# An investigation of standard test part design for additive manufacturing

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## Abstract

This paper investigated the efficiency of the standard test part feature designs. Standard geometrical dimensioning and tolerancing criteria were analyzed for their efficiency in representing process characteristics of additive manufacturing (AM) processes. The design efficiency of the standard test part proposed by NIST was evaluated, and based on the analysis, the part was redesigned. A minimum characteristic set method was proposed to be used for future development of standard test part design. In addition, it was suggested that feature dimensional effect as well as feature orientations are both critical to geometrical quality evaluations, and therefore should be included in the feature design of the standard test part.

## Introduction

With the rapid development and increasingly widespread adoptions, the capabilities of additive manufacturing (AM) technology have been expanding at unprecedented speed with both the types of materials and the selection of processes. Currently there exist more than 100 different professional AM models and over 200 varieties of available materials [1]. Some materials are compatible with multiple systems, such as many metal alloys with powder bed fusion processes, while some materials are only compatible with specific models. On the other hand, the physical and mechanical performance of parts made via different process/material combinations are often difficult to compare even if they are similar. Therefore, the users are facing increasingly challenging issues with the comparison and selection of the most suitable process/material combinations for their applications. In order to enable direct comparison between processes and materials, the standard test parts or standard benchmark parts have been proposed by many researchers [2-25]. In general, standard test parts incorporate multiple features which represent certain geometrical characteristics, and either quantitative evaluation or qualitative comparison would be made directly between the features generated by different processes or machines. When first adopted for the early AM systems, the primary functions of the standard test parts were to provide evaluations of geometrical qualities of the prototype parts, which included accuracy, precision, repeatability, feature resolution, and surface finish [7, 8, 9, 12]. As the applications of AM expanded to functional structures and components, standard test parts were also designed to evaluate the mechanical properties of the parts made by a certain process/material combinations [10, 25]. Recently, it has been suggested that the AM benchmark parts should not only enable direct comparisons of performance, but also provide insights into the sources of errors/defects as well as the selection of process parameters [15, 16, 19]. Therefore, the AM standard test parts could be categorized into three different types according to their target functions [3]:

1. Geometric benchmark: used to evaluate the geometrical quality of the features generated by a certain machine.
2. Mechanical benchmark: used to compare the mechanical properties of features or geometries generated by a certain machine.
3. Process benchmark: used to develop the optimum process parameters for features and geometries generated by certain process systems or individual machines.

It should be noted that the benchmark designs of the first two types also imply that the “highest standards of excellence”, e.g. the best process parameters, should be used for the feature generation and comparison. This becomes obvious when one considers the use of such parts. From the functionality perspective, types 1 and 2 test parts will likely be adopted by groups such as design engineers and AM system end users, who need detailed knowledge of the comparison of accuracy, precision, surface quality, resolution and repeatability for each material/process combinations. These information will usually transfer directly to customer specifications and requirements, therefore is more crucial in providing explicit guidance about the qualities of the final parts. On the other hand, these users might not have the expertise or need to perform process development for AM systems. As a result, they usually rely heavily on the “best practice” parameters provided by the AM system OEMs or other sources. For these users, a benchmark part that also requires considerations of process parameters could complicate the decision making process and render the test part ineffective.

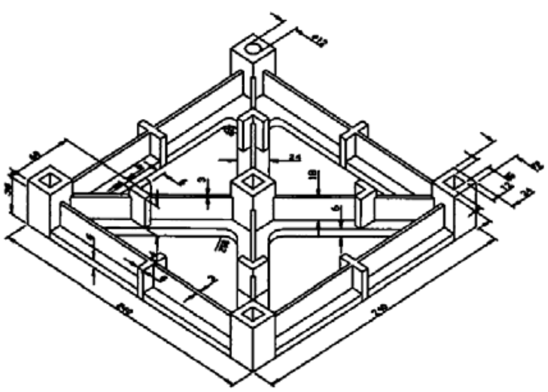
On the other side of the spectrum, there also exist another type of users that focus on the development or characterization of new materials, processes or structures, such as academic researchers and machine OEMs. For these users, the type 3 standard test part designs will more likely be adopted. Standard tensile coupon is an example of such test part designs with relatively simple geometrical design and evaluation objectives. The challenge with the design of this type of test part is that the evaluation criteria is often affected by multiple highly coupled process parameters simultaneously, which makes it extremely difficult if not impossible to establish correspondence between individual process parameters and the final part quality. For example, in SLA process, the dimensional accuracy of a feature is not only dependent on a variety of process parameters such as bath temperature, material absorptivity, laser power, laser scanning speed, scanning pattern and recoating, but also influenced by other factors such as ambient environment, feature size and laser beam focus [26-32]. Similarly, the dimensional and mechanical characteristics of parts made by FDM are also controlled by many factors. In addition to the shape of the deposited track, which is in turn controlled by the nozzle size, nozzle travelling speed, process temperature and substrate conditions, other factors such as material additives, raster pattern, inter-track gap distance, part orientation, feature geometry type and layer thickness [33-39]. Various experimental studies also suggested that coupled interactions between process variables play significant roles in the dimensional accuracy control of FDM process [34, 36, 39]. While the physics of SLA and FDM processes are relatively well understood, other AM processes pose even more challenges. For example, the powder bed fusion AM processes involve rather complex physical, chemical and mechanical phenomenon, since the processes involve heat transfer, phase transformation and energy conversion [40-49]. Despite numerous modeling works, currently no comprehensive theory has been established that could accurately evaluate the dimensional and mechanical characteristics of an arbitrary metal parts made by powder bed fusion AM processes [45, 50-51]. Recent development of multi-scale process models is promising, however considerable efforts are still required to refine these models in order to produce systematic analysis [52].

