Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

# DIMENSIONAL ANALYSIS OF METAL POWDER INFUSED FILAMENT - LOW COST METAL 3D PRINTING

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## ABSTRACT

The process of Additive Manufacturing (AM) is the newest form of fabrication with the primary method being layer-by-layer production. The most common form of this technology is Fused Filament Fabrication (FFF), where material is deposited layer by layer to produce a highly customized part. When compared to subtractive manufacturing the production of waste is greatly reduced. This study presents some innovations on a new metal fabrication technique for FFF printing. By printing a PolyLactic Acid (PLA) compliant metal powder composite filament, a part can be made with approximately 90% metal composition and sintered. The sintering process removes the PLA bonding leaving a 100% metal part fabricated on a low cost FFF printer. Overall, this study reports the initial findings on dimensional changes in low cost metal 3D Printing process.

## INTRODUCTION

During the process of AM, material is deposited additively to produce a part with minimal waste. There exist many methods of AM such as resin-based photopolymer Stereolithography (SLA), Powder Bed Fusion (PBF), and Fused Filament Fabrication (FFF) [1]. The process of FFF is the safest, least expensive, and most common method of AM. This technique of 3D printing involves the fusion of material in a layer-by-layer process as demonstrated in Figure 1 [2]. This unique form of fabrication has allowed for opportunities in biological [3], concrete[4], and outer space printing [5]

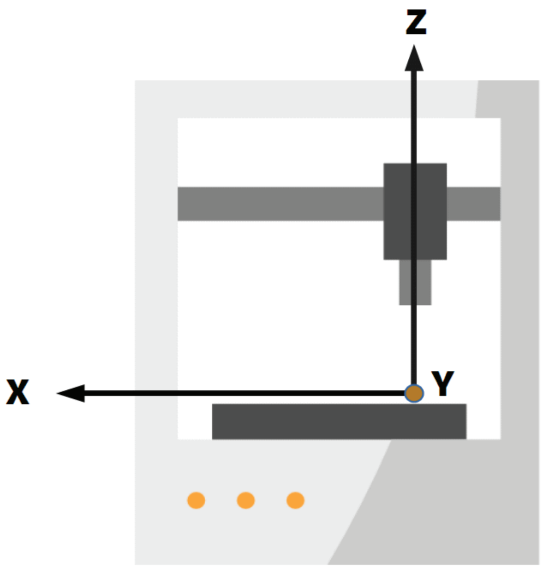

Figure 1. FFF 3D printing platform

The most common material utilized for this process is polymers such as PolyLactic Acid (PLA). The research presented in this paper is that of the process of Metal FFF (MFFF) printing a field that has been scarcely researched in comparison to other metal 3D printing techniques. By extruding metal polymer composite filament via FFF, parts with approximately 90 vol% metal composition can be fabricated. Following the printing process, the parts can be sintered in order to remove the polymer bonding agent and fuse the metal powder yielding a 100% metal part. This research study explores the MFFF process as a metal 3D printing technique and the associated dimensional losses.

The process of MFFF is only possible through the utilization of a metal polymer composite filament in this case Metal PLA (MPLA) composite material. The material composition and utilization in the MFFF process is shown in Figure 2.

