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Reviewed Paper

QUANTIFYING ACCURACY OF METAL ADDITIVE PROCESSES THROUGH A STANDARDIZED TEST ARTIFACT

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Abstract

Two limitations of AM processes when compared to CNC subtractive processes are reduced dimensional accuracy and rougher surface finish. Accuracy and surface finish of metal additive processes, such as DMLS or SLM, are generally much looser than precision turning or grinding processes. Because of this, it is important to have an understanding of an AM machine's capabilities—the designer must be satisfied with the tolerances and finishes possible, or additional post-processing must be added. One way to examine the capabilities of an AM process is by printing and measuring test artifacts. This paper examines a test artifact proposed by NIST that is intended to demonstrate many different capabilities and types of accuracy. Three identical builds are printed on a Concept Laser metal additive machine and measured. The capabilities of the machine are quantified and discussed, along with additional recommendations for improving the test structure design and the measurement process.

Introduction

Additive Manufacturing (AM) is a field that continues to develop in capabilities and in breadth of applications. Additive processes in general have many strengths over conventional subtractive processes, including increased freedom in design complexity, quick turnaround on design changes, and better economy at low volumes. Of course, AM has several well-documented shortcomings as well, such as anisotropic material properties and relatively slow manufacturing time. AM typically produces parts with lower accuracy and surface finish than can be produced by precision machining processes (Figure 1 and Figure 2). Deformation due to warping, shrinkage, and delamination can also be a concern.

For end users of commercially available AM machines (or 3D printers), the accuracy available for a specific process can be largely unknown. Nominal layer thickness can be selected, and sometimes a vendor will list typical accuracy values or minimum feature sizes, but these can be highly dependent on the individual machine, the material, the process parameters, and the manufacturability of the designed part. Because of this, it is essential that operators of AM machines be able to measure and predict the accuracy of their specific set up.

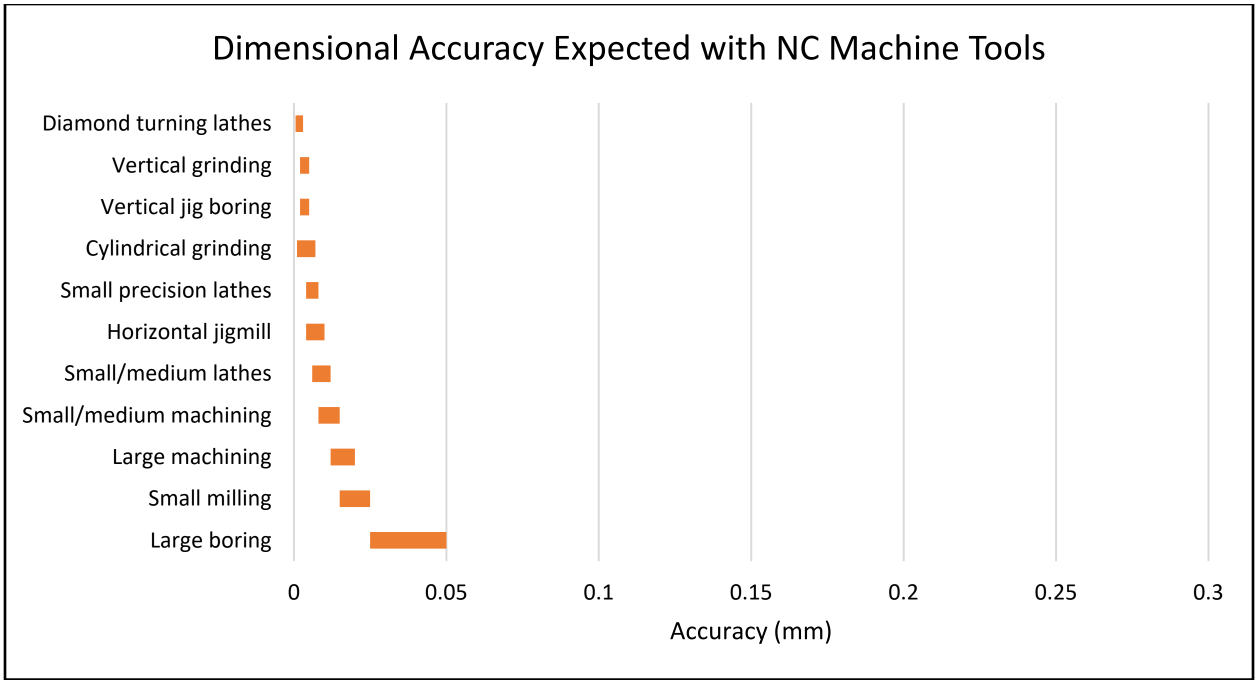

Figure 1. Typical accuracy, precision subtractive processes [1].

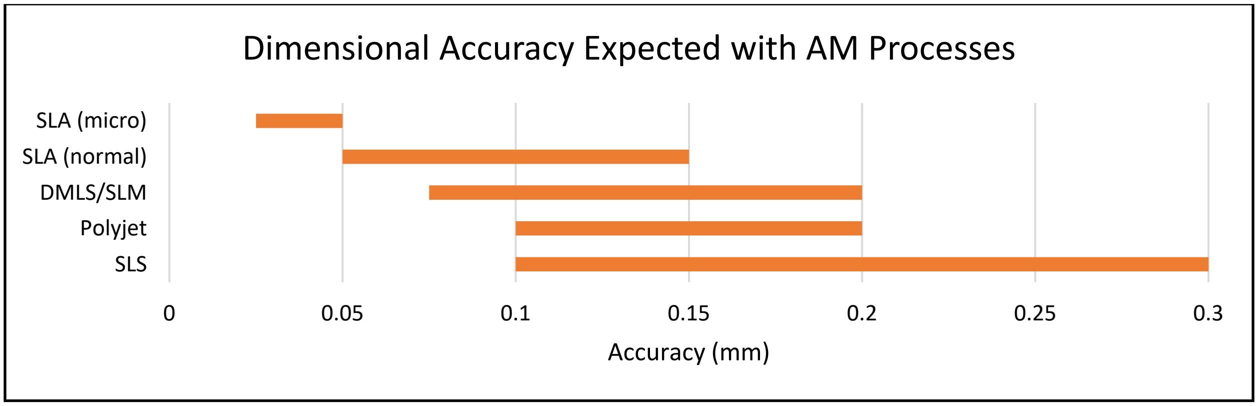

Figure 2. Typical accuracy, precision additive processes [2] [3].