In short, the considerable differences of process characteristics between different AM systems make the design of a “universal” process development test part extremely difficult. In order to reveal more information about the process quality, the features of the standard test part for process development should be designed in such a way that slight deviation from optimal process parameters would result in significant defects. However, limited understanding with the processes makes predictive design of such geometries nearly impossible. In most proposals of standard test parts, the feature geometries are more or less designed arbitrarily. In addition, many of the features designs were relatively simple geometries such as cylinders, cubes, holes, slots and pyramids, which appear to have strong heritage from traditional manufacturing.  While these features could provide explicit evaluations for geometrical dimensioning and tolerancing (GD&T) characteristics for traditional CNC processes, they could not provide much insight into process quality for AM processes due to the issues described before. Some standard test part designs attempted to incorporate geometries that are more unique to general AM processes, such as the overhanging features [21, 22] freeform geometries [8], features for part warpage [10-12], and stairs [15]. However, the selection of the detailed geometries were still largely arbitrary, and fundamental factors associated with the processes such as thermal history and melting pool evolution were largely overlooked in the design. For these reasons, standard test part designs that aim to provide both geometrical and process information often ended up with very complex set of geometries while still incapable of achieving the designed purposes.

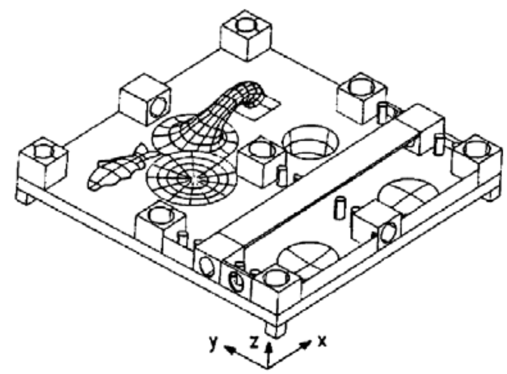
On the other hand, when effort is focused on the direct comparison of geometrical qualities of different systems, it appears reasonable to use one universal test part for all the processes. In this scenario no process development issue should be considered such as part warping or distortion. Due to the freeform geometric generation capabilities of AM processes and the highly coupled interaction between the feature geometry and the process quality, the design of most efficient features for geometrical characterization is a challenging task. In the present work, the effort will be focused on the improvement of the feature efficiency based on the existing standard test part design.

