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Reviewed Paper

ANALYSIS OF POWDER REMOVAL METHODS FOR EBM MANUFACTURED TI-6AL-4V PARTS

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Abstract

Additive Manufacturing (AM) allows the creation of complex geometries that are not achievable through subtractive manufacturing. Regardless of the advantages that 3D Printing offers, technology limitations often constraints the desired geometry. When fabricating Ti-6Al-4V parts in Electron Beam Powder Bed Fusion (EBPBF), the electron beam is used to preheat the powder bed to maintain the desired temperature gradient during the build. One disadvantage of EBPBF during the fabrication process is the trapped powder within internal channels gets partially sintered and require extra processing. This research analyzes several powder removal methods and compares their effectiveness. This work utilizes two types of samples, both made of Ti-6Al-4V in EBPBF; with geometries that resemble typical features when designing a component. The target weight of each cylinder is calculated based on dimensions and effective density of the sample. The results summarizing the effectiveness of each method are presented.

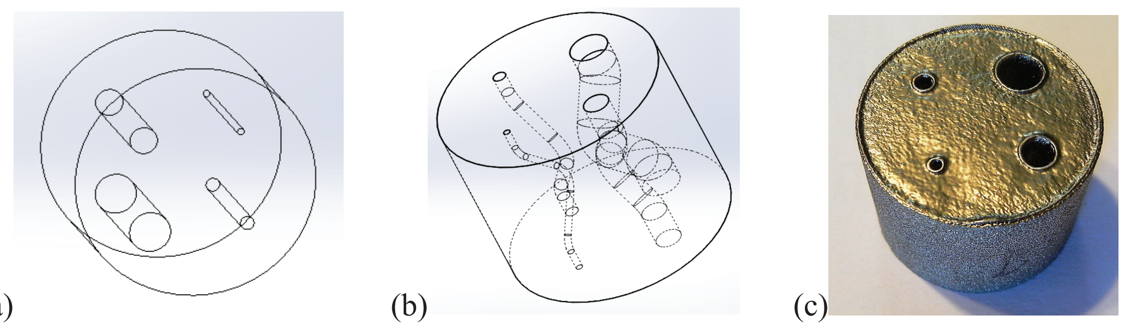
Introduction

When fabricating parts using Electron Beam Powder Bed Fusion (EBPBF), the powder bed is preheated using the electron beam; Gong et al. indicates that this serves two purposes: holding the metal in place during the subsequent melting scan and reducing the thermal gradient in the build part [1]. The decrease in temperature difference between layers helps to avoid residual stresses within the printed part, making it one of the advantages of this technology. Nevertheless, one of the main disadvantages of EBPBF is the sintered powder that gets trapped inside of the build part during the fabrication process. The trapped sintered powder inside of channel-like features is of primary interest as 3D printed components often have lines and channels that require a clear passage for their end design.

Studies and experiments have been conducted to remove powder from parts made using Selective Laser Sintering (SLS), Tenney et al. (2018) proposed the use of traveling waves as a de-powdering process for additively manufactured parts [2]. Thompson et al. (2015) used venting holes in the prototype design to remove the packed powder via pumped fluid; these vent holes were integrated to de-powder each layer separately [3]. The sintered powder is not an issue on laser-based systems since most of the processing is done at low temperatures [4]. In the case of EBPBF, few studies have been conducted to research methods to remove the sintered powder.

Hasib et al. (2015) presented a method which consisted of exposing an EBPBF printed Ti-6Al-4V lattice to a chemical etcher with results that are not completely successful and conclusive [4].

The purpose of this research is to perform preliminary analysis of potential methods that can remove the sintered powder from channels and hollow features from parts made of Ti-6Al-4V, manufactured with EBPBF. Figure 1 shows the two types of cylinders used for this study; a cylinder with straight channels and a cylinder curved channel. The selected geometries resemble typical channel design configurations used in applications such as cooling lines. The methods to evaluate are Powder Recovery System (PRS), Ultrasonic, Ultrasonic with Mechanical Impact, Vapor Blast, Chemical Etching, and Liquid Nitrogen with Ultrasonic. The samples were printed on an ARCAM A2X machine with ARCAM's default standard parameters for Ti-6Al-4V alloy.