One method often used to gauge the capabilities of an AM process is through printing and examining test structures. These test structures come in many varieties; most are designed to assess one or a few aspects of print quality for a specific type of process. Some test structures are geared towards qualitative judgements on overhangs, stringing, etc. (Figure 3), while others are used to quantitatively measure dimensional accuracy. In the past few years, there have been efforts by many authors to develop standardized test structures [4] [5] [6]. One such test structure was proposed by Moylan, et al., in 2012 for the National Institute of Standards and Technology (NIST) [7] [8]. This structure, shown in Figure 4, is suitable for any AM process, but is especially well-suited for metal AM processes, like direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM).

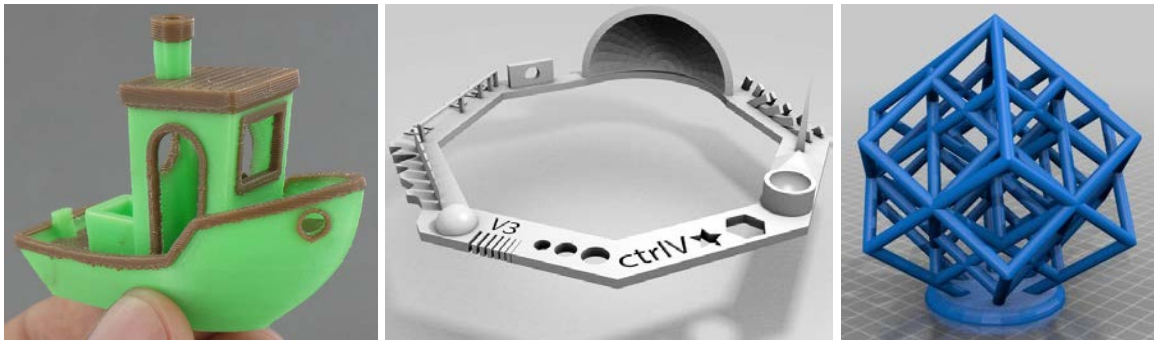

Figure 3.”Torture test” type test structures [9] [10] [11].

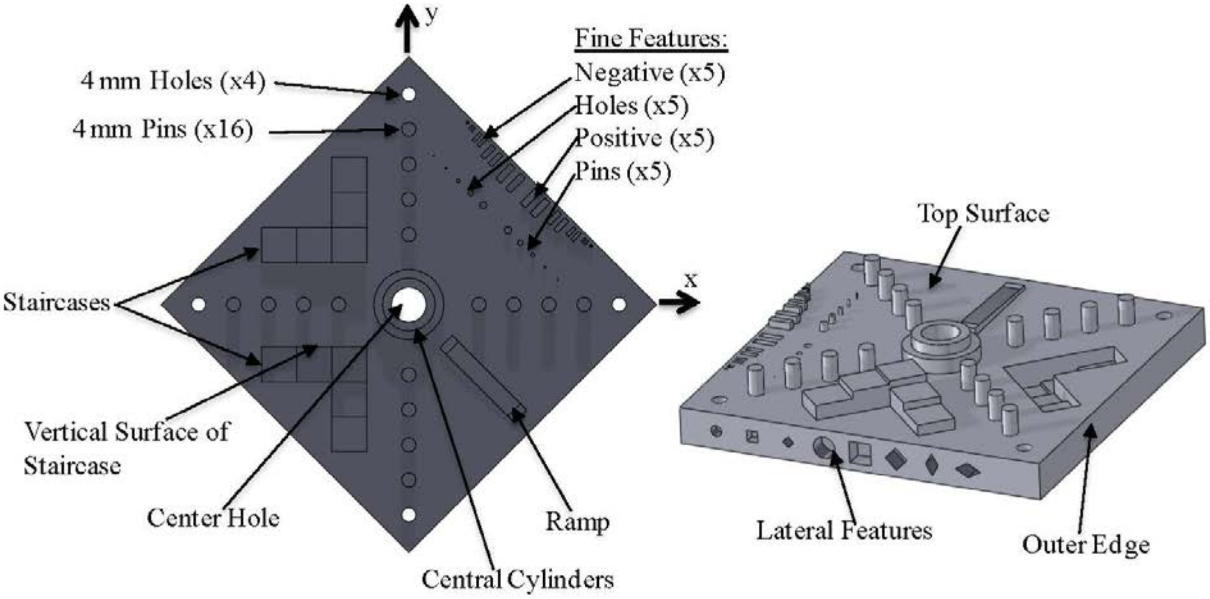

Figure 4. NIST test artifact proposed by Moylan, et al [12].

The NIST test artifact is designed to encompass a wide variety of feature types for quantitative and qualitative evaluation. The engineering drawings and a complete description of these features are available on the NIST website [12] and in the two papers by Moylan, et al. [7] [8], and are summarized in Table 1.

Features on part	Available measurements
Top surface	Flatness, surface roughness
Center hole	Cylindricity, perpendicularity to surface
Pins and holes	Position, diameter, height
Staircases	Height, straightness, parallelism, perpendicularity
Outer edges	Straightness, parallelism, perpendicularity
Central cylinders	Roundness, concentricity
Ramp	Layer height (surface profile)
Lateral features	Dimensions, angles, qualitative evaluation of overhangs
Fine features	Dimensions, minimum feature size

Table 1. Features and measurements on the NIST test artifact.

In this paper, we use the NIST test artifact to assess the capabilities of a Concept Laser Mlab cusing machine. The purpose of this study is twofold: to understand and predict the accuracy available from this specific AM process and to review the usability of the NIST test artifact.

Method

From the STL file available on the NIST website [12], three test artifact were printed in 316SS stainless steel on a Concept Laser Mlab cusing machine (Figure 5). Due to the available bed size, the parts were scaled to 50% of the original model size. No post processing occurred before measurement. The methods followed for measuring selected features in Table 1 are listed below. Due to equipment limitations, not all measurements were able to be made; the remainder may be described in a future paper.