## Review of Current Designs

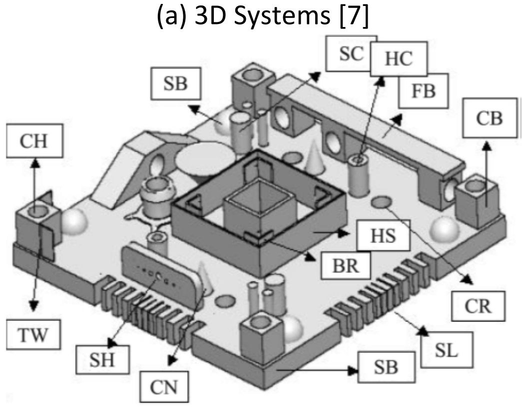
Some of the standard test part designs proposed by various groups are shown in Fig.1. The test part used by 3D Systems as shown in Fig.1(a) was one of the earliest test part designs used in the AM industry. It has relatively simple geometries are was largely designed to evaluate laser positioning accuracy and part warping. It was quickly realized that the geometrical quality of the parts made by AM processes has strong dependency on the actual feature geometrical designs, therefore standard test parts with many representative features were proposed as shown in Fig.1(b)-(d). Some of the unique characteristics of AM processes were also identified in some of the designs, such as the freeform shape, overhanging geometry, step effect and surface texture. In addition, due to the additive nature of materials in AM processes, thin extrusion features could be designed to evaluate the process limitations, and therefore were included in many standard test part designs. In some studies, real world part designs were used for standard test par, as shown in Fig.1(e)-(g). These designs are less efficient and often provide values only to specific families of products. In addition, these parts are often difficult to perform thorough metrology with. In several works, specific AM processes were considered, and standard test part designs were consequently tailored for these processes. For example, the two standard test parts shown in Fig.1(i)-(j) were designed for the surface texture and general geometrical accuracy of the FDM process. In recent years, Fahad and Hopkinson suggested that the standard test part should also evaluate the spatial tolerance repeatability [3], which was reflected in their test part design proposal as shown in Fig.1(l). On the other hand, it was also suggested that the same objective could be achieve by placing multiple standard test parts at different locations of the build envelop. In 2012, National Institute of Standards and Technology (NIST) carried out a comprehensive analysis of the previous works with standard test parts, and proposed a new design that aims for universal adoption [15]. The proposed design is shown in Fig.1(n), which incorporated features for geometrical accuracy and spatial repeatability evaluations. This part is considered as one of the most advanced designs for AM standard test part and was adopted by this study for further evaluation.



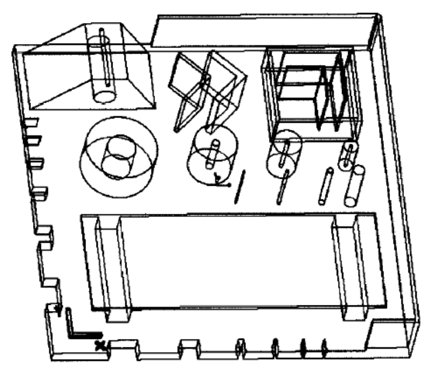
(a) 3D Systems [7]




(b) Childs and Juster [8]

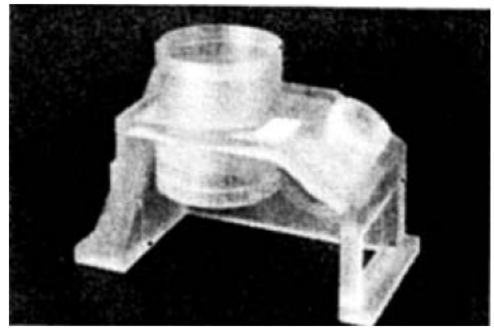



(c) Mahesh et al. [11]



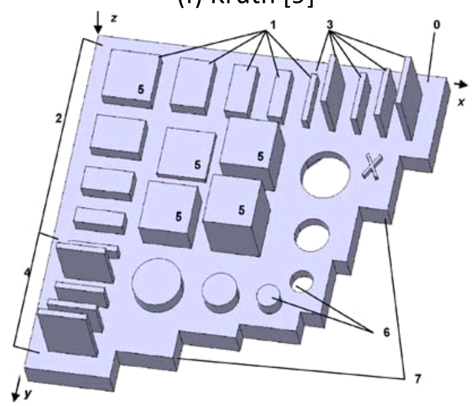
(d) Wong and Loh [22]

(e) Kim and Oh [2]

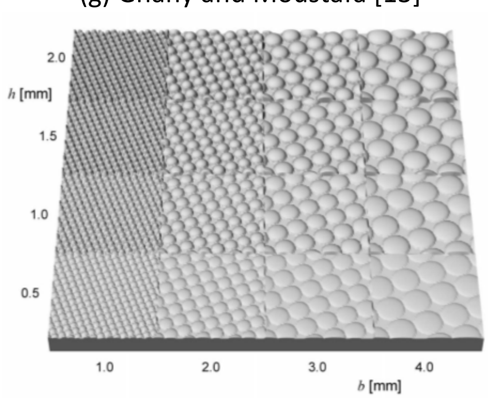


(f) Kruth [9]