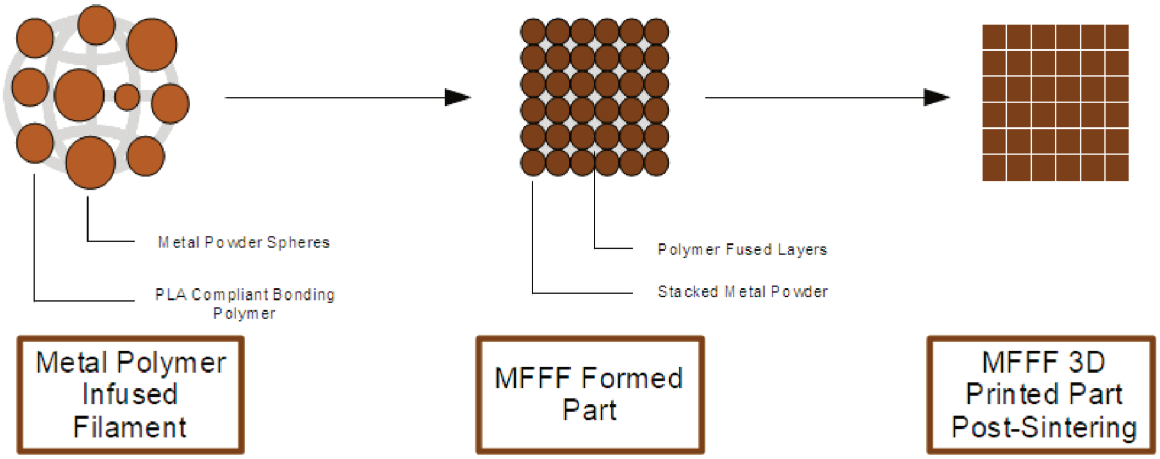

Figure 2. MFFF using MPLA material

The sintering procedure is the process in which post-printed parts are heated to near-melting temperatures for the metal powders within the composite material. This results in the fusion of the metal powder, and the removal of the polymer bonding agent. This procedure is common in manufacturing techniques that utilize powdered metallurgy to achieve superior part complexity. Newer metal AM technologies often utilize this method of post-printing processing to yield fully formed metal objects. For the method of MFFF, sintering is utilized to both bond the metal powder and remove the polymer. Specimens at each step in the procedure are further shown in Figure 3.

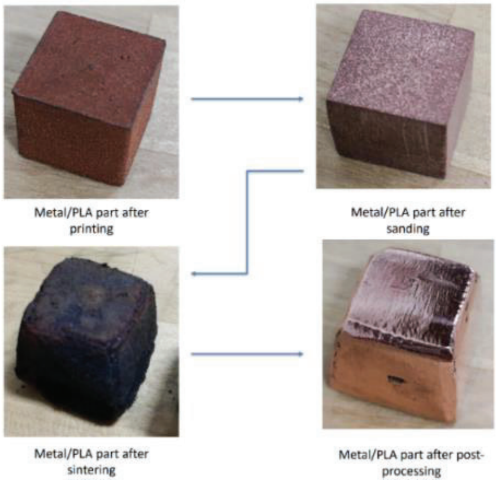

Figure 3. MFFF specimens at each stage of fabrication

This method of metal 3D printing provides many benefits when compared to other techniques. Common methods of metal printing are Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Direct Metal Deposition (DMD). These fabrication technologies have higher health concerns, are more expensive, and require large areas to operate [6].

## **REVIEW**

The overall process of metal 3D printing has been widely explored for methods of fabrication, mechanical properties, microstructural behavior, and useful applications. Metal AM is widely used in fabrication of complex or high part count assemblies most commonly found in aerospace. The part consolidation and increased part complexity that the metal AM process introduces is irreplaceable by any other method.

As discussed in William Frazier's article on Metal 3D Printing (M3DP) [6], the common M3DP techniques contain processing defects that result in a loss of stress that the fabricated parts can withstand. These processes are also shown to be expensive in both time and money expenditures. The business case assessment will ultimately determine the success of AM as it is currently favored in smaller production lots with the higher cost of raw materials being offset by lower fixed costs related to conventional manufacturing. But there is a large value to be put on AM due to the versatility and adaptability of the process. Overall, AM is projected to lead to new advancements in manufacturing components and will continue to grow with technology [6].

Two of the most common M3DP techniques (SLM and DMD) were examined and compared to other Powder Metallurgy (PM) techniques by a research group out of Nanyang

Technological University [7]. It was found in a comparative study that SLM is a more applicable choice for fabricated parts that require complex geometries such as internal structures and cavitations. The process of DMD is able to produce larger parts at the expense of dimensional accuracy and can serve as an alternative to the fabrication of large-scale components.