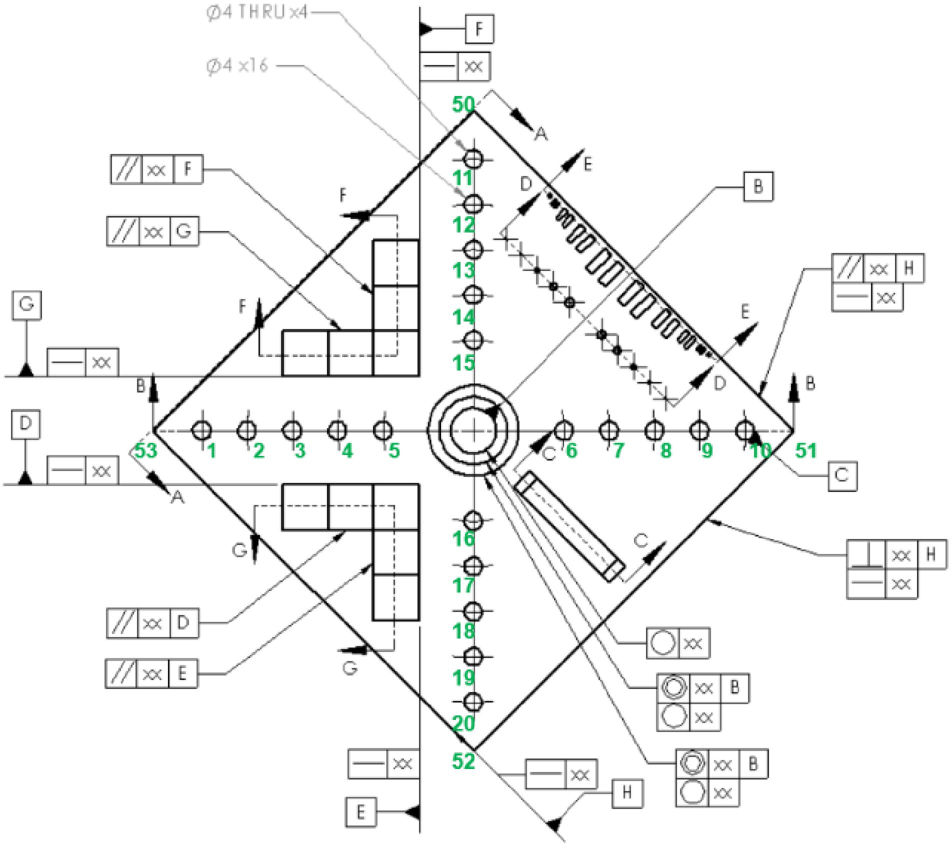

Figure 5. Measurement points on the test artifact.

Horizontal dimensions: Measurements were taken with a RAM Optical OMIS II optical measurement system (Figure 6). The procedure used for measuring the X-Y coordinates of each feature was the following:

Positions and diameters of pins and holes (features 1 through 20 in Figure 5)

1. Boot up optical measurement system.
2. Secure test artifact to bed of machine with tacky clay with points 51 and 53 along the marked horizontal (X) axis.
3. Track the machine's cursor between points 51 and 53 and pivot the test artifact by hand until the two points are aligned horizontally.
4. Measure the horizontal distance between points 51 and 53. Zero the X axis at the midpoint.
5. Measure the vertical distance between points 50 and 52. Zero the Y axis at the midpoint.
6. Measure the positions of the left and right borders of pins/holes 1-10 relative to the center of the artifact.
7. Measure the positions of the top and bottom borders of pins/holes 11-20 relative to the center of the artifact.
8. Remove the test artifact from the bed.
9. Repeat: take three sets of measurements for each of the three test artifacts, removing the artifact between each set of measurements. Average the three measurements for each feature.

Figure 6. OMIS II optical measurement system inspecting fine feature.

Dimensions of rectangular fine features (along views E-E in Figure 5)

1. Boot up optical measurement system.
2. Secure test artifact to bed of machine with tacky clay with points 50 and 51 along the marked horizontal (X) axis.
3. Track the machine's cursor between points 50 and 51 and pivot the test artifact by hand until the two points are aligned horizontally.
4. Measure the horizontal distance between points 50 and 51. Zero the X axis at the midpoint.
5. Zero the Y axis at the line between points 50 and 51.
6. Measure the positions of the left and right borders of each rectangular boss and pocket relative to the origin.
10. Remove the test artifact from the bed.
11. Repeat: take one set of measurements for each of the three test artifacts, removing the artifact between each set of measurements.

Vertical dimensions: Vertical measurements were taken using a dial indicator mounted on CNC machine (Figure 7). Measurement of the downward staircase steps was not possible with this set up due to the angle of the probe.

Figure 7. Dial indicator measuring pin height.

Heights of pins (features 2-9 and 12-19) and staircase (along view F-F in Figure 5)

1. Turn on CNC machine.
2. Place test artifact into machine with point 50 and point 51 along horizontal (X) axis
3. Use toe clamps to fix the support plate to the machine table.
4. Move dial indicator along the edge between points 50 and 51. Pivot the artifact by tapping with a hammer until the two points are horizontal with each other (within 0.01 mm).
5. Move the dial indicator to the surface of the support plate and press down approximately 0.4 mm, then zero the Z-axis coordinate.
6. Raise the dial indicator and set it above the center of the pin or stair step to be measured.
7. Lower the dial indicator until the dial reads “0”.
8. Record the absolute Z measurement given on the controller of the machine.
9. Move the indicator about 3 mm along the Y axis and lower it to the top surface of the test artifact.
10. Record the absolute Z measurement given on the controller of the machine.
11. Raise the indicator and move it to the next feature.
12. Repeat until all pins and stair steps have been measured.
13. Repeat the procedure while the artifact is still fixtured in the machine for two more sets of measurements (three total sets of measurements for each of the three artifacts). Average the three measurements for each feature.

Results

Pin and hole diameter: The OMIS II was used to measure the pin and hole diameters on three builds of the NIST test artifact. Measurements were taken by visually aligning cursor with the edge of the top surface of the pin or the surface of the bed surrounding the hole. These measurements proved difficult because the appropriate edge of the round features was not always easily determined. Often, the edge of a pin or circle would have spatter or undercuts along the perimeter (Figure 8) and the inspector would have to make an approximation as to the location of the quadrant. This certainly led to some minor variation in measurements.

Figure 8. Micrograph of a pin edge on the test artifact.