(a) (b) (c)

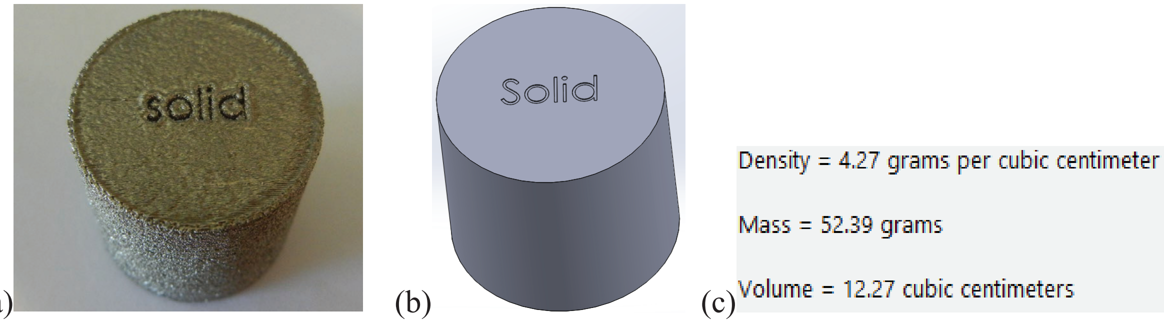
Figure 1 – (a) CAD cylinder design with straight channel features, (b) CAD cylinder design with curved channel features, and (c) Additive Manufactured Cylinder.

Methodology

To evaluate the powder removal methods, fourteen parts; seven curved- channel cylinders and seven straight-channel cylinders; were manufactured to evaluate each proposed methodology. All parts underwent the Powder Recovery System (PRS) methodology before any of the proposed research methods were applied. Each described research method was used on one curved-channel cylinder and one straight-channel cylinder. All of the samples were weighed before and after all powder removal methods were applied. To facilitate this comparison, the effective density of EBPBF part was calculated, as described in the next section.

Effective Density

The density of uncured Ti-6Al-4V powder is estimated to be 2.54 g/cm^3 while the density of Ti-6Al-4V ranges from 4.429 g/cm^3 – 4.512 g/cm^3. To determine a value that reflects the as-built density of a part made of Ti-6Al-4V using the EBPBF process, the mass of three printed solid cylinders was measured and averaged. Each part is a cylinder 25 mm in diameter and 25 mm height and is illustrated in Figure 2. After the build, each part was individually cleaned with the PRS to remove all sintered powder from its walls, measured to determine its volume, and weighed to calculate its corresponding density. The average of the three calculated values resulted in an as-built effective density of 4.2691 g/cm^3. This calculated density was used in the CAD mathematical model to have the CAD software calculated mass reflect a result, more accurate to a real printed component.



(a) (b) (c)

Figure 2 – (a) Solid cylinder build to calculate the density of Ti-6Al-4V after EPBF, (b) CAD model of the cylinder, and (c) the mass properties results from SolidWorks 2018.

Powder Recovery System (PRS)

The first methodology identified for the powder removal process, to evaluate its effectiveness was the Powder Recovery System (PRS), which is an auxiliary machine that is supplied with the Arcam EBM machine. The PRS operates under a pressure of 6 mBar to pressurize air and Ti-6Al-4V powder, which is required to breakdown sintered powder and facilitate its removal. The powder size used in the PRS is 45-106 µm. This methodology requires each sample (with straight and curved channels) to be cleaned intermittently at 2-minute intervals, each hole sprayed with the air-powder mixture for thirty seconds. After each two-minute interval, the parts are weighted and recorded; repeated this method until no significant differences in weights are observed from the previous interval.

Ultrasonic Powder Removal

This method uses a machine that transforms electrical energy into mechanical energy. The energy is transferred with the use of an attachment which transfers the energy onto a part using a frequency that impacts the part. The apparatus operates at the same frequency of 20 kHz at all times while the amplitude can be varied. For this methodology, the amplitude was kept constant 40% power. Using a process similar to that of the PRS, each sample parts is affected by the Ultrasonic process for 2-minutes and then the post process weight of the part is recorded. This process is repeated for several intervals until the parts are either cleared of the trapped powder or until no significant weight difference is observed from the previous interval.

Ultrasonic and Mechanical Impact Powder Removal

This method adds a mechanical impact process using a hammer in addition to Ultrasonic method previously described. The hammer or mallet used has a head made of rubber on one side and plastic on the other side to prevent the parts from getting damaged due to repeated impacts. The Ultrasonic and mechanical impact approach required to mechanically impact the part for one minute (to break off any loose powder), followed by the Ultrasonic for 2 minutes to further remove trapped powder inside of each cavity, and finally mechanically impact the part for thirty seconds.

The 2-minute ultrasonic approach was followed to maintain consistency with the rest of the testing procedures.