The current techniques that are able to utilize FFF technology for fabricating metal parts is indirect metal fabrication. Through the process of casting, patterns and sand-formed parts can be indirectly formed using 3D printed parts that are used to generate a mold [8], [9]. These techniques encompass all of the expenses and safety requirements associated with casting to fabricate parts.

A research group from the company Pentair produced a literary review on many forms of M3DP techniques with the benefits and drawbacks of each method being explored [10]. This overview paper gives design and general information for metal fabrication methods. The number of methods that are mentioned and discussed here is very extensive. The group performed a comparison of the various processes in relation to material, labor, and energy costs. Despite being a detail exploration into the various metal print technologies, there were no M3DP techniques that utilized FFF.

The research group from Fraunhofer IFAM produced their own metal infused polymer composite material by infusing a Polyamide Nylon (PA) matrix with a metal powder filling [11]. The weight percent of metal polymer composition is varied between 0-65%. The created filament has properties brittle properties and is to remove the bonding agent. The process shown is the only available research that explores the MFFF process.

The research group from The University of Texas at El Paso found a method of infusing ABS with a metal powder to form a metal polymer composite material[12]. The combination involves the infusion of ABS with copper and iron powder. The metal content is varied from 10-50% by weight. However, the material is similar despite the research never exploring the post printing sintering process that produces an entirely metal part. The results of this study showed that tensile strength decreased with the introduction of metal powders with an increase in thermal conductivity.

## PROCEDURE

The MPLA filament that is used for the MFFF process is a metal powder polymer composite material with the highest available metal composition. The printing parameters that are used for the study are based on the combined properties of the composite material. MPLA can be printed with minimal changes to the printing parameters from the base matrix polymer. The settings that need to be modified are 100% infill, decrease in printing speed (around 20 mm/s), and an increase in material flow (around 110%). Printing parameters can be further tuned with settings such as retraction and fan speed; however, the three aforementioned settings have the most influence on the printability of MPLA.

Post-printing, the formed parts must be fired in a furnace/kiln to yield a 100% metal part. This procedure involves the use of a crucible, refractory ballast to support the specimen, and a furnace capable of 1200 C with ramping temperatures. A ceramic crucible is used to suspend the specimen and refractory ballast with minimum contaminants. The two ballasts that are tested in this study are a carbon graphite mixture called Magic Black Powder (MBP) and green sand. The selection of these two materials are based on the preservation of oxidation and dimensional accuracy. For the temperature and times, the sintering temperature sweeps are shown in Table 1.

Table 1. Description of the time and temperature sweeps used for the sintering process

| Temperature (°C) | Time |
|---|---|
| 150 | Hold for 75 Mins |
| 400 | Ramp over 200 Mins at 1.25 C/Min |
| 983 | Ramp over 180 Mins at 3.24 C/Min |
| 983 | Hold for 240 Mins |

In post-sintering, the metal parts are processed to removed oxidation and contaminants. This step is to accurately report the dimensional changes associated with producing a metal polymer composite material, and the yield of the specific metal originally used. For example, this study specifically analyzes the copper polymer composite filament, and therefore the copper oxide remaining in the part post sintering is not included.

## RESULTS

The process of powder metallurgy allows for highly complex and customized parts however the sintering portion of fabrication involves the removal of the powder bonding agent. The removal of approximately 10 vol% polymer material results in dimensional losses. If the shrinkage associated with the MFFF process is characterized, then during the design stage parts can be sized to compensate.

By using cubes that are symmetric across all major cartesian axes and specifically analyzing the copper MPLA, the shrinkage can be better understood. The two printing parameters that have the greatest influence on precision for this MPLA filament is layer height and print speed. The specimens that are used for analysis are definite with the nomenclature shown in Table 2 in accordance with the changed variables parameters.

