerations. Often such features accelerate traditional degradation mechanisms, and better experiments and quantification methods are still needed to understand the impact on part lifetimes.

Flash thermography, widely used for Nondestructive Evaluations (NDE) of composite laminates and sandwich structures, is a potential characterization technique for AM because many part designs consist of solid outer wall shells filled with internal lattice structure cavities. Changes in outer wall thickness, lattice interface, polymer chemistry, or trapped liquid/media all affect the heat transfer physics measured by thermography. The goal of this investigation is to identify appropriate specimen designs, measurement challenges, and procedural approaches before conducting more thorough aging, characterization, and development research.

2. MATERIALS AND METHODS

Even though many environmental aging mechanisms are of importance to FDM parts, water absorption was selected as a simple starting place for investigation. Water absorption occurs rapidly and changes the heat transfer properties significantly which allows for quicker experiments and measurement testing. The Markforged X7 printer was selected for these tests along with their proprietary Onyx material which is a Nylon formulation with embedded carbon particulate. The carbon provides a strong black color and opaque qualities for good heat generation at the surface from radiated flash lamp energy. Data was collected using a Thermal Wave Imaging ThermoScope 3 flash thermography system and analyzed with their Virtuoso software suite of tools.

3. RESULTS AND DISCUSSION

3.1 Categorization of water absorption states

Before developing the measurement approach, it is useful to categorize the expected material states that may occur for water absorbed FDM parts. Five primary categories have been defined for initial considerations (and illustrated in Figure 3.1.1): 1. partial water ingress into outer shell wall that has not reached the inner boundary, 2. Full water ingress into outer shell that has reached the inner boundary, 3. full water ingress with additional internal pooling, 4. partial water egress from the inside out with internal pooling (or where external surface has begun to dry), and 5. fully dry.

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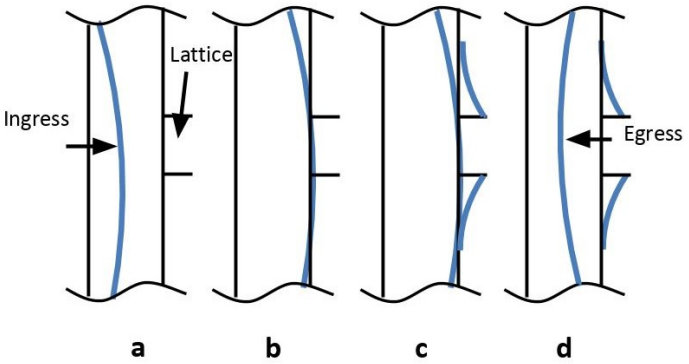

FIGURE 3.1.1: A) PARTIAL INGRESS B) FULL INGRESS C) FULL INGRESS WITH POOLING D) PARTIAL EGRESS WITH POOLING

3.2 Thermography parameters of interest

In evaluation of traditional thermography inspection parameters, a few were selected with specific interest for initial testing. In flash thermography, radiating heat from a flash pulse is absorbed at the material surface, and the surface cooling, or temperature decay, is monitored in time after the pulse event with an infrared camera. Characterization is performed using the Thermographic Signal Reconstruction (TSR) method [2,3], where the logarithmic time history of each pixel is fit with a low order polynomial, creating a noise-free replica of the original data sequence for analysis, differentiation or other mathematical operations. A linear decay of slope -1/2 in the TSR time history indicates a thick (semi-infinite) material. Since water presence should change the level of energy absorbed from the flash, the Y-intercept of the temperature decay line is the first measurement parameter of interest. This value can be determined for an individual pixel with a log-log plot of temperature with time or viewed as an image of all pixels using the first frame capture after the flash pulse. Figure 3.2.1 shows two example TSR curves.

Another common parameter of interest is the first derivative of the temperature curve. As heat transfers through the outer shell wall it eventually meets an air, water pool, or lattice structure internal boundary. The cooling rate effectively changes at this point, and the time at which the curve deviates from linear corresponds to the thickness of material where boundary occurs. The first derivative makes visualization and quantification of the internal boundaries easier.

The second derivative obtained through TSR is another widely used thermography parameter that is potentially useful in discriminating between wet and dry boundaries. Heat traveling from wet to dry, or from material to air, will experience an insulation effect, but heat traveling from dry into wet, or material to water pool, will experience increased conductivity. Therefore, the second derivative should be at zero during linear temperature decay and change to positive or negative values corresponding to insulating or conducting boundaries respectively.

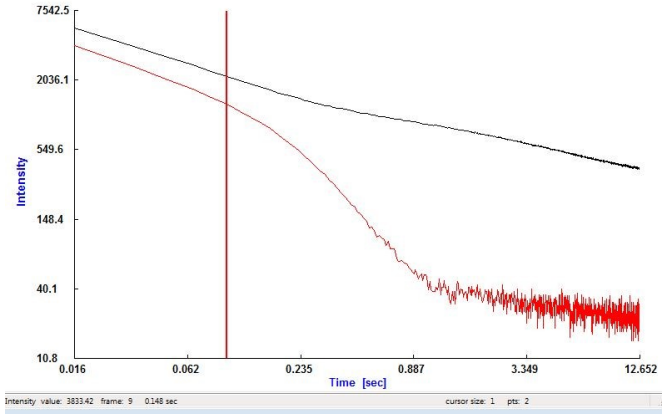

FIGURE 3.2.1: LOG-LOG PLOT OF DRY CUBE (TOP LINE) AND CUBE WITH INTERNAL WATER (BOTTOM LINE)

3.3 Test specimen designs and water absorption

The initial specimens tested were primarily 1.5 cm x 1.5 cm x 1.5 cm cubes printed. The default settings on the printer were not changed, resulting in 0.2mm side wall thickness, 0.4mm roof and floor wall thickness, and a 37% triangular lattice infill. The specimens were exposed to water in a few different methods. Some were placed in water with various faces contacting water. Others just had a few drops on the top of the cube, and a few were cross-sectioned and had water placed directly inside of them.

