Finite Element Analysis of Polymer Based Additive Manufacturing: A Derived Approach

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ABSTRACT

Additive manufacturing is a manufacturing process used to create end user parts from depositing a material in an additive manner to build up a 3-dimensional part layer by layer. Additive manufacturing is becoming more accessible and popular thanks to the declining cost of 3D printers and materials, and it is now widely used in a variety of industries and applications such as automotive, medical, and aerospace. A wide variety of materials can be used in 3D printing such as metal and polymer. While the finite element analysis (FEA) has been used to simulate additive manufacturing using metal, it has yet to be applied to polymer-based additive manufacturing. This paper presents some preliminary results of the deformation of 3D printed structures with various polymer materials, including ABS, Elegoo ABS-like, Molazon SER, Resion M58, Vero Black Plus, and ABS-M30 FDM. Autodesk Fusion 360 was utilized to perform the FEA simulation using the parameters of these materials provided by their manufacturers. The simulation results conform to the experimental results very well with a relative error that is less than 5% at 50N force. In addition, this paper also presents the experimental results of an immersion test in a chlorine solution as it is related to the future application of the printed parts. The changes in two attributes of the part were recorded and compared after the immersion, including thickness and hardness. Molazon SER and Vero Black Plus exhibited the least changes in thickness and hardness, while Molazon SER is deemed the most feasible material thanks to its low cost for the application to be developed.

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INTRODUCTION

Additive manufacturing has been used within industry leading back to the early 1980's. In the early 2010's it became a more accessible and popular method of prototype manufacturing due to the drop in costs to manufacture polymer-based 3D printers. These lower cost 3D printers were of a Fused Filament Fabrication (FFF) type. FFF is the generic term for what Stratasys developed with the trade name of Fused Deposition Modeling (FDM). The terms FFF and FDM are used interchangeably in the current discussions of filament-based 3D printers produced today. This paper focuses on the analysis of this type of 3D printing process and will not discuss the use of methods with regards to Selective Laser Sintering (SLS) or Stereolithography (SLA) based resin 3D printing. There are six popular filament-based polymers used within the 3D printing workspace. These filaments include: Polylactic Acid (PLA), Polyethylene Terephthalate Glycol (PETG), Acrylonitrile Butadiene Styrene (ABS), Thermoplastic Polyurethane (TPU), and Polyamide 11 and 12 or also called Nylon 11 and 12 (PA 11, PA 12). (Cattenone, Morganti, Alaimo, & Auricchio, 2019)

The use of simulation to perform Finite Element Analysis (FEA) has been a long-established practice. To that end, this paper will describe the FEA methods that were used in additive metal manufacturing to establish a way forward for conducting FEA on polymer-based additive manufacturing. Since simulation imitates one process to produce results for another process (Gruene-Yanoff & Weirich, 2010), this work will use the polymer materials as an analog to the metal-based practices that already exist. 1D Boundary FEA methods were used for experimentation. Follow-on research would be needed to determine physical experimentation methods. Those experiments would provide validity to any simulation model produced and it is highly encouraged to conduct experiments. (Gruene-Yanoff & Weirich, 2010)

BASIC ADDITIVE MANUFACTURING CONCEPTS

Additive manufacturing is a manufacturing process used to create end user parts from depositing a material in an additive manner to build up a 3-dimensional part layer by layer. This contrasts with subtractive or traditional manufacturing where a billet of material is held, and the part is carved out of it through cutting and turning processes done on mills and lathes (Shaikh, Singh, Kate, Freese, & Atre, 2021). One form of additive manufacturing (AM) is metal fused filament fabrication. This method uses powdered metal infused into a polymer substrate to form the extruded layers on the build plate of the 3D printer as seen in Figure 1. This filament is a 50%-60% metal volume to polymer filament (Shaikh, Singh, Kate, Freese, & Atre, 2021). This process also applies to carbon fiber-based polymer filaments without the additional sintering steps. For polymer-based 3D printing the sintering step is removed and the initial printing step is the only step in the process.