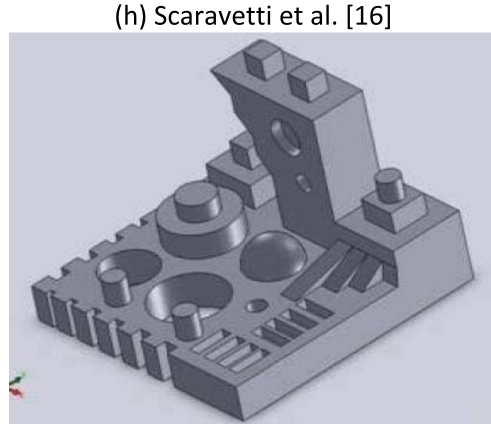
(g) Ghany and Moustafa [13]



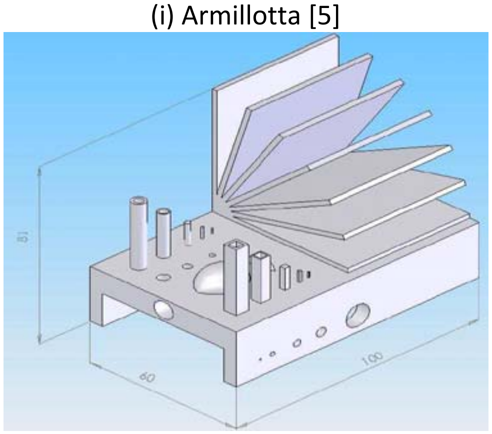
(h) Scaravetti et al. [16]



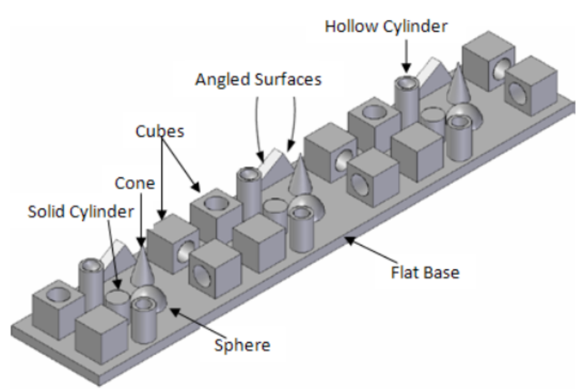

(i) Armillotta [5]



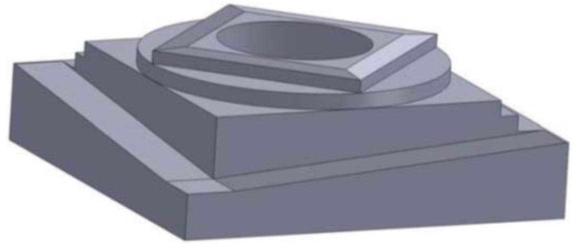
(j) Johnson et al. [10]



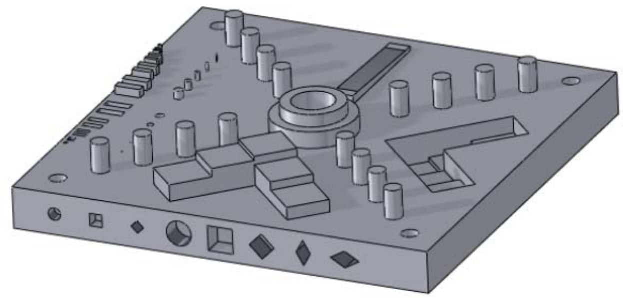
(k) Castillo [21]




(l) Fahad and Hopkinson [3]



(m) Cooke and Soons [23]



(n) Moylan et al. [15]

Fig.1 Designs of standard test parts

For each of these test part design, the combination of feature geometries is intended to provide a comprehensive evaluation of the GD&T characteristics. The correlations between geometrical designs and the corresponding GD&T criteria is well established [3, 15]. For example, a cube could be used for squareness (perpendicularity), parallelism, linear accuracy and surface finish evaluation, and a cylindrical hole could be used to evaluate the roundness, cylindricity, radius accuracy and positioning accuracy. Therefore, in order to evaluate all the characteristics, all these features should be incorporated into the test part design.

On the other hand, it’s worth noting that the current set of GD&T characteristics was designed largely for material removal processes such as milling and turning, in which relatively simple geometries such as straight lines, circles, flat surfaces, cylindrical surfaces, cubes, rectangular slots and round holes are predominantly fabricated. In fact, from the perspective of process characterization, a smaller set of independent GD&T characteristics might be sufficient to fully identify the process. For example, for a CNC milling system, the positional accuracy and tolerance of the milling head in the x and z directions for a given tool at optimal processing parameters can be determined with a set of holes by measuring true positions, and the accuracy of the linear interpolation can be determined with parallel features in the x-y plane and cylinders by measuring parallelism and cylindricity. Similarly, certain geometrical characteristics are driven by the same process characteristics, therefore could theoretically be derived from each other. One such example is the perpendicularity, which could be represented by the combination of straightness and parallelism in many cases.