Measurements for each pin and hole were taken three times. The average measured diameters for the pins and holes are shown in Figure 9 and Figure 10, respectively. Measurements of roundness or cylindricity were not taken for these features, but micrographs from the top view would sometimes show enough variation between build layers that lower layers would be visible along the feature perimeter.

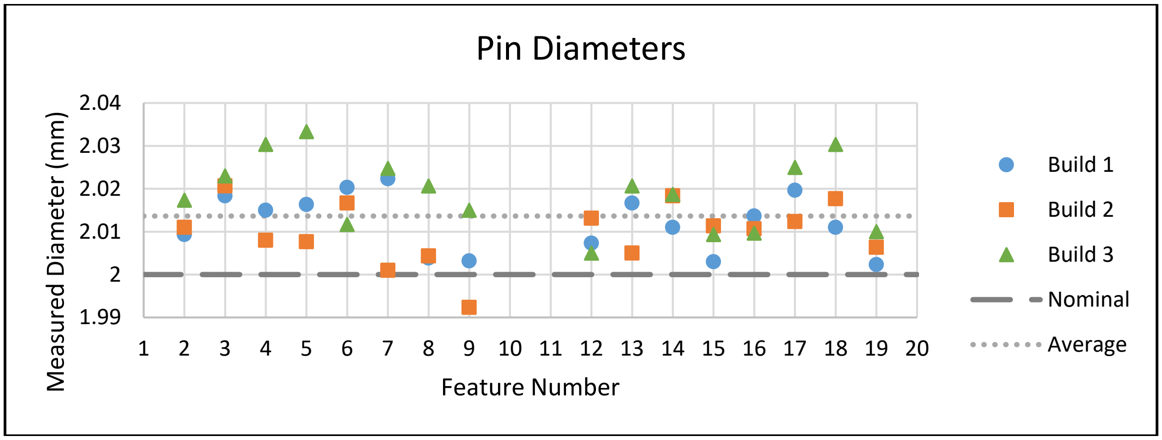

Figure 9. Pin diameters (average of three measurements).

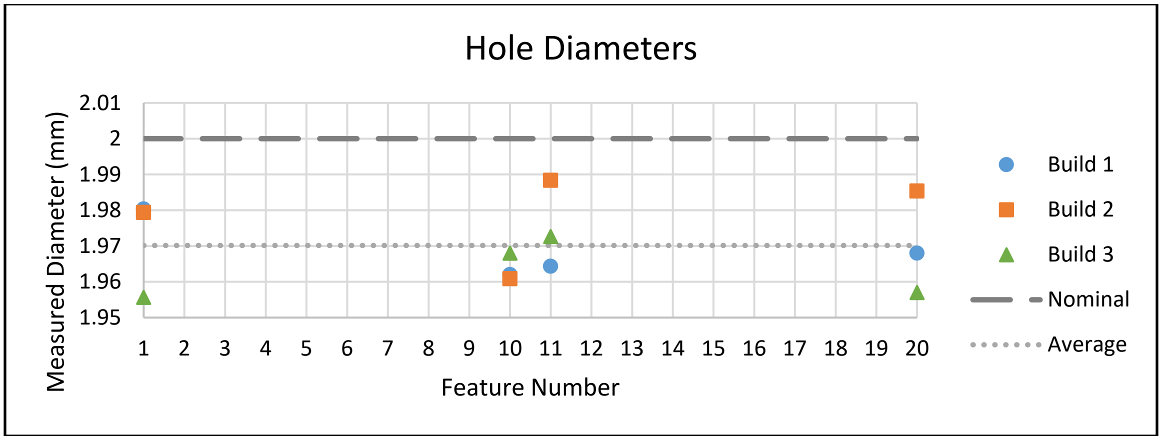

Figure 10. Hole diameters (average of three measurements).

Pin and hole position: The same measurements were also used to determine the positional accuracy of the pins and holes. The distance from the center of each feature to the center of the artifact was compared to the nominal position on the original design. Figure 11 shows the deviation of each feature's position, calculated as the nominal position minus the measured distance.

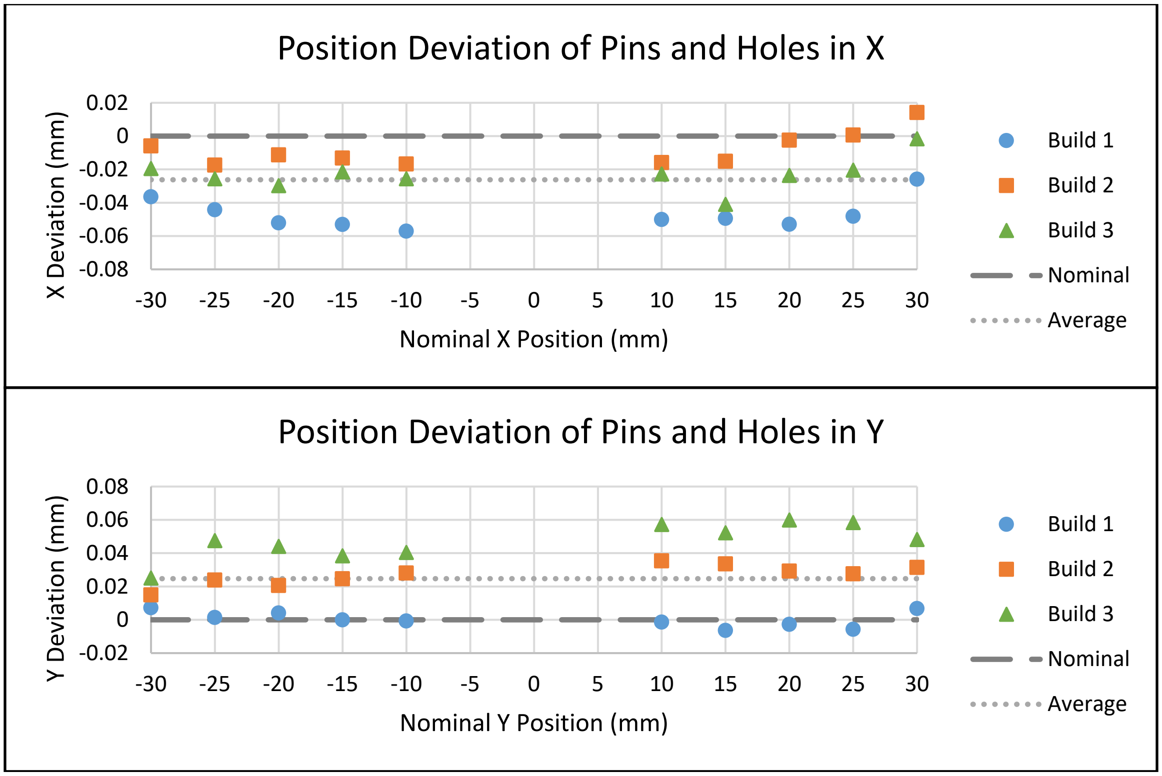

Figure 11. Position deviation (nominal minus measured) of pins and holes (average of three measurements).