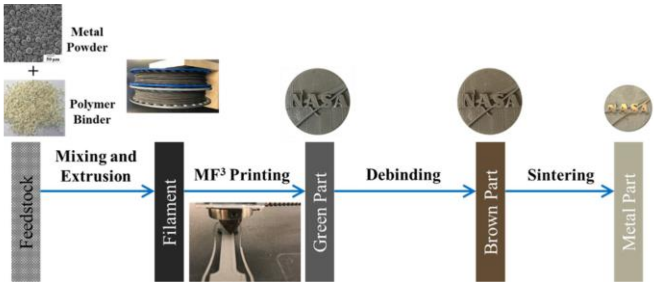

Figure 1. Metal FFF Process (Shaikh, Singh, Kate, Freese, & Atre, 2021)

Another method of additive manufacturing is the process known as Selective Laser Sintering (SLS) or Selective Laser Melting (SLM). In this process, a laser is shot at a powder bed of metals or polymer depending on the printer setup, and the laser solidifies that section of the object. The bed is then lowered, and a sweeper pushes more media on top of the part creating the layers of the print, see Figure 2. After all the layers are built, the remaining powder drops into a storage container and the 3D printed part is revealed and can be processed to make it the completed part (Yang, Knol, van Keulen, & Ayas, 2018). The SLS/SLM process is an expensive process that requires large expensive printers along with high quality dust collection systems as the powder is harmful to breathe in and can cause respiratory issues.

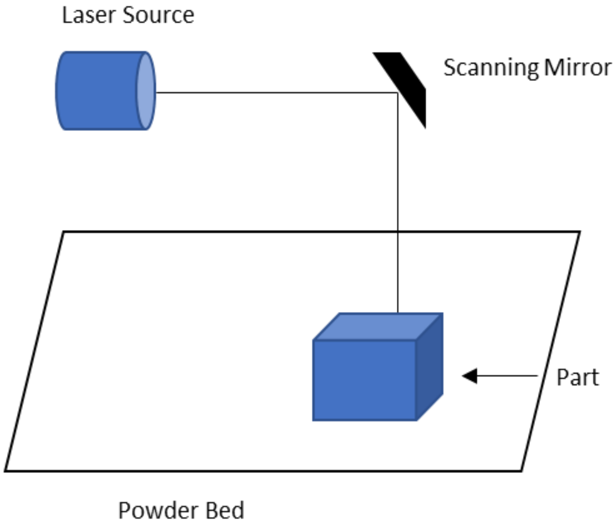

Figure 2. Illustration of the SLS/SLM Process

These are the reasons why many prefer to use the metal FFF process instead. The production machines are less expensive, and the production processes are less harmful to humans. There are however, additional processing steps involved with the use of metal FFF, sintering ovens and de-binding processes are required which can take more time. A final consideration working against the use of metal FFF is that through the sintering process there is a 40%-50% shrinkage rate due to the polymer filler being removed. This requires designs to be calibrated to account for these issues (Shaikh, Singh, Kate, Freese, & Atre, 2021).

TEST METHODS

Testing procedures with regards to additive manufacturing are conducted similarly to those of traditional manufacturing. The difference is that the material in traditional manufacturing is homogeneous and uniform in nature, while additive manufacturing can cause issues of contamination of the material and layer adhesion. Tension tests are used to test measured yield and tensile strength of the material (Slotwinski, Cooke, & Moylan, 2012). Compression tests are used to determine the compressive strength of the material (Slotwinski, Cooke, & Moylan, 2012). Modulus tests are performed after tension and compression tests are completed. These modulus tests are performed to obtain the Young's, tangent, and chord modulus values of the material (Slotwinski, Cooke, & Moylan, 2012). Hardness tests are used to analyze the resistance to deformation, however there are several types of hardness tests. Brinell and Rockwell tests are the most common hardness tests used (Slotwinski, Cooke, & Moylan, 2012). These tests use a calibrated press material that is used to indent the material tested. This indentation is then measured by the sensor to determine indentation and determine the hardness of the material. Of more importance to additive manufactured parts are fatigue, fracture, and crack growth tests (Slotwinski, Cooke, & Moylan, 2012). These tests are useful to help design a finite simulation for the additive parts as these tests will show if there are layer adhesion issues. ASTM and ISO (Slotwinski, Cooke, & Moylan, 2012) have provided additional guidance to perform tests on additive manufactured parts. Some tests such as ASTM D638 – 10 have additional guidance to perform the test such as dog bone tests. Other tests such as ISO 14129:1997 cannot be used to conduct shear tests on additive manufactured parts (Forster, 2015). These tests once complete are then used to build a multiscale model. Materials have different thermal properties, and thus different thermal conductivity, which will affect the layer adhesion process (Chen, et al., 2019). The following example test in Figure 3 uses Inconel 718 to produce a single layer detailed process model. This process uses the Goldak model, and this concept can be applied to polymer based additive manufacturing (Chen, et al., 2019). To compare materials with this approach each material will need to be tested with the same shape. These tests are generally done with powdered metals which are laser sintered (Li, Liu, Fang, & Guo, 2017).

