

STUDY OF ACCURACY OF PARTS PRODUCED USING ADDITIVE MANUFACTURING

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INTRODUCTION

Additive manufacturing (AM) shows significant promise towards revolutionizing discrete parts manufacturing. Traditional subtractive manufacturing offers a variety of capabilities which can be carried out at a high level of precision, however the range of shapes that can be produced is limited by the access of cutting / abrasive tools to designed features. With additive manufacturing, forms which could not be achieved before are feasible, making available a new level of functionality and capabilities to designers.

The purpose of this presentation is to focus discussion onto the issue of accuracy and uncertainty of parts made with additive manufacturing processes.

TEST ARTIFACTS

One method to characterize the performance of a machine or process is through the production and measurement of a test artifact. A standard test artifact has clear benefits: the same standard artifact produced by different machines or processes can be easily compared. Additionally, if designed properly, the standard test artifact can be used to test machine or process limitations. The standard test artifact can also serve as a method for performance verification between users and vendors, as well

as provide vendors with a platform that allows them to demonstrate improvements in their AM systems.

In the proposed Additive Manufacturing Test Artifacts, we seek a design that can help us identify / analyze the capabilities and limitations of a machine or process, quantify a machine or process accuracy, and provides us with a diagnostic tool for isolating specific machine defects. Further, we seek a design whose features all serve a specific purpose, are simple in design, and are easy to measure with low measurement uncertainty. The primary characterization of the AM system obtained by building and measuring the AM test artifact is via geometric accuracy and surface roughness of the test artifact (see Figure 1). However, because a standardized artifact will be widely employed by many users with a variety of needs, the test artifact and its features must be versatile enough to allow many different types of measurements by a variety of measurement systems.

The test artifact shown in Fig. 1 was built in stainless steel (see Fig. 2) on an EOS M270 powder bed fusion AM system using default machine parameter settings for that material. The part was connected to the build platform with hatched support structures.

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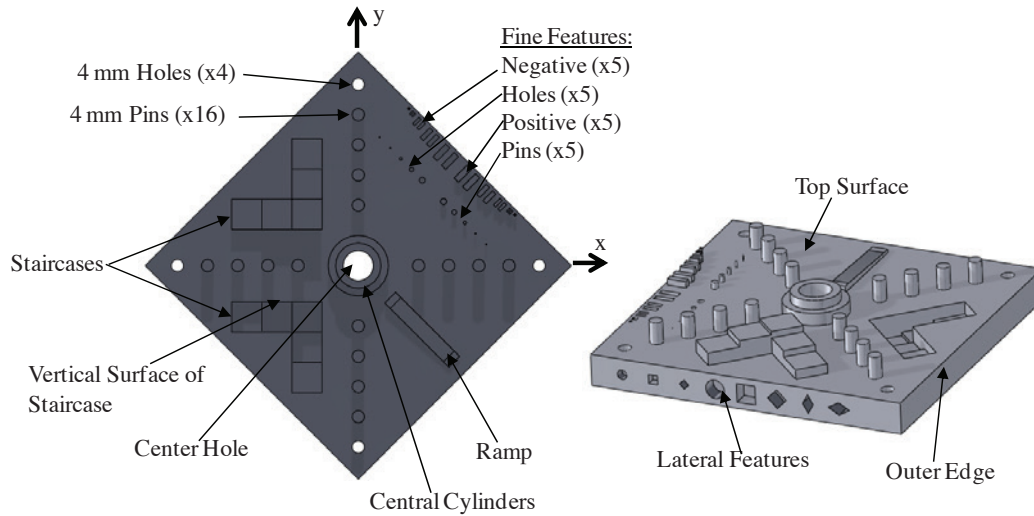


FIGURE 1. Solid model of the proposed test artifact showing a top view (left) and an oblique view (right) with arrows pointing to important features.