For material removal processes, it is reasonable to include the entire conventional GD&T set, since these characteristics could be directly used to identify most of the basic feature geometries that are commonly generated by these processes, therefore making quality evaluation straightforward. However, this would likely not be the case for AM structures, as one of the most utilized advantages of AM is their freeform fabrication capabilities. Therefore, it would not be possible to create standard test part that represents all possible geometries, and it might be less efficient to adopt the entire set of GD&T characteristics. On the other hand, some features that might be redundant for traditional processes, such as sloped surface, overhanging features, thin features and lateral features could become critical for AM processes. The geometrical qualities of AM processes are often coupled with the actual shape of the geometries. For example, for laser powder bed fusion processes, sharp corner often result in more significant thermal distortion due to the excessive heat input resulted from the longer dwelling of laser beam at the corner. Also, smaller features will have different thermal history due to the reduction of scanning vectors, which implies that the process accuracy might become a function of the feature size. Therefore, in the design of the standard test part features, it is important to incorporate these special boundary conditions into considerations.

## Minimum Characteristic Set Analysis

In the attempt to reduce the feature design redundancy and improve the efficiency of the standard test part, it was proposed that the part could include a minimum set of geometrical features with various dimensional scales. The geometrical features should provide adequate information about the process capabilities, therefore a matrix of relationships between GD&T characteristics and the underlying process characteristics for AM processes was first established as shown in Table 1. It is important to distinguish process characteristics that fall under the category of "process development evaluation" and those that fall under the category of "process capabilities". In order to visually distinguish them, in Table 1 the process characteristics of the first category are highlighted in bold fonts.

In Table 1, part distortions were considered as process development characteristics. In fact, part distortions introduced by thermal and gravity effects often have compound effects to both the overall part shape and individual geometrical characteristics such as flatness and cylindricity. However, part distortions could be considered primarily as a process defect, therefore, optimal processes should be developed to minimize distortion effects before the process capabilities can be evaluated. Similarly, process development should be carried out first to achieve maximum melting pool stability for fusion type of processes before the optimized parameters could be used for capability evaluation. The matrix in Table 1 lists only the major process characteristics and is not intended to be comprehensive at this point. For example, the environmental factors were completely ignored in this matrix, and the spatial repeatability was also not listed as it could be potentially achieved by using multiple parts in one build. As these additional characteristics are identified, they could be added to the matrix subsequently for design improvement.

From Table 1, the geometrical characteristics for all types of processes are affected by gravity distortion, which implies that the orientation of the features need to be considered. Also, for the processes that will be affected by thermal distortion and melting pool stability, a set of features with a range of dimensions will be needed to account for the coupled effects. On the other hand, it is obvious that each geometrical characteristics are affected by multiple process characteristics, therefore only several of them are needed to fully characterize the process capabilities. For example, straightness, flatness, circularity, cylindricity, line profile, surface profile, perpendicularity, angularity, parallelism and concentricity are all influenced by the same set of process characteristics for all types of AM processes listed, therefore it is possible to use only several of these criteria for the standard test part.

| Characteristics | Extrusion | Photo-polymerization | Powder bed fusion | Direct energy deposition | 3D print | Direct write |
|---|---|---|---|---|---|---|
| Straightness | 1 2 3 4 6 7 10 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Flatness | 1 2 3 4 6 7 10 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Circularity | 1 2 3 4 6 7 10 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Cylindricity | 1 2 3 4 6 7 10 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Profile (line) | 1 2 3 4 6 7 10 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Profile (surface) | 1 2 3 4 6 7 10 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Perpendicularity | 1 2 3 4 6 7 10 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Angularity | 1 2 3 4 6 7 10 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Parallelism | 1 2 3 4 6 7 10 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Symmetry | 1 2 3 7 | 1 2 6 | 1 2 3 5 | 1 2 3 5 7 11 | 1 2 7 8 | 1 2 7 11 |
| Positional tolerance | 1 2 4 7 | 1 2 4 6 | 1 2 4 5 | 1 2 4 5 7 11 | 1 2 4 7 | 1 2 4 7 11 |
| Concentricity | 1 2 3 4 6 7 10 | 1 2 4 6 10 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Surface roughness | 7 9 10 | 9 10 | 5 9 10 | 5 10 11 | 9 10 | 7 9 10 11 |
| Step effect | 6 11 | 6 11 | 6 11 | 6 11 | 6 11 | 6 11 |
| Free overhanging angle | 3 4 6 7 11 | 4 6 10 11 | 3 4 5 6 10 11 | 3 4 5 6 7 10 11 | 4 7 8 10 11 | 4 7 10 11 |
| Free overhanging dimension | 1 2 3 4 6 7 11 | 1 2 4 6 10 11 | 1 2 3 4 5 6 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 10 11 | 1 2 4 7 10 11 |
| Min. solid thin feature | 1 2 3 4 6 7 10 11 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |
| Min. hollow thin feature | 1 2 3 4 6 7 10 11 | 1 2 4 6 10 11 | 1 2 3 4 5 6 9 10 11 | 1 2 3 4 5 6 7 10 11 | 1 2 4 7 8 9 10 11 | 1 2 4 7 10 11 |