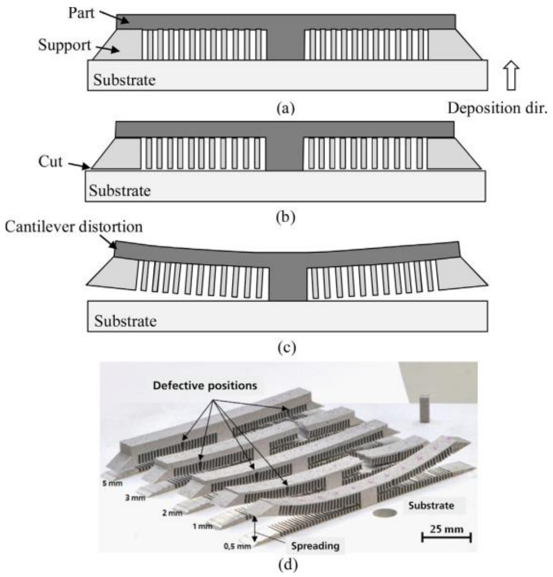

Figure 3. Schematic Procedure Showing Cantilever Distortion (Li, Liu, Fang, & Guo, 2017)

FINITE SIMULATION ANALYSIS OF ADDITIVE METALS

Powdered metal used in Selective Laser Sintering processes is produced by gas atomization which creates sets of uniform particles in the shape of a sphere. Since the material becomes spherical, the total capacity of the powder bed is assumed to be 68% of the total solid density (Galati, Luliano, Salmi, & Atzeni, 2017). Due to the conductivity of the powdered metal being sintered, there is a heat transfer based on the thermal conductivity of the material. This heat transfer is not homogeneous within the part. This material phase change from solid to molten happens quasi-instantaneously. This can cause layer adhesion stresses between layers post melt as heat change can be extremely localized (Galati, Luliano, Salmi, & Atzeni, 2017). One of the challenges to producing a material model is that materials behave differently at different temperatures. Part of that is due to the material temperature starting at room temperature and then during the laser process instantaneously climbing to over one thousand degrees. After this instantaneous heating, and melting the material then begins to cool, and as the layers form the heat density increases (Luo & Zhao, 2018). Material density plays a large role in this model and the associated simulation to create accurate results. The test bar has the dimensions of: 100mm x 40mm x 6mm. The force was applied at the central location of the test bar with pin constraints at either end as shown in the FEA deformation results.

One of the issues with powder metal SLS manufacturing is deformation which requires the Lagrangian formulation to account for the deformation (Denlinger, Gouge, Irwin, & Michaleris, 2017). Unfortunately, Finite Element Analysis of powdered metal is still in a relatively early stage; there are inconsistencies in approaches taken. To that end there are several points that are agreed on such as the greatest stress is applied to the longitudinal plane as well as multi-layer builds create high stress levels which exceed the yield strength of tension and that the lower layers are forced to compress (Denlinger, Gouge, Irwin, & Michaleris, 2017).