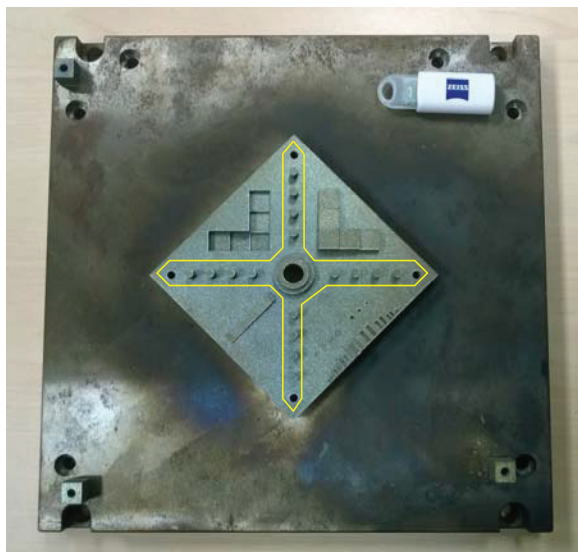


FIGURE 2. Test artifact manufactured in stainless steel. Flatness data was collected along yellow path, with 0.3 mm spacing generating 1,700 points of data

A second test artifact was created to exemplify the type of metrology challenges encountered in present AM parts. This part is shown in Fig. 3 and is a 3x3x3 lattice composed of 4.5mm octet truss unit cells. The octet lattice truss is a microstructural architecture, which combines low density with high structural stiffness. Considered as a macroscopic element, the octet structure can produce material properties outside the range of modulus-to-density ratios found in natural materials.

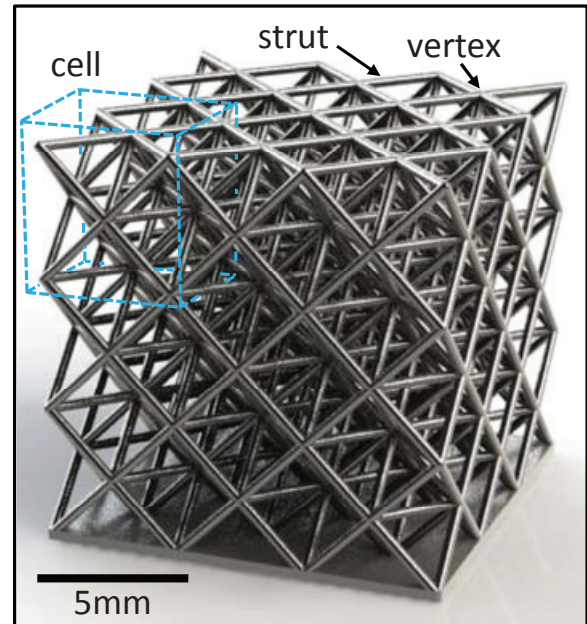


FIGURE 3. Octet lattice test artifact, with edge dimension of 14mm on a side

The lattice truss artifact was fabricated out of stainless steel powder on a Concept Laser M2 Cusing laser additive manufacturing machine. Sets of 4 identical copies of the artifact were fabricated at a laser power of 60W and speed of 0.6m/s over the power bed. The lattice truss artifacts were sent in pairs to computed tomography (CT) metrology systems at Zeiss and LLNL [1]. The measurements of dimensional variability provided a gauge of both the quality of the build (lattice failure rates,

warping) and consistency between builds via the comparison of multiple identical copies. The artifacts were then swapped and the measurements repeated to compare the capabilities of the two CT metrology systems.

MEASUREMENTS

Complexity of the parts will require multiple evaluations with optical, tactile and X-ray sensors. The main focus will be on defining the geometric accuracy of produced components, surface flaws, accuracy of internal features, porosity, and material stress effects on dimensional stability.

Currently, metrological CT systems can perform successful measurements with sub-micrometer interpolated resolution of edge detection. Those measurements can be performed with accuracy better than $2\text{ }\mu\text{m}$. Figure 4, shows measurement deviation from a calibrated value of a distance between selected spheres. The artifact was calibrated using a scanning CMM and the uncertainty of this calibration was $1\text{ }\mu\text{m}$.