(1) Accuracy and precision of the motion/scan control system
(2) Resolution of the linear interpolation of the motion/scan control system for off-coordination lines
**(3) Thermal distortion of part**
**(4) Gravity distortion of part**
**(5) Melting pool stability**
**(6) Curing/shrinkage distortion**
**(7) Material transport stability**
**(8) Post process induced distortion**
(9) Surface sintering/attachment
**(10) Surface energy induced distortion**
(11) Minimum material deposition rate (including z step size)

Table 1 Process characteristics – Geometrical characteristics matrix

## Investigation of NIST standard test part

Based on the discussion in the previous section, a more detailed investigation was carried out with the standard test part proposed by NIST [15]. The geometry and measurement criteria of the NIST standard test part are shown in Fig.2 and Fig.3. The design details were demonstrated in details elsewhere [15] and will not be elaborated in this paper. In Fig.3, the geometrical characteristics that were listed in Table 1 are illustrated by red circles with numbers, and it is clear that there are a total of 33 individual measurements defined for the test part. These measurements fall under six types of geometrical characteristics, which are listed in Table 2. These six characteristics were analyzed in more details as below:

*Straightness*: All the surfaces measured have orientations in x-y plane (lines along z direction not measured). The straightness is evaluated at several levels of feature dimensions. Measurement 5 and 8 are on features with dimensions of 10mm, measurement 1 and 4 are on features with much larger dimensions, and measurement 9, 15 and 17 are on features with 100mm dimensions. Note that for negative features (slots), the feature dimensions refer to the dimensions of the solid side of the feature, since for AM process only the areas with materials will be affected by the process directly. It is apparent that for the negative slots in the NIST test part, the feature dimensions are difficult to define due to the non-parallel feature alignments.

*Parallelism*: The same discussion for straightness applies to parallelism.

*Perpendicularity*: Only one measurement is taken for this characteristics, although more is possible from the design of the test part. As discussed before, perpendicularity might not add substantial knowledge to the process capability when both straightness and parallelism are known.

*Roundness*: All the roundness are measured in the x-y plane, while there is no evaluation of roundness in the other planes. On the other hand, with lateral cylindrical hole features designed in the test part, it is possible to measure the roundness in the other planes. The roundness is evaluated at several levels of feature dimensions. The roundness of the center hole (measurement 10) are measured at three levels of feature dimensions at different depth, while the roundness of the smaller and larger center cylinders are each measured at a level of feature dimension. Again, according to Table 1, the roundness measurements might only add limited information if the straightness and parallelism are both known.

*Concentricity*: The same discussion for roundness applies to concentricity.

*True position for pin*: The features are located at different locations in x-y plane, therefore could provide repeatability information. All the features have the same size, so no additional information of the influence of feature dimensions could be drawn.

*True position for z plane*: The features are located at different z levels for the measurement or z-direction dimensional accuracy. All the measurements have different feature dimensions, so additional information about their effect in the z direction could be drawn.

In addition, another advantage of having multiple measurements for each characteristic is to enable statistically significant analysis, although this could also be achieved by building multiple parts. In fact, the second scenario might be preferable since it enables both spatial repeatability check and time repeatability check (e.g. multiple batches built over a period with the same system).