APPLICATION OF SIMULATION ANALYSIS FOR ADDITIVE POLYMERS

One of the inherent issues with performing accurate Finite Element Analysis of the additive manufacturing process is that it is extremely difficult to obtain accurate heat gradients as there is a wide range of temperatures that exist at the melting position of the part. Even with known temperatures, it is still computationally expensive as each step of the melt process must be considered (Siewert, Neugebauer, Epp, & Ploshikhin, 2019). This type of issue can be negated slightly by use of a continuous simulation approach as it uses real-time data and can potentially be applied to this problem. To solve some of the issues, Keller devised a method based on welding simulations which have similar thermal histories. This method is called the Mechanical Layer Equivalent (MLE) process. This thermal history is then applied to the entire part body. To identify inherent strains, the use of simulations on a small region can be used or calibrated measurements can be used (Siewert, Neugebauer, Epp, & Ploshikhin, 2019). Sensitivity analysis of the material is used at the mid YZ cross-section to determine the thermal load which can then be analyzed against the FE simulation (Lu, et al., 2018).

Another method to compare and confirm a simulation model is to attach thermal couples to the substrate and then compare those values to those used in the model. Then these values can be calculated to find the error percentage:

$$\%Error = \frac{100\sum_{i=1}^{n}\left|\frac{(x_{exp})i-(x_{sim})i}{(x_{\mathrm{exp}})i}\right|}{n} \text{ (Lu, et al., 2018).}$$

While these calculations were applied to Ti-6A1-4V powdered titanium alloy, they can be applied to most materials. This is where it can become a little complicated when mixed material polymers are used as there will be different thermal strain limits between a heterogeneous composite polymer versus a homogeneous one. Once a test part is printed there will need to be a reference material used that was not constructed through the AM process. For example, the use of a billet of extruded ABS could be used as test reference to the AM produced billet. Then the part and reference are tested for the elastic limit, Young's modulus, and thermal expansion. These values should be similar between the reference and AM part to confirm the test data. This data can then be used in input into the simulation to for future testing (Lu, et al., 2018).

TEST RESULTS

Using the design and simulation tools within Autodesk Fusion 360, a test bar was designed for experimentation. This test bar was then 3D printed with SLA, FDM, and Polyjet processes. In addition to those parts that were printed, a reference part was machined out of billet material. Only the reference part and FDM printed part were pure ABS, the rest were ABS type materials that are designed for SLA processes. Of note at the time of writing this paper there is a bug within the simulation engine used by Fusion 360 that reduces the deformation parameters by 90%. With that said the simulation results versus the actual material test results for the reference part were within 0.06 mm of each other which could be due to measurement error. With the simulation engine validated for the reference material the data for the various resin-based materials could be entered into the simulation engine for analysis. Note that these materials are all homogeneous in nature and do not contain binders or other foreign material to aid in bonding or rigidity.

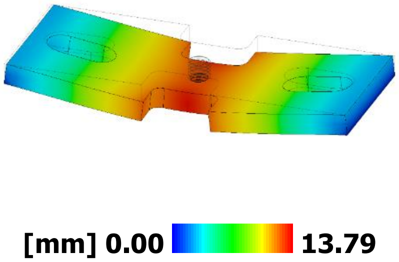

Figure 4. Deformation Simulation Result in Fusion 360.