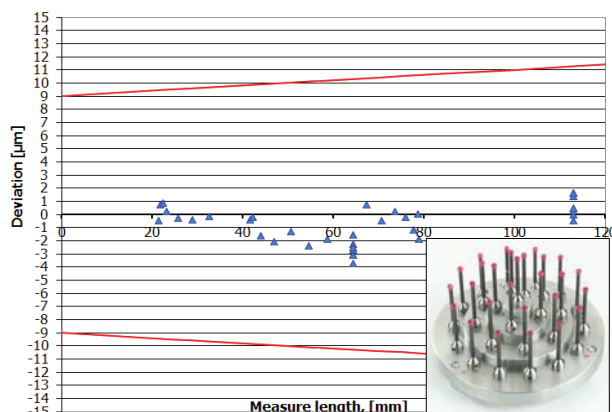


FIGURE 4. Metrological CT – Metrotom 1500 the accuracy of distance measurement between multiple spheres based on VDI/VDE 2630 standard. The horizontal axis show increments of 20 mm as a distance between spheres, and vertical axis shows $1\text{ }\mu\text{m}$ increments as deviation from calibrated distance between spheres using high accuracy CMM. Red lines define manufacturer specification.

Measurements of the artifact shown in Figure 1, were performed with Contura G2 coordinate measuring machine (CMM) equipped with Vast XXT scanning sensor with measurement accuracy stated by manufacturer as $1.8\text{ }\mu\text{m} + L/300$ (L – length in mm) and resolution of $0.2\text{ }\mu\text{m}$. Measurement of flatness was performed

along path shown as a yellow line on Fig. 2. Cylindricity of the central bore was measured by inspecting the profile at five different heights of the Center Bore from the bottom surface at: 3, 6, 9, 12, and 15mm.

Figure 5 shows a typical result of the flatness measurement. The flatness deviation is likely due to residual stress in the part and build platform causing warping. In fact, if the part is separated from the build platform (without heat treating), the residual stress state in the part changes and the warping is far more pronounced, as seen in Fig. 6. These large flatness deviations demonstrate the tremendous residual stress developed during many metal powder bed fusion processes.

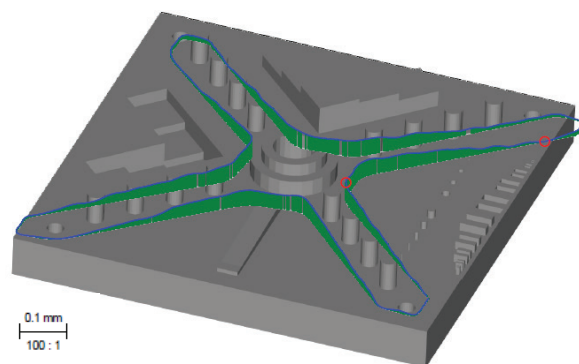


FIGURE 5. Evaluation of flatness of the artifact on the base plate right after build. The maximum deviation from inside to outside is 0.049 mm. The artifact was created by EOS M270 using 17-4 stainless steel.

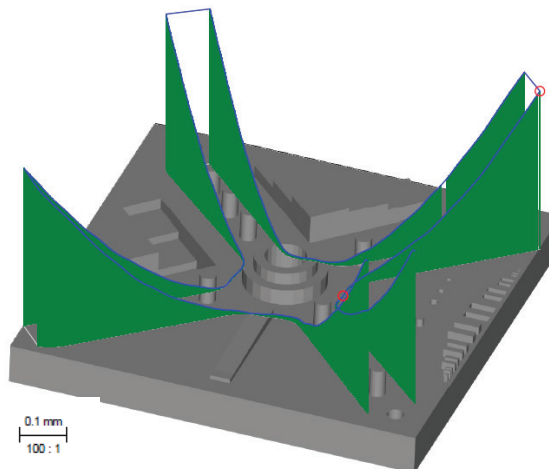


FIGURE 6. Evaluation of flatness of the artifact removed from the base using wire electrical discharge machining. The artifact was not heat treated. The maximum deviation from inside to outside is 0.498 mm.

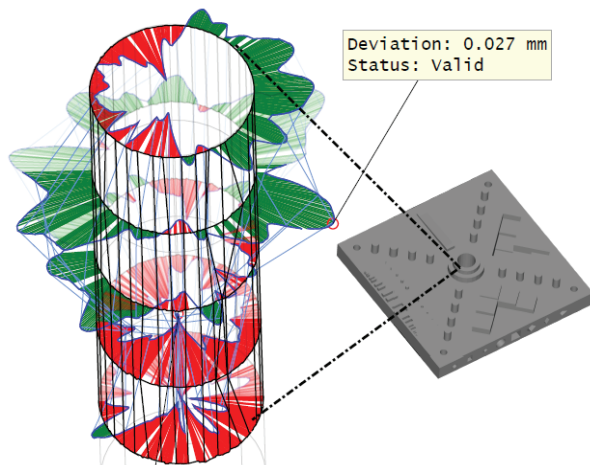


FIGURE 7. Cylindricity of the center hole right after build is 0.0531 mm.