Pin height: The height of each pin was measured using a dial indicator mounted on a CNC machine by comparing the Z position at the center of each pin's upper surface with the surface of the artifact about 3 mm away from the pin. These heights were measured three times per build. The average measured height for each pin is shown in Figure 12.

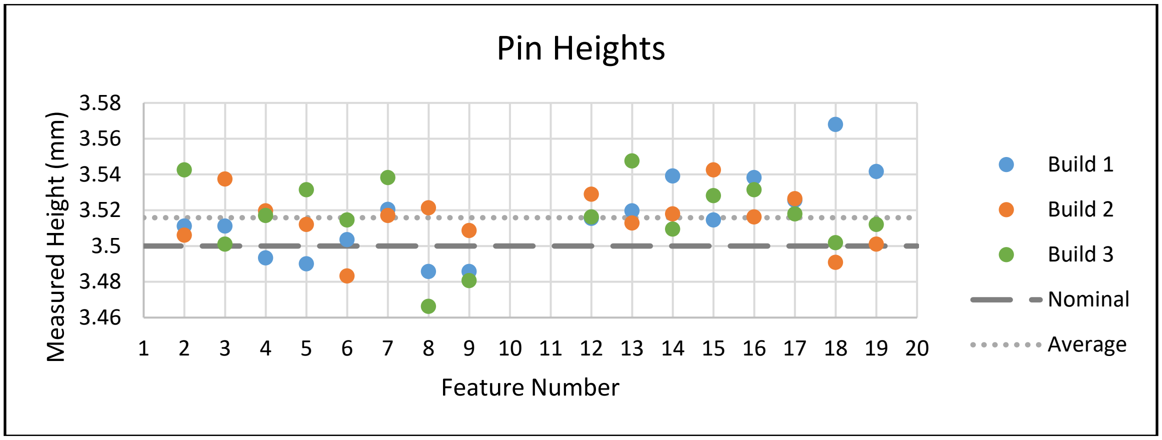

Figure 12. Pin heights (average of three measurements).

Fine Features: Four types of fine features are included on the artifact: rectangular bosses, rectangular pockets, circular pins, and circular pockets. The OMIS II was used to inspect these features to determine the dimensional accuracy and minimum feature size of small features. Figure 13 shows the deviation in width of each pair of rectangular bosses or pockets (nominal minus measured). Figure 14 shows the deviation in diameter for each circular pin or pocket (nominal minus measured).

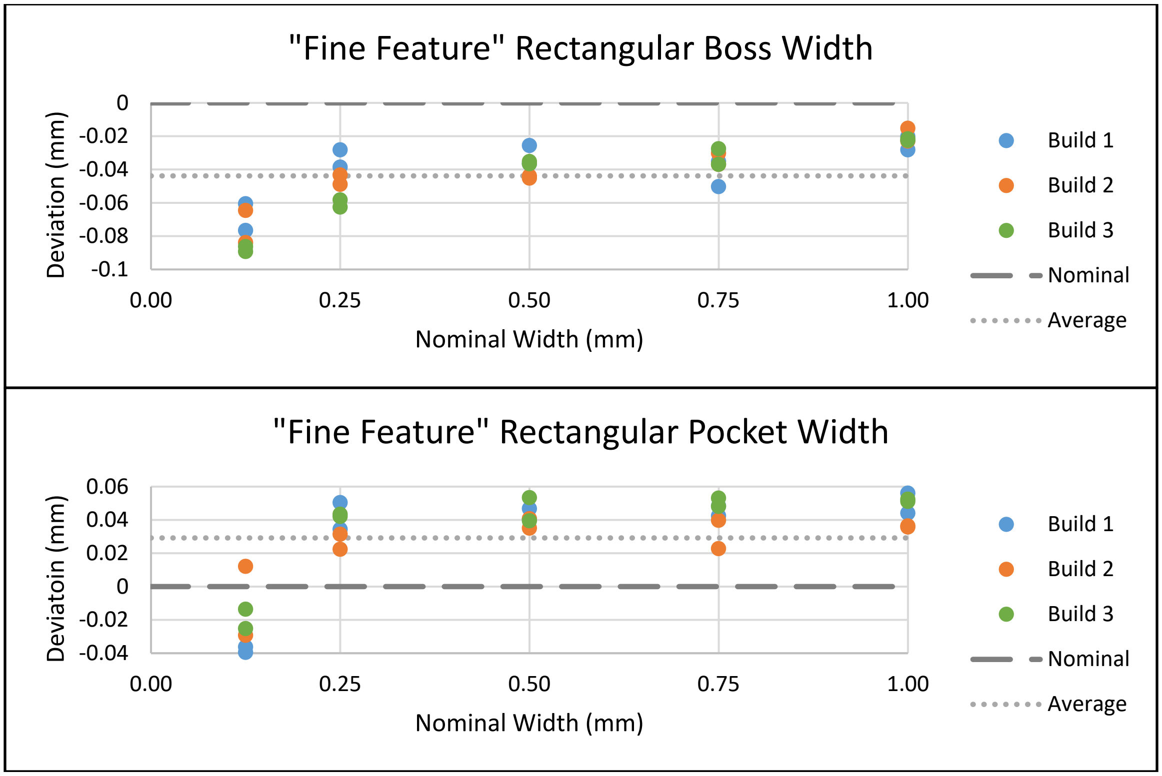

Figure 13. Width deviation (nominal minus measured) of rectangular fine features.