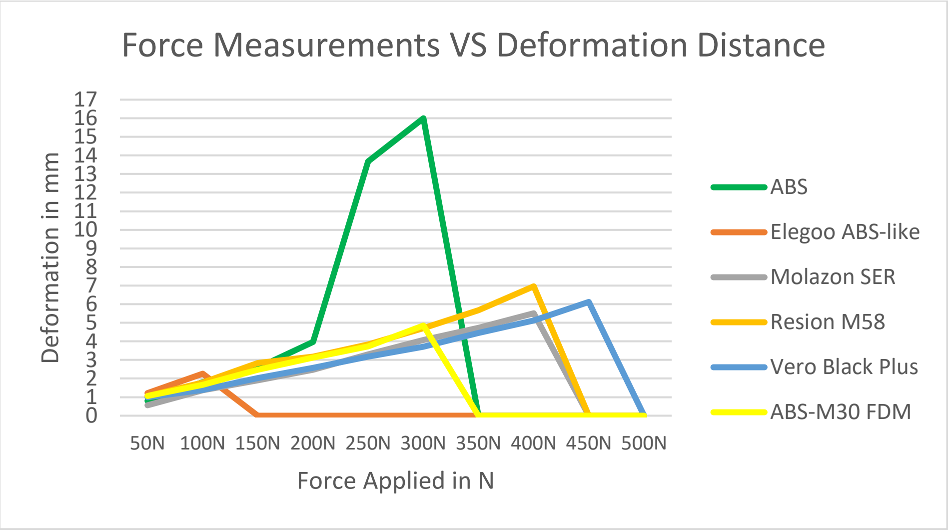

Figure 5. Real World Deformation Testing Conducted on Test Bars.

Another test that was conducted on the materials was to immerse them in a 10 PPM solution of water with chlorine. This was done as this is an environment for which the researchers need to test use cases in the future. This chlorine concentration is a common level used in US Navy water survival training tanks. The test bars were immersed in this solution for 30 days. Prior to immersion they were tested using a Shore A hardness tester and measured using micrometers to determine the initial hardness and thickness of the materials. Post immersion testing each test bar was wiped dry with a paper towel and retested on the same two measuring devices.

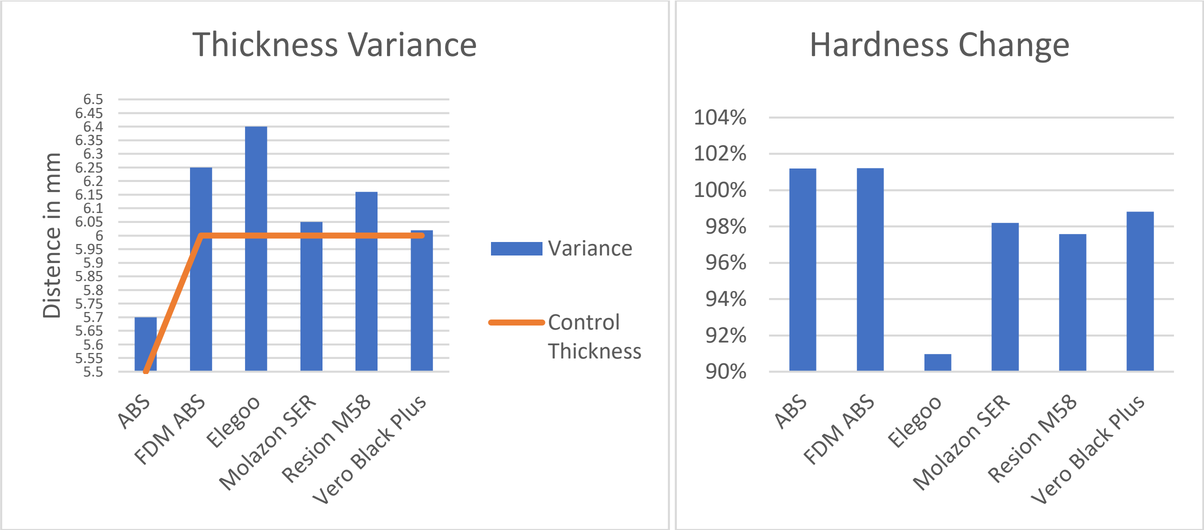

Figure 6. Test Bar Immersion Test Results.

The results of the test show that both the reference part and FDM produced ABS part increased in both thickness and hardness. As expected, the FDM part swelled more due to being more porous despite being printed at a 100% infill. This will cause additional absorption of water as there is more exposed surface area in contact with the solution. There does also appear to be a potential correlation between the amount of water solution absorbed and the change in hardness between all the resin-based materials. The Elegoo ABS like material had an what can only be concluded as an adverse reaction with either the chlorine in the water, or the water itself as it grew in almost half a mm of thickness and lost nearly 10% of its hardness post immersion. The Vero Black Plus and Molazon SER had the least amount of change prior to and after immersion.