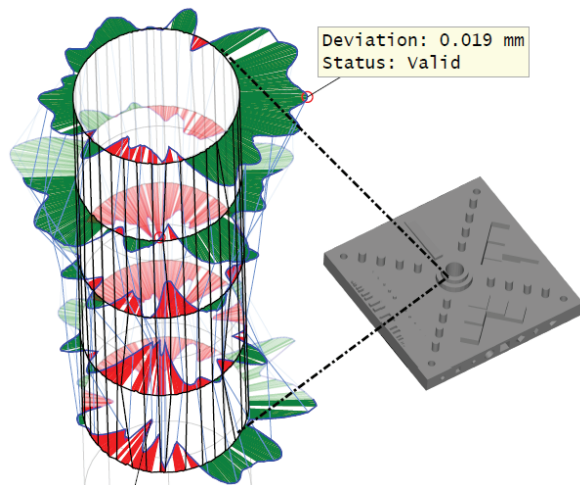


FIGURE 8. Cylindricity of the center hole after part was removed but not heat treated is 0.0457 mm.

Figure 7 shows a typical result of the cylindricity measurement. The maximum external deviation of 0.027 mm shows the expected tolerance this machine can expect to hold on a circular feature. Again, removing the part from the build platform changes the shape of the part, in this case resulting in better cylindricity.

The metrology carried out in this work provides important insights towards improving the fabricated lattice truss performance. The structure is intended for large volume patterning to retain part strength while reducing weight. This requires a repeatable lattice truss structure with minimal necking, breaks, warping or excess material. All of these error sources reduce the strength/weight ratio of the structure.

Repeat measurements of the same part shown in Fig. 9 indicate that the CT measurement error was on the scale of a few micrometers, well below that observed between parts or between the part and the design. This confirms that the CT measurements are able to capture the errors in the lattice truss structure.

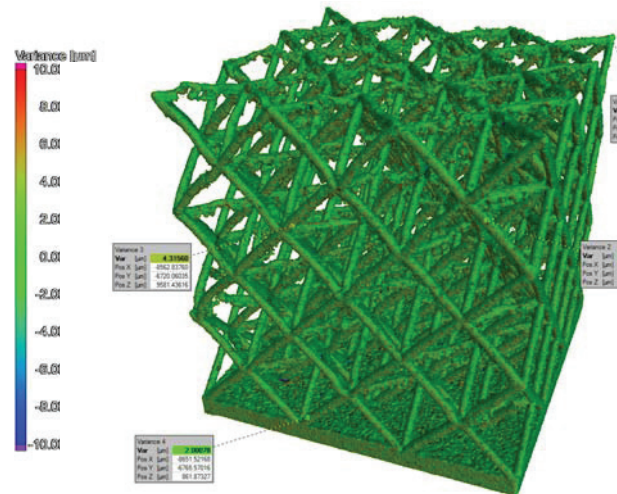


FIGURE 9. Repeatability map of 3 measurements. The measurements repeat with 4 μ m variance. CT data created by scanning the artifact with Zeiss Metrotom 1500 at 130kV, 225 μ A, and 29 μ m Voxel.

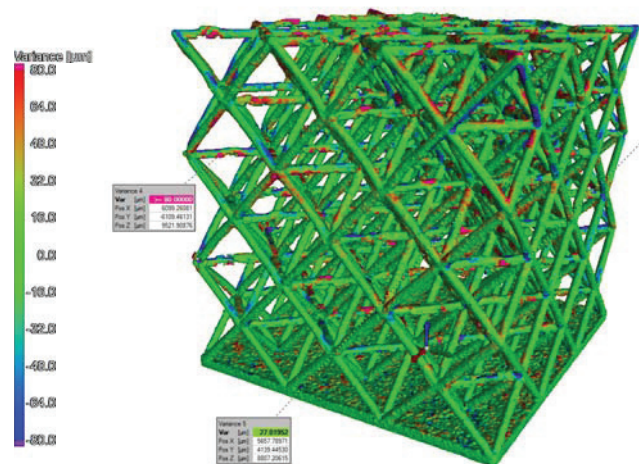


FIGURE 10. Reproducibility of the process between 2 same parts built by the M2 Cusing machine. The deviation exceed 100 μ m at certain locations. Same CT parameters as Figure 9.