After water was inside or on the part, the water began to absorb into other portions of the cube. In some cases, it would dry out too fast to collect much data. This made it difficult to obtain consistent data on each of the parameters. To counter this issue, immediately after the water was trapped in the cube, the cube was placed in a freezer and frozen. The assumption is that ice would have similar properties to the liquid water but would maintain stable location over time.

A consistent calibration process for inspecting water absorption and other degradation mechanisms will eventually be needed and other stair-step style specimen designs are also being considered. The key will be having consistent procedures that allow replication of the data across time, temperature, wall thickness, and lattice design variations. The current procedures are to remove specimens from the freezer, quickly capture flash thermography data, and immediately return to the freezer. Initial evaluations have shown that specimens can be taken from the freezer for repeat measurements, but more evaluation and development of consistent procedures and calibration methods are still needed.

3.4 Initial measurements

In the Virtuoso TSR image (Figure 3.4.1), water can be seen in cubes A and B. In the image, cube C is a dry cube to act as a control specimen. The blue shade on the cubes indicates less energy absorption which in this case, means that water is present. The image indicates that cube A has the most water inside and cube B has less or very little water.

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This aligns with the expected data based on how the cubes were soaked.

The first derivative (Figure 3.4.2) shows where internal boundaries occur. However, it does not differentiate between water and the internal lattice structure. This differentiation occurs in the second derivative (Figure 3.4.3) where there is a clear distinction between lattice structure, empty space, and water. In this image, the yellow color represents a zero value second derivative. The positive red color then represents heat conduction into an insulator (air) while the negative blue color represents increased conduction (into water). Since the lattice is the same material as outer shell, it remains near the zero value for second derivative. Since specimen A has significant water saturation and no internal lattice structure, it shows a solid blue conductor behavior. Small areas of pooling are evident in specimen B as well, but the overall lattice to cavity color contrast is less than the dry specimen C.

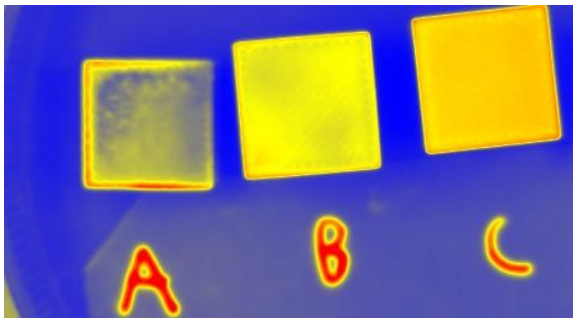

FIGURE 3.4.1

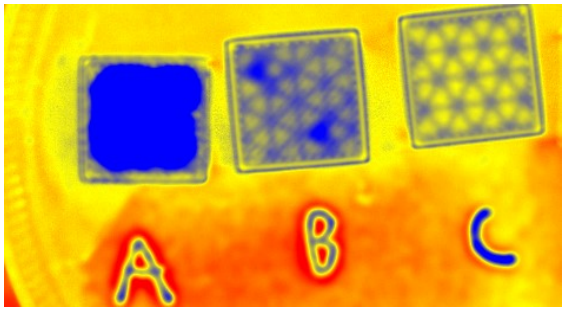

FIGURE 3.4.2

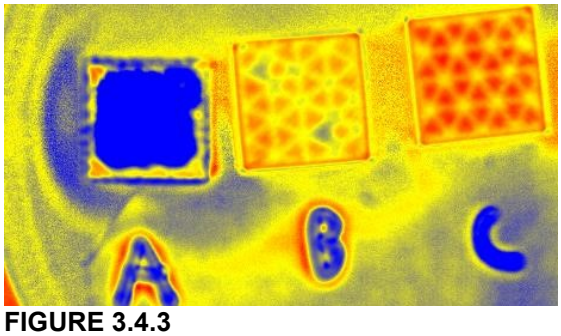

FIGURE 3.4.3

4. CONCLUSION

Freezing the experimental specimens shows potential to be an effective procedure to trap water in the specimens and allow for data to be repeatable. The same parameters of interest that occurred in specimens with water also showed up in the frozen specimens. This shows that freezing the specimens may be a viable procedure to gather consistent thermography data on different water absorption states in FDM parts.

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REFERENCES

[1] S. Freed, “High resolution ultrasonic Rayleigh wave interrogation of a thermally aged polymeric surface”, Ph.D. Dissertation, Univ. of Dayton, Dec. 2010.

[2] S. Shepard, Y. Hou, J.R. Lhota, T. J.M. Golden. *Automated processing of thermographic derivatives for quality assurance*, 2007

[3] Temporal noise reduction, compression and analysis of data sequences, U.S. Patent 6,516,084

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