In order to further investigate the design, samples of the NIST test part were produced by three different processes including SLS, EBM and FDM, using Sinterstation 2500+, Arcam EBM S400 and Makerbot Replicator 2 respectively. The materials used for each process were DuraForm PA nylon 11, Ti6Al4V ELI and PLA, respectively. With each process, the parts were produced with the default process parameters without any modifications, which was assumed to be the "best practices". For the EBM process, the support structure generation was performed in Materialise Magics with the default setting, since the shape of the substrate is relatively simple. Similarly, for the FDM process, the support was automatically generated by Simplify 3D. In addition, 0.2 infill was used by default for the FDM part. The layer thickness of the SLS, EBM and FDM process are 0.05mm, 0.05mm and 0.1mm, respectively. Fig.4 shows the samples produced by these processes. Visible warping occurred at the substrate block of the SLS part, and localized warping is also present at the corners of the EBM part. The numbered measurements were obtained for each sample by a CMM machine (Brown & Sharpe One 7.7.5) with a Renishaw TP20 probe. The results are listed in Table 2.

Several observations could be clearly made from the results of SLS and EBM samples. First, several geometrical characteristics did appear to be redundant as analyzed. For example, the perpendicularity tolerance can be obtained by stacking tolerances for straightness and parallelism, and the roundness appeared to be statistically identical to the straightness. Secondly, dimension effect also appears to be present, although more quantitative discussion is somehow complicated by the overall warping of the samples. From straightness values, it appeared that the overall tolerance increases with increasing feature dimensions. These observations also agree with the previous discussions.

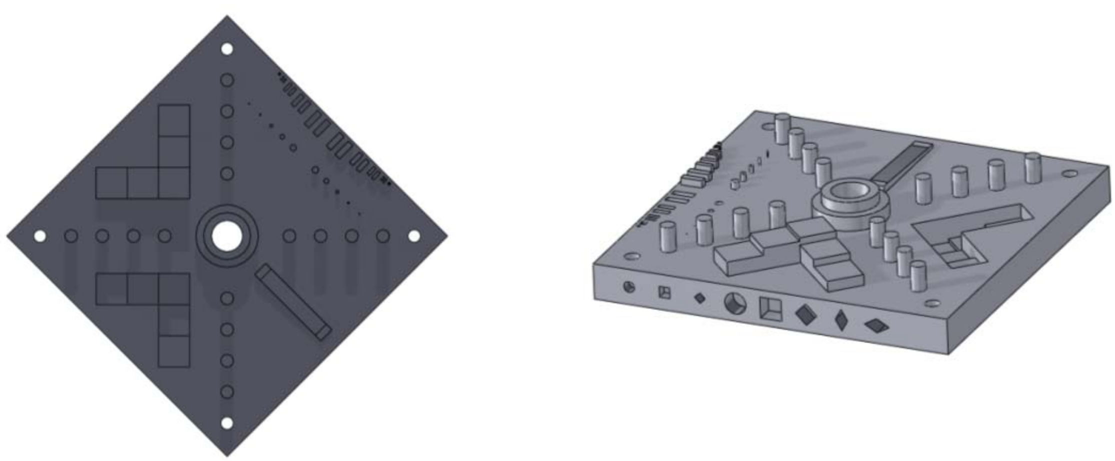
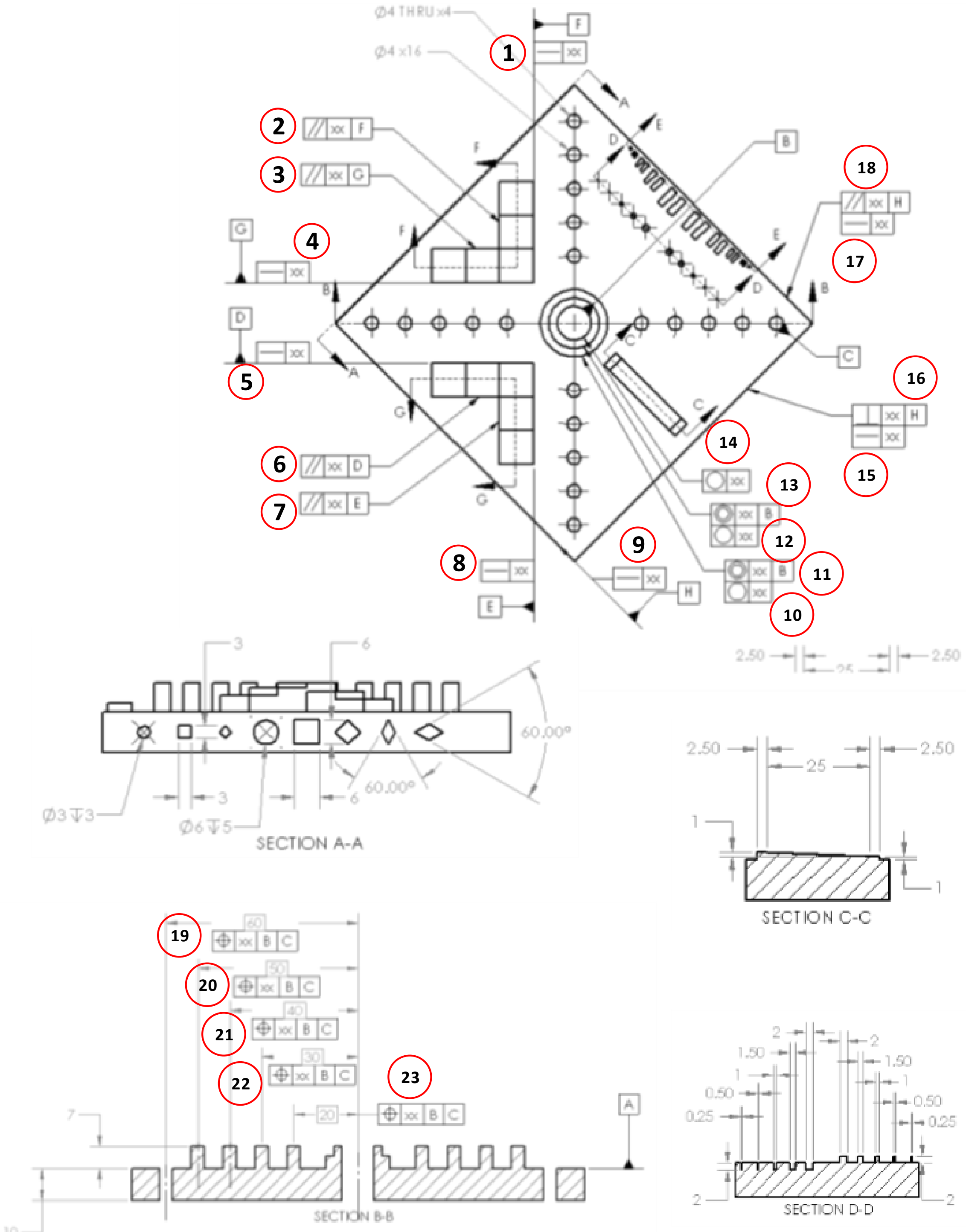