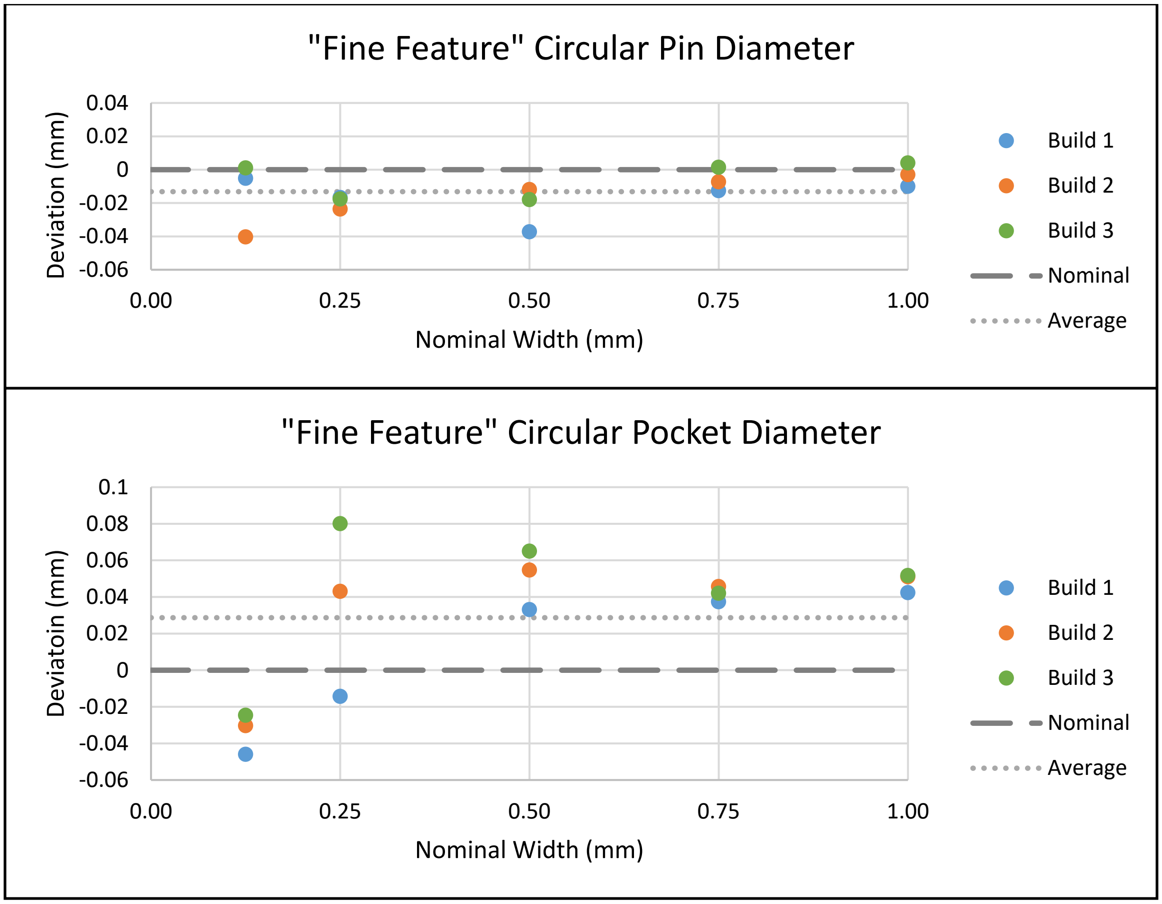

Figure 14. Diameter deviation (nominal minus measured) of circular fine features.

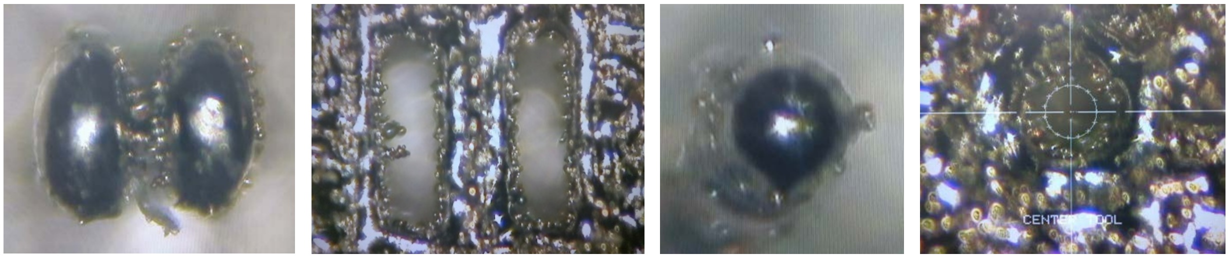

Figure 15. Micrographs of smallest printed fine features.

Figure 15 shows examples of some of the smallest features that were successfully printed on all three builds of the test artifact. All rectangular bosses and pockets were printed, with nominal widths of 0.125 mm. All circular pins and pockets were also successfully printed, with nominal diameters of 0.125 mm. However, as can be seen in Figure 15, there is significant irregularity to the shape of these features, due to spatter, loss of sharp corners, etc.

Upward Staircase Steps: The heights of the upward staircase steps were measured using a dial indicator mounted to a CNC machine. The probe on the dial indicator is set at an angle of 45° from vertical, which prevented measurement of the recessed (downward) staircase at this time. Figure 16 shows the deviation in height of each step (nominal minus measured) for the three builds of the test artifact.

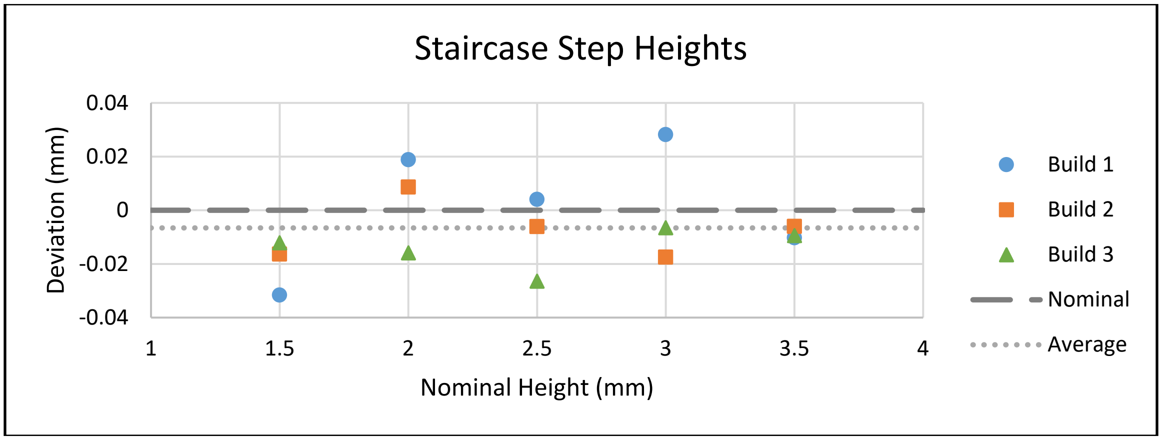

Figure 16. Height deviation (nominal minus measured) of staircase steps.