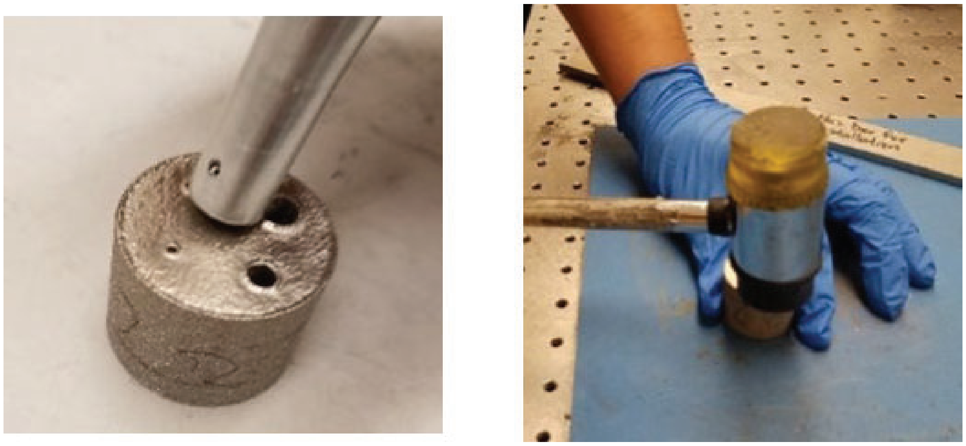


Figure 3 – (Left) Ultrasound being applied onto the part. (Right) Part being hammered.

Vapor Blast Powder Removal

The Vapor Blast (VB) testing is a powder removal method that uses a machine that cleans the surface of metal parts using a slurry of water and sand. Inside the machine chamber, the pressurized slurry is sprayed through a nozzle and directed to the cylinder channels. This testing process is different compared to the previous methods since it involves water. Each part of the sample pair was cleaned using the VB process for five minutes intervals, after which the parts were dried inside an oven for about 40 minutes at 120°C. After the drying process is complete, the parts were weighed, and the values were recorded. The testing process was repeated for the required iterations until the current iteration shows no significant weight difference.

Chemical Etching Powder Removal

Powder removal using chemicals used for etching; Kroll's reagent and Keller's reagent, was another method evaluated as part of this research. Chemical etching is a technique used to remove material using chemicals where the corrosive chemical, known as the etchant, reacts to the target material, dissolving the material at a time-dependent rate. Etchants, in general, are used for the dissolution of the surface of a metal part and are mostly used for metallography to analyze the microstructure. Kroll's reagent is an etchant used for Ti-6Al-4V, this solution is 92 mL of deionized water, 6 mL of nitric acid, and 2 mL of hydrofluoric acid. Keller's reagent is an etchant used for aluminum, Ti-6Al-4V has 6% aluminum, making this etchant another viable method to analyze. The solution is 90 mL of deionized water, 5 mL of nitric acid, 3 mL of hydrofluoric acid, and 2 mL of hydrochloric acid. The testing process for this method requires exposing a part to the etchant. The testing method is the same for both etchants and requires placing droplets of the solution into the holes of the part, waiting for one minute to allow the solution to affect the part, and observe if any additional powder is removed. Then, the part is rinsed and dried using an oven before weighing the part. The testing process was repeated for the required iterations until the current iteration shows no significant weight difference.

Liquid Nitrogen and Ultrasonic Powder Removal

The final powder removal method analyzed used a combination of ultrasound and liquid nitrogen. The first step involved submerging the sample parts (with curved and straight holes) into liquid nitrogen for twenty minutes, followed by an ultrasonic application for two minutes. The parts are weighed, and their values recorded, and the testing process repeated until the current iteration shows no significant weight difference from the previous one. Figure 4 shows the parts submerged in liquid nitrogen.

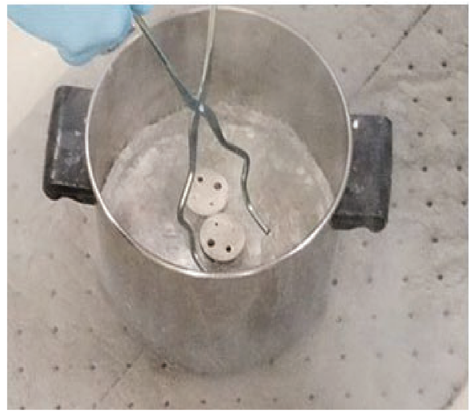


Figure 4 – (Left) Parts before they are submerged inside a pot with liquid nitrogen. (Right) Parts submerged inside a pot with liquid nitrogen.

Results

The results of each methodology are shown in a table for comparison. The table presents the type of cylinder, its weight before the PRS, its weight after the PRS, and the weight difference after being exposed to the assigned methodology. An estimate evaluation of the theoretical weight of the parts and the target weight was conducted to evaluate the effectiveness of each method.