To calculate the FEM for a material we developed a small MATLAB program to conduct an analysis of the bar using both a Galerkin 3 step approach for a global result, and the FETI-Dual method which was used for more complex larger calculations. The only vendor of the above tested materials that provided the material properties of their resin was Resion M58, as such that was the one we tested this method on.

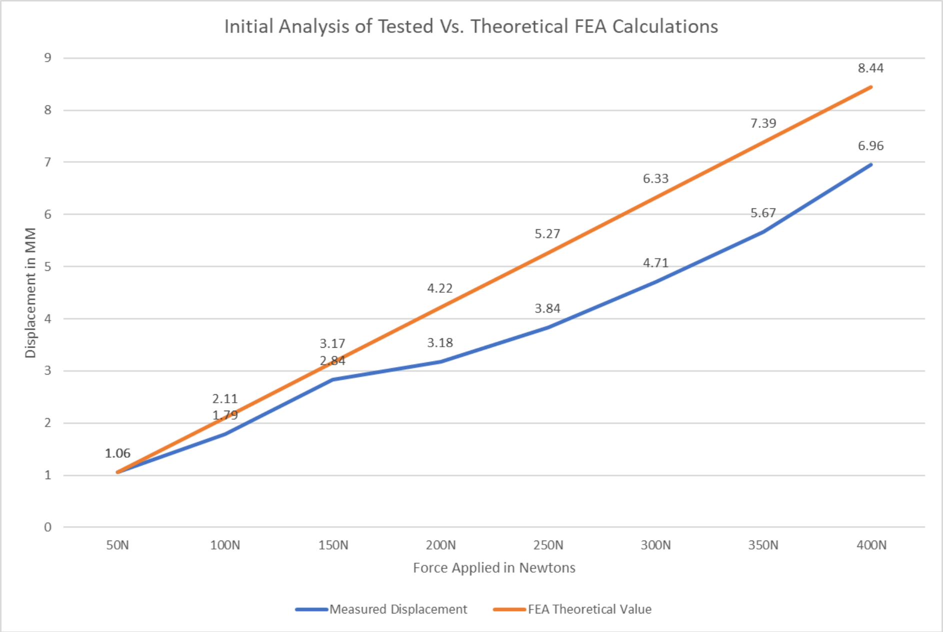

Figure 7. Tested Vs. Theoretical Results.

Force in Newtons	Absolute Error	Relative Error
50N	0 mm	0 %
100N	0.32 mm	15 %
150N	0.33 mm	10 %
200N	1.04 mm	25 %
250N	1.43 mm	27 %
300N	1.62 mm	26 %
350N	1.72 mm	23 %
400N	1.48 mm	18 %

Figure 8. Table of displacement with difference of displacement.

It was found that above 50 newtons of force that the calculations become less valid as a result. At this time, it is unclear as to why this occurs. One potential issue is that each distance had to be handwritten down as the force was applied to the test bar while holding the force at the desired value. There was less than two total millimeters of difference between theoretical and written values. It is also of note that as the required holding force was increased this variance increased which may be the reason for the less-than-ideal results. We believe that the math and formula are correct and that this is a case of needing a better-quality measurement tool which can digitally record the distance as well as the force applied.

CONCLUSIONS

While nearly all the research within the AM workspace has been focused on powdered metal SLS/SLM processes these concepts can be applied to all thermal AM processes with some process changes that may need to be adjusted. For use with FFF AM processes the MLE process should be well suited to use as it follows much of the same effect that welding does. Within the metal fabrication world, FFF AM is a near exact polymer process to that of the Gas Metal Arc Welding (GMAW). Both processes use a spool of a material that is heated at the impact point as needed. They both also create high levels of local heating.

As for resin-based SLA 3D printing of homogeneous materials, they perform well treated as a uniform material type within standard FEA simulation software, at least as far as Fusion 360 goes. While the exact deformation distances are not the same, they do fall within less than 0.1 mm of deformation distance as tested at 50 Newtons of force. Further investigation should be conducted using a more robust measurement instrument. The MATLAB program currently is only designed to calculate along the X and Y axis. Future work will be to add the Z axis to the program to calculate the rotational forces applied and the corresponding deformation.

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