Lateral Features: The recessed pockets on the side of the test artifact were viewed with the OMIS II. Dimensions were not measured, but images were taken for assessments on overall quality. Sample images of each shape are shown in Figure 17.

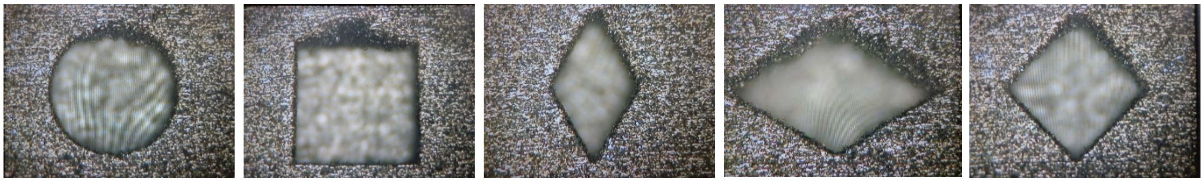

Figure 17. Sample micrographs of lateral features on the test artifact.

Discussion

Pin and hole diameter (Figure 9 and Figure 10): For all three builds, pin diameters were consistently larger (about 0.013 mm) than the target dimensions, while holes were consistently smaller (about 0.027 mm). This is consistent with the physics behind DMLS/SLM/EBM processes. As shown in Figure 18, the laser or electron beam used in such processes has a cross-sectional area that must be taken into account in path planning. If the actual effective beam size (including the heat affected zone) does not match the size used in path planning calculations, there will be a consistent mismatch between positive and negative features, i.e., positive features will be too large and negative features too small, or vice versa.

Concept Laser's slicing software uses a theoretical beam spot size in conjunction with a beam offset distance to determine the beam path. The machine automatically adjusts which side of the geometric profile the beam will travel, but the slicing software does not offer an easy way to adjust the beam offset. For the machine used to produce the test artifacts, the beam size was fixed at 0.090 mm diameter (for a beam offset of 0.045 mm). The actual effective beam size can be calculated by using the following equation:

$$\emptyset_{Beam} = 2\left[Offset + \left|\frac{\emptyset_{Measured} - \emptyset_{Theoretical}}{2}\right|\right]$$

With an offset of 0.045 mm and the measured data from the test artifact, we calculate that the beam diameter is effectively 0.103 mm for pin features and 0.117 mm for hole features. This increase in beam size in relation to the fixed value leads to maximum material conditions for features in the X and Y directions (positive features increase in size, negative features decrease in size). Introducing an option in the software to test and adjust for beam size, either offline or in a closed-loop self-test, would allow for enhanced calibration and optimization of the AM process and more dimensional accuracy in small features.

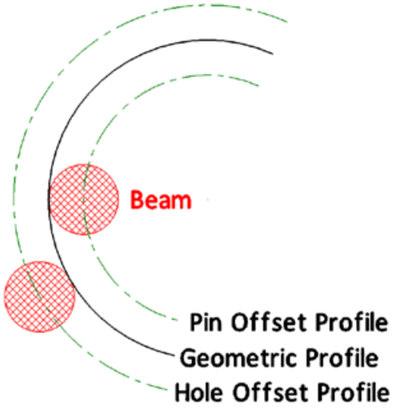

Figure 18. Beam offset used in metal AM processes.

Pin and hole position (Figure 11): The positions of the pins and holes relative to the center of the artifact were compared to the nominal distances. For all three builds, the pins and holes along the X axis were shown to be consistently to the right of their nominal position by an average of 0.026 mm. Likewise, the positions in the Y axis were an average of 0.025 lower than the nominal position. These biases could be due to an actual shift in the pin position on the part, or more likely, by insufficient accuracy in determining the true center of each artifact. The three builds each exhibited different levels of deviation, but within each build, the position of the pins were quite consistent, within ranges of 0.064 mm for Build 1, 0.053 mm for Build 2, and 0.101 for Build 3.

Pin height (Figure 12): Pin heights were measured with a CNC machine that used a dial indicator to locate the top of each pin in reference to the surface of the artifact. Observation of the pins to measure diameter revealed that the top surface of each pin had a slight concavity (see Figure 19). This concavity could be due to the difference between exterior walls and the infill and the material shrinkage during the melting and cooling processes. This concavity made it difficult to measure the heights on the CNC machine, as it could give deviations of up to 0.075 mm. To mitigate this error, the operator was careful to always measure at the center of the pin, at its lowest point. Additional error may have been introduced by measuring from the surface of the artifact. When clamping the base plates to the table, we observed that the base plates were slightly bowed up, likely due to the stresses of the artifact being sintered directly onto it. The clamping forces pulled downward on the base plate and may have changed the dimensions of the test artifact. Pin heights averaged at 3.516 mm, slightly higher than the nominal 3.5 mm. The data indicate two possible trends. In the X direction (pins 2 through 9), there appears to be a slight decrease in pin height from left to right. In the Y direction, the pins all tended to be taller than the target (versus the X direction, where the pins were equally distributed about the target height). Both of these trends, if real, may be due to the aforementioned warping of the base plate, either during the process or afterwards. If these results were shown to be consistent from part to part, the original design file could be altered to increase the accuracy of the final product.

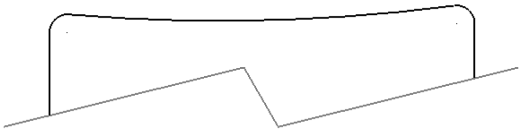

Figure 19. Illustration of concavity at the top of each pin (not to scale).