Weight Comparison

The first analysis performed included all of the information on the PRS cleaning. The cleaning of all the samples with the PRS allowed gathering more sample information on this methodology. Table 1 below shows the average weight before and after for 14 samples.

Table 1 – Table Summary of Powder Recovery System (PRS) Method

	Weight					
	Before (grams)		After (grams)		Change (grams)	
Procedure	**Straight**	**Curved**	**Straight**	**Curved**	**Straight**	**Curved**
PRS (7 Set average)	112.9015	112.7740	109.9842	109.8504	2.9173	2.9236

After all the sample cylinders were clean with the PRS, a pair of cylinders, consisting of one straight channel cylinder and one curved channel cylinder, were exposed to the assigned methodology. Table 2 below shows the results of each powder removal methodology and the change of weight each cylinder.

Table 2 – Weight Comparisons After Each Powder Removal Method

	Weight					
	Before (grams)		After (grams)		Change (grams)	
Procedure	**Straight**	**Curved**	**Straight**	**Curved**	**Straight**	**Curved**
PRS (8 Set average)	112.9015	112.7740	109.9842	109.8504	2.9173	2.9236
Procedures After PRS						
Ultrasonic	110.6036	110.5155	110.5053	110.3459	0.0983	0.1696
Ultrasonic and Mechanical Impact	108.6181	108.6381	108.6145	108.6156	0.0036	0.0225
Vapor Blast	110.7748	110.0365	110.7657	110.0385	0.0091	-0.0020
Chemical Etching - Kroll	108.8232	108.6834	108.8232	108.7664	0.0000	-0.0830
Chemical Etching - Keller	110.6683	110.0564	110.6614	110.0564	0.0069	0.0000
Liquid Nitrogen and Ultrasonic	110.589	109.7461	110.4663	109.5941	0.1227	0.1520

Effectiveness

The effectiveness of each methodology cannot be evaluated based on a change of weight alone. There are non-destructive evaluation methods that can assist in the effectiveness evaluation, for this preliminary work, it was decided to use mathematical methods to calculate a rough estimate on the mass and volume of each cylinder before any method was applied.

Target Weight

During the part formation in the Electron Beam Powder Bed Fusion, the powder goes through phase changes, from powder to liquid and then solid. One main advantage of building in an Electron Beam machine is the preheat cycle that reduces the temperature difference of the powder between layers. This added step in the process is an excellent aid in reducing the residual stresses, but when the part is finally cooled down and removed from the machine, the final part does experience a degree of shrinkage. To understand how much powder needs to be removed from a newly printed part, the CAD mathematical model was taken as a reference point of start and adjusted its density to the effective density initially calculated to provide an ideal weight. From the software calculations, the initial ideal weight was found to be 117.4871 grams for the cylinder with straight channel cavities, and the ideal weight for the cylinder with curved channel cavities was found to be 116.9109 grams.

The ideal weights represent a CAD model with no change in dimensions caused by shrinkage. The actual printed part experiences a degree of shrinkage, and physical measurements were done to verify the change in volume. The exterior dimensions were easily measured, whereas the 2mm & 1mm holes represented a challenge to measure with simple tools. A trend line analysis was used to evaluate the shrinkage for the 2mm & 1mm holes, using the holes actual dimensions and the actual outer diameter of the cylinder. Table 3 below shows the actual dimensions of 4 samples and the forecasted shrinkage of the 2mm & 1mm holes.

Table 3 – Actual Shrinkage Calculations

	Actual Dimensions (mm)					
Cylinder Sample	**Diameter**	**Height**	**Hole 1**	**Hole 2**	**Hole 3**	**Hole 4**
Straight Cylinder 1	34.2	28.5	5.5	3.4	1.996	0.9966
Shrinkage %	2.29%	5.00%	8.33%	15.00%	20.00%	34.00%
Curved Cylinder 1	34.2	28.5	5.3	3.5	1.99725	0.99854
Shrinkage %	2.29%	5.00%	11.67%	12.50%	13.75%	14.60%
Straight Cylinder 2	34.4	28.5	5.5	3.4	1.9954	0.9959
Shrinkage %	1.71%	5.00%	8.33%	15.00%	23.00%	41.00%
Curved Cylinder 2	34.1	28.5	5.5	3.5	1.9965	0.9973
Shrinkage %	2.57%	5.00%	8.33%	12.50%	17.50%	27.00%

One of the main assumptions for the analysis was that each calculated and estimated shrinkage was the same through all the channel features in the cylinder. With the actual dimensions, now it is possible to calculate the volume of printed cylinders. Table 4 below shows the ideal theoretical weight and the calculated target weight.