Table 2. Description of the changed variables for Dimensional Analysis

| CU.0225.20.0 | |
|---|---|
| **Material** | |
| CU | Copper Filament |
| **Layer Height** | |
| 03 | 0.3 mm |
| 0225 | 0.225 mm |
| 015 | 0.15 mm |
| **Print Speed** | |
| 10 | 10 mm/s |
| 20 | 20 mm/s |
| **Specimen Size** | |
| 0 | 0.5 $in^3$ |
| 1 | 1.0 $in^3$ |

For the sintering process, two methods of firing the specimens is performed. The MBP ballast used is mixed with water in approximately a 1.8:1 ratio mixture; the specimens can be coated and suspended to reduce oxidation during the sintering procedure. Post-sintering the containments and oxides are removed to obtain a valid value for the dimensional changes. The second sintering criteria utilized the same MBP mixture, time, and temperature sweep. The changed variable is the ballast in which the specimens are suspended in. For the secondary case, casting green sand is utilized to suspense the specimens. To reduce the oxidation, the parts are coated in the MBP mixture and then pressed into the sand. The working principal behind this is the greater density of the sand will assist in the conservation of dimensional accuracy while the MBP will minimize oxidation.

The first sintering criteria resulted in an average dimensional loss due to the MFFF process is approximately 15.8% when averaged between specimens and planar view. The trend of shrinkage shows that the more precise printing parameters result in less dimensional loss. The second sintering criteria resulted in an average dimensional loss of approximately 11.1% when averaged between specimens and planar view. Similar to the first process, the trend of shrinkage shows that more precise printing setting result in less dimensional loss.

Table 3. Dimensional losses from using MBP

| Dimensional Analysis by Specimen | CU.015.10.0 | CU.015.20.0 | CU.0225.10.0 | CU.0225.20.0 | CU.03.10.0 | CU.03.20.0 |
|---|---|---|---|---|---|---|
| Pre-Sintering (in) | 0.500 | 0.502 | 0.504 | 0.503 | 0.503 | 0.505 |
| Post-Sintering (in) | 0.429 | 0.423 | 0.429 | 0.431 | 0.409 | 0.419 |
| Dimensional Loss | 14.27% | 15.84% | 14.87% | 14.28% | 18.69% | 16.99% |
| Average Dimensional Loss | 15.82% | | | | | |

| Dimensional Analysis by View | XY | Z | Weight |
|---|---|---|---|
| Pre-Sintering (in) | 0.505 | 0.501 | 8.103 |
| Post-Sintering (in) | 0.417 | 0.429 | 4.24 |
| Dimensional Loss | 17.07% | 14.63% | 47.65% |
| Average Dimensional Loss | 15.85% | | |

Table 4. Dimensional losses from using green sand

| Dimensional Analysis by Specimen | CU.015.10.0 | CU.015.20.0 | CU.0225.10.0 | CU.0225.20.0 | CU.03.10.0 | CU.03.20.0 |
|---|---|---|---|---|---|---|
| Pre-Sintering (in) | 0.500 | 0.502 | 0.504 | 0.503 | 0.498 | 0.506 |
| Post-Sintering (in) | 0.474 | 0.466 | 0.442 | 0.435 | 0.436 | 0.419 |
| Dimensional Loss | 5.16% | 7.16% | 12.23% | 13.52% | 12.60% | 17.05% |
| Average Dimensional Loss | 11.48% | | | | | |

| Dimensional Analysis by View | XY | Z | Weight |
|---|---|---|---|
| Pre-Sintering (in) | 0.505 | 0.501 | 8.102 |
| Post-Sintering (in) | 0.444 | 0.454 | 4.385 |
| Dimensional Loss | 12.10% | 9.27% | 45.88% |
| Average Dimensional Loss | 10.69% | | |

The trend shown in the data for Tables 3 and 4 is further demonstrated in Figure 4. As printing precision increases, the overall axial dimensional loss decreases. Therefore, as the accuracy decreases the influence of oxidation on the dimensional parameters during sintering become greater than that of the printing parameters.