The part-to-part variation comparison shown in Fig. 10 indicates that the fabrication process is anisotropic, which has been reported for laser sintering [2,3]. The largest variability ($\approx 100\mu$ m)

is mainly confined to the horizontal plane. This is significantly larger than the error observed on the angled off-horizontal struts. The part-to-part comparison also shows few large scale trends, meaning that the fabrication process is large scale repeatable and does not produce large warping variations between parts.

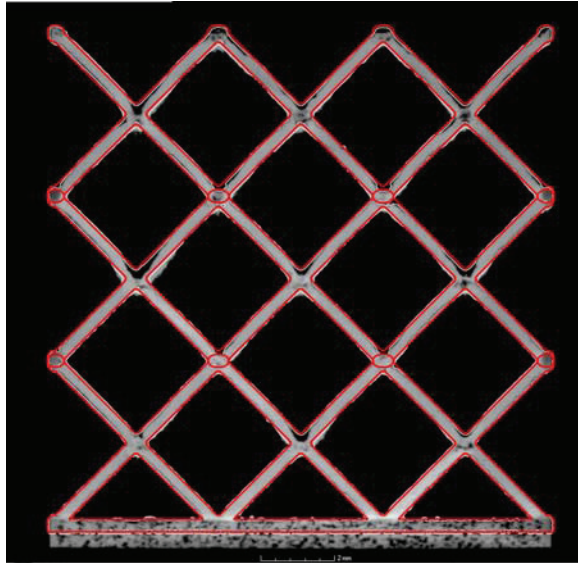


FIGURE 11. Side view – vertical cross section of the volume in Figure 3, showing typical deviations between the design (red line) and actual part. The deviation exceeds 100 μm at certain locations. Same CT parameters as Figure 9.

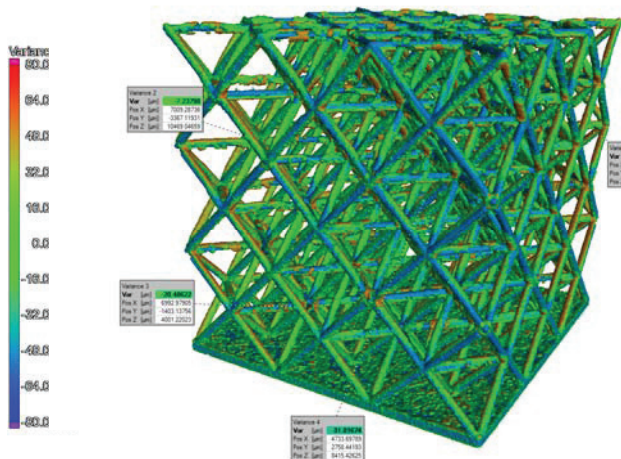


FIGURE 12. Typical deviations between the design and actual part. The deviation exceeds 100 μm at certain locations. Same CT parameters as Figure 9.

Several trends are visible in the absolute error of the part vs. the CAD model shown in Figs 11-14.

The angled struts often have small bends on their lower third, shown in Fig. 11, which would result in reduced buckling load capacity.