Table 4 – Actual Post-Build Weight Based On Shrinkage Calculations

	Weight (grams)			
	Mathematical Model		Actual build parts	
	Straight	Curved	Straight	Curved
Part mass	117.4900	116.9100	107.4900	107.1200

Effectiveness

The calculated target weights were for reference use only and there are better methods to obtain the actual volume and mass of the cylinders, such as a CT scan. However, for this preliminary work, estimates were used to get a reference mass to use as a target weight. For the cylinder with straight channel cavities the target weight was estimated to be 107.49 grams, and the target weight for the cylinder with curved channel cavities was estimated to be 107.12 grams. Each methodology was evaluated for its effectiveness with these target weights; Table 5 below shows the efficiency of each methodology for removing sintered powder after the PRS process.

Result Discussion

The PRS was the most effective method to remove sintered powder when the part was taken out of the machine. The PRS can remove only a portion of sintered powder, after a certain number of iterations, the change in weight was no different from the previous iteration. These proposed methodologies aim to remove the remaining sintered powder trapped in the features inside the printed geometry. From the methodologies tested, we see that the most efficient methods are: Ultrasonic, Ultrasonic & Mechanical Impact, and Liquid Nitrogen & Ultrasonic. Further research and testing of the most effective methodologies are to be conducted to improve the powder removal and, simultaneously, have more accurate information about the effectiveness of the methods. Table 5 summarizes the results of the powder removal study.

	Weight (grams)							
	Before (grams)		After (grams)		Change (grams)		Efficiency %	
Procedure	**Straight**	**Curved**	**Straight**	**Curved**	**Straight**	**Curved**	**Straight**	**Curved**
PRS (8 Set average)	112.9015	112.7740	109.9842	109.8504	2.9173	2.9236	53.89	51.68
Procedures After PRS								
Ultrasonic	110.6036	110.5155	110.5053	110.3459	0.0983	0.1696	3.15	4.99
Ultrasonic and Mechanical Impact	108.6181	108.6381	108.6145	108.6156	0.0036	0.0225	0.32	1.48
Vapor Blast	110.7748	110.0365	110.7657	110.0365	0.0091	0.0000	0.28	0.00
Chemical Etching - Kroll	108.8232	108.6834	108.8232	108.6834	0.0000	0.0000	0.00	0.00
Chemical Etching - Keller	110.6683	110.0564	110.6614	110.0564	0.0069	0.0000	0.22	0.00
Liquid Nitrogen and Ultrasonic	110.589	109.7461	110.4663	109.5941	0.1227	0.1520	3.96	5.78

Table 5 – Effectiveness Analysis

Conclusion

In conclusion, the preliminary work accomplished was the first step towards investigating the most efficient methodology that removes the remaining sintered powder inside printed parts on EBPBF. The trapped sintered powder inside of a printed component is one of the many drawbacks that this Additive Manufacturing technology faces and little work have been done to understand how to remove the sintered powder. It is true that during the building process the sintered powder plays a vital role as support for the final printed component but imposes design limitations that do not allow to have the full advantage of this Additive Manufacturing technology. From the results obtained, the PRS is the most effective method to remove the sintered powder; however, after several iterations, the effectiveness comes to a stall. Ultrasonic, and Liquid Nitrogen & Ultrasonic are methods that can remove more sintered powder from the channels after the PRS. Ultrasonic waves can travel through the part, allowing it to reach the channels, while liquid nitrogen can easily access the channels directly and adapt to the channel form. This preliminary work shows that there are methods that can improve the removal of the sintered powder.

Future Work

Future work will involve the actual testing of the most promising methodologies obtained in a physical complex fuel injector. Additionally, it is intended to use a CT scan as a nondestructive method to evaluate the powder removal, instead of using a weight comparison method. The methodologies discussed in this paper could be used to analyze different channel geometries, e.g., square or triangular channels. Lefky et al. have performed research using chemical corrosion attack to remove support structures from metal printed components [6][7]. The chemical corrosion attack or chemical etching is a method that will be further investigated since the etching rate is dependent on several factors, and the preliminary experimentation to determine this rate was not performed for this work. There are several chemical etchants more adequate for Ti-6Al-4V, and to determine the etch rate before any exposure to the part is vital for the methodology to work correctly. Additionally, the determination of how much surface is required to be removed by the chemical etchant to clear channels of the sintered powder is part of the future work to be done.

A second experiment can be the evaluation of these proposed methodologies with parts that have were not initially exposed to the PRS process. All of this preliminary research is the first step to address the need for further investigation in the topic of removing sintered powder from internal cavities on EBM manufactured parts.

Special Thanks

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