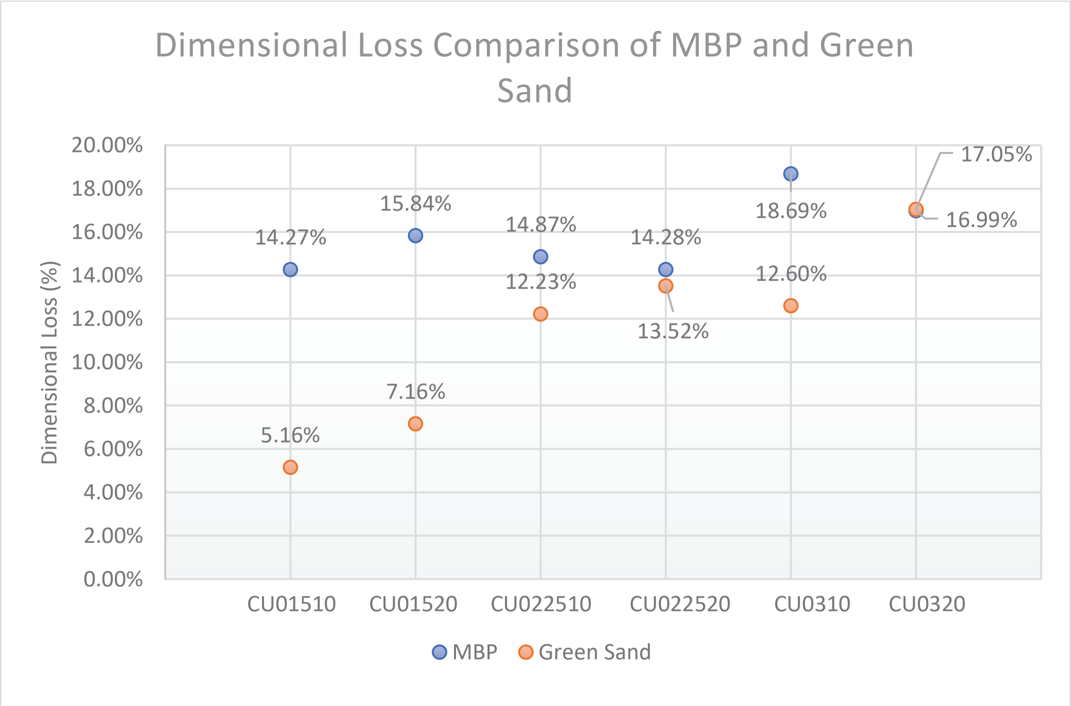

Figure 4. Correlation between printing parameters and dimensional analysis for MBP and green sand ballasts

Using a vacuum furnace, VF expects an average shrinkage value of 7%. This study is on the process of low-cost metal 3D printing and therefore an open-air furnace is used and the results are within accountable tolerances. The lowest shrinkage was achieved with a green sand ballast and precise printing parameters resulting in a dimensional loss of 5.16%.

## CONCLUSION

The process of MFFF is an incredibly new and innovative method of producing metal 3D printed parts. This technology could provide more energy efficient methods of producing metal objects. Characterization of this fabrication technique is an important metric for utilization and dimensional characteristic are necessary especially during the design stage. With a minimum dimensional loss of approximately 5%, the printing and sintering procedures could be tuned to acceptable levels for a specific application. These results solidify MFFF as a possible method of M3DP for future industrial and academic applications. Further work will examine the mechanical and microstructural properties to better account for the expected behavior of MFFF fabricated parts.

## ACKNOWLEDGEMENTS

This study has been made available and funded through NSF Award 1801120, Smart Manufacturing for America's Revolutionizing Technological Transformation, and partially NSF Award 1601587, AM-WATCH: Additive Manufacturing - Workforce Advancement Training Coalition and Hub. The testing for this research was performed at Tennessee Technological University’s Material Science and Cryogenics Laboratories. The authors of this paper would like to show appreciation to the operators and technicians of these spaces.

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