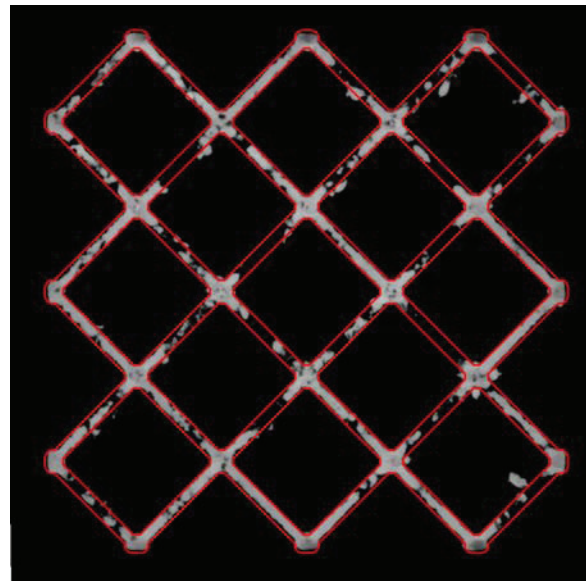


FIGURE 13. Top view - cross section of the volume in Figure 3, showing typical deviations between the design (red line) and actual part. The deviation exceeds 100 μm at certain locations. Same CT parameters as Figure 9.

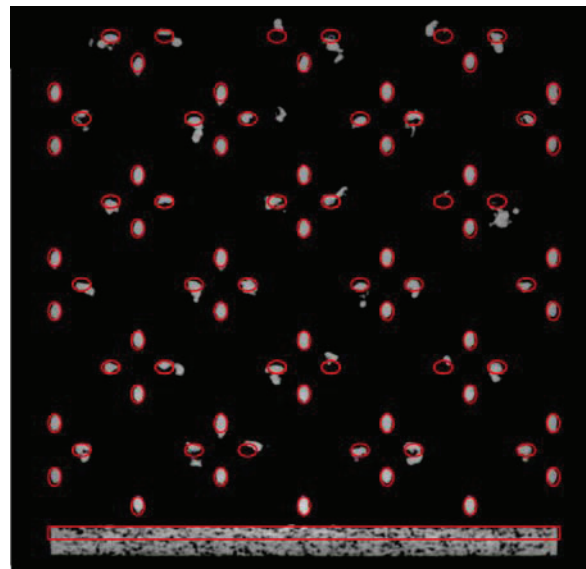


FIGURE 14. Node view - cross section of the volume in Figure 3, showing typical deviations between the design (red line) and actual part. The deviation exceeds 100 μm at certain locations. Same CT parameters as Figure 9.

The angling may be due to thermal effects at the vertex, and may be fixable by a slight increase in the structural mass above each vertex. The

parts show a trend of undersized struts in the corner facing the reader in Fig. 12. This is visible via the increasing blue seen in this area. The horizontal struts show an increased incidence of voids in Fig. 13, which reduces lattice truss strength. This appears to be a function of the fabrication process, and may be reduced by angling the part during fabrication. Finally, the cross-sections of the angled struts in Fig. 14 indicate that while most are in the correct location and size, the unwanted material does not form a Gaussian distribution around the desired area, but rather shows some significant outliers.

DISCUSSION

One of the difficulties in using test artifacts to characterize machine performance is that it is a post-process measurement. Because the part is removed from the AM machine before measurement, local datum features must be used to establish a local coordinate system and features can only be measured relative to each other (instead of relative to any machine datum surfaces). For the test artifact shown in Fig. 1, the top surface and the central hole are intended as primary and secondary datum features for measurement. The results shown here demonstrate the significant errors that can be present in these features. Using these as datum features may mask some of the deviations present and may transfer some of their deviations to the results of relative measurements of other features, confounding the ability to link specific deviations to specific machine/process sources. One might speculate that the build platform might be a better datum feature, but the build platform has no locating features in the x- and y-directions, and the platform is only aligned to the recoating blade to within 0.05 mm. Further, the building process starts with a layer of powder already atop the build platform.

The results of the CMM measurements also demonstrate the issue of when to measure the parts to best characterize the machine. It is easy to see that after the part is removed from the build platform, the shape is significantly different. However, it is difficult to say that these errors are fully the result of machine performance, especially if there is a heat treatment before removal. Measurement immediately after the part has been removed from the machine might give better correlation to machine performance, but since AM parts are

almost always post-processed in some way, these results may not be as indicative of an actual part's performance.

The CT metrology work shows that the lattice truss structures can be repeatably fabricated. It also aids in identifying several error trends which can be used for further part improvements, including location and general form of part variation as well as error. This knowledge can be used to both adjust the design and the fabrication process to improve the lattice truss strength and reliability.

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