Fine Features (Figure 13 and Figure 14): The relative size of the positive and negative fine features match the general trends described earlier regarding the 2-mm pin and hole diameters: the rectangular bosses and circular pins were consistently larger than designed, while the rectangular and circular pockets were generally (but not always) smaller than designed. The negative features exhibited more variation in size than the positive features. One reason for this is likely due to the use of powder in the process. As positive features were created, any excess powder in the area would be exposed to the hot finished part in one localized direction, minimizing the undesired sintering of additional material. However, as negative features were created, the pockets would surround unfused powder on all sides. This powder would continue to be heated from multiple directions over several layers, leading to increased partially sintered material. An additional reason for this variability may be in the increased difficulty in visually measuring such negative features, where the additional spattered material makes an irregular surface and lighting can be less ideal.

The test artifact was designed to also show the minimum feature size feasible in a process by having sequentially smaller fine features, the smallest of which may not physically appear on the printed part. However, the Concept Laser machine was able to successfully print all of the fine features, even at 50% scale of the original NIST design. The rectangular bosses and pockets are positioned on the artifact in pairs, demonstrating the minimum separation needed between features as well. The smallest pair of pockets, which were 0.125 mm in width with a 0.125 mm wall separating them, were successfully printed and distinct on all three builds. Likewise, the smallest pair of bosses, which were 0.125 mm in width with a gap of 0.125 mm between them, also printed without fusing together. However, with the variation due to beam offset and shape irregularity from spattered material, the gap between the two bosses was only 0.046 mm.

Staircase step height (Figure 16): staircase heights were measured on the CNC machine because the optical comparator could not focus on them. Heights tended to be slightly taller than the nominal dimensions, by an average of 0.007 mm. This deviation is less than most of the variation exhibited in the X and Y directions. This is to be expected, because as consecutive layers of powder are deposited onto the parts, the layer heights are largely self-correcting.

Lateral Features (Figure 17): The printer demonstrated a decent ability to construct small overhanging patterns without the use of support structures (other than the unfused powder). On shapes with more extreme overhangs, such as the circle, the square, and the wide rhombus, the overhang does show a rougher texture from less tightly packed fused particles. Some of the straight edges also show minor but noticeable curvature. However, none of the features failed to print or demonstrated significant changes in geometry. The difference in quality between the different shapes (narrow rhombus to medium rhombus to wide rhombus to square) can aid the designer in knowing how far to push the capabilities of the machine in creating “real world” features like threaded holes.

Conclusions

This study provides the opportunity to both examine the capabilities of the Concept Laser Mlab cusing machine in printing the NIST test artifact and to review the test artifact itself. Conclusions and recommendations in both of these areas are offered below.

Capabilities of the AM process: Through measurements of the test artifact, it appears that the machine, process, and material used led to consistent results from build to build and from feature to feature. Overall, even the most extreme measured features fell into a range of ± 0.1 mm from the nominal dimensions or positions. This places the accuracy of this process at the lower end of the estimated accuracy given in Figure 2. Of course, with more complex part designs and other materials, accuracy will not necessarily remain at the same level. Even with this commendable level of accuracy, however, improvements could be made to offer better results. Much of the variability exhibited in the test artifacts was due to biased means in the measurements. In other words, the feature dimensions were very precise, but were not centered on the target value. The Discussion Section above mentions the bias in positive and negative feature size due to an inaccurate beam offset. Similar biases also appeared to occur in the pin height, possibly from warped base plates or sloped top surfaces, and in pin position, possibly from measurement errors. If these three biases could be eliminated, the resulting variation in dimensions and positions would shrink to about ± 0.05 mm or even better. The possibility of introducing user-initiated or closed-loop tests to account for these biases can enable optimization of machines for specific materials and even for specific part designs.

Review of the NIST AM Test Artifact: Overall, both the machine operator and the inspectors were pleased with the usability of the test artifact. Some of the benefits noted by various users included:

- The standardized geometry (circular and rectangular features) simplified the measurement process.
- Arrangement of features at 0°, 45°, and 90° aided measurement from baselines on the part perimeter.
- Fine feature array offered a wide variety of quantitative and qualitative analyses in a small number of features.

Several shortcomings or opportunities for improvement were also offered:

- By covering much of the build platform with a solid block of material, considerable time, material, and cost is expended in each build. Multiple separate parts or a smaller base structure would reduce expenses considerably.
- Because many of the features are purposefully as small as can be consistently built, they are also fragile and difficult to interact with. Using a physical coordinate measuring machine (CMM) would damage many of these features, which limits the inspector to visual means, which can be more subjective and error-prone. In addition, it may be hard to visually identify the smallest features with an optical system, especially small holes in a flat surface.

- Because of the arrangement of the features on the artifact, it is not possible to use a visual CMM system to measure every feature from the side. Rearranging the features or splitting them into different bodies may better facilitate measurements with an optical comparator, where a silhouette view is needed. In the current arrangement, cutting the part or using different methods on different features is necessary.
- Because the artifact is built onto a base plate substrate, any irregularities in the base may be included in measurement of the part. If the base remains attached, it may be difficult what variation is due to the base plate and what is occurring in the printed material itself. If the base plate is removed, this introduces additional variation and irregularities from the machining process.
- Many of the positions are measured from the center of the part. This is a through hole surrounded by concentric cylinders. With the correct set up, this can lead to an appropriate feature off which to base a datum. In many cases, however, it can be difficult to calibrate with sufficient precision without an actual feature visually present at the center axis. If the center is determined, as in our study, by finding the midpoint between the artifact external surfaces, this calculated center may not perfectly line up with the printed features surrounding it.
- Additional fine features would be beneficial. One of the purposes of the fine feature array is to determine the lower limits of printing ability and the minimum feature size possible. However, the Concept Laser machine was able to produce all designed features, even at 50% scale. Two or more sets of pins, bosses, and pockets would be beneficial to ensure that the design goes beyond the capabilities of most machines.
- Along with standardized test artifacts, a standardized process would also be beneficial. Moylan, et al. make progress in this area [8], but specific guidance on measurement strategies could be generated. Standardization of recommended post processing (heat treatment for stress relief, bead blasting or other surface treatments, etc.) would also allow for better replication between research groups.

Future Work: Work will continue on the three builds of the NIST test artifact to measure the remaining recommended features, including the center hole and cylinders, the ramp, the staircases, and the surfaces of the main block. Following these measurements, the builds will be subjected to post processing and remeasured to assess any changes. This procedure may be repeated on other machines or with other materials and processes to gauge the usability of the proposed artifact across the AM field. Additional investigation into other influencing factors, such as the position and orientation of the artifact on the print bed and the resolution of the original STL mesh, would also be insightful.

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