Fig. 2 NIST standard test part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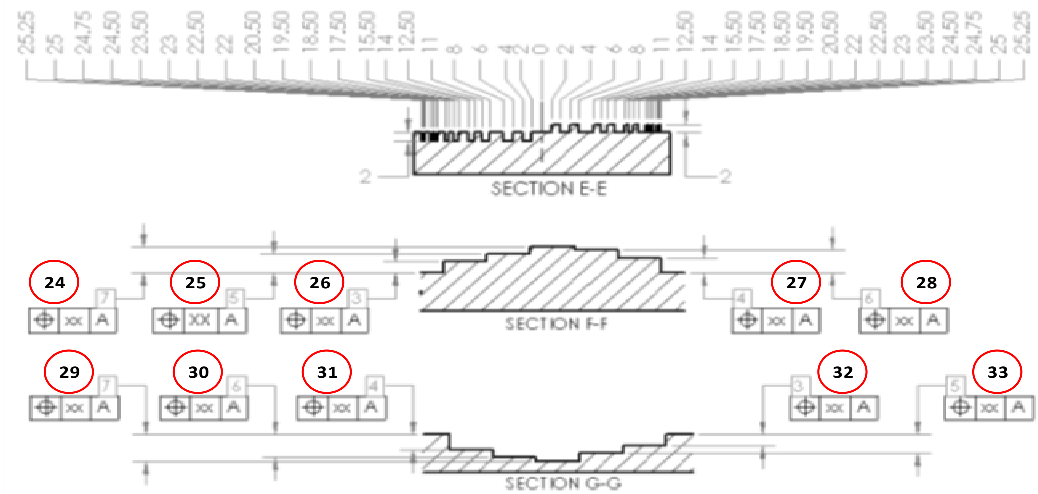
(a) Part 1




(b) Part 2

Fig.3 Geometrical characteristics of NIST standard test part [15]

In comparison, the FDM part exhibited different characteristics. First of all, no significant feature dimension dependence was observed for geometrical tolerances except for the z direction. This could be explained by the process characteristics of the FDM process. Without the powder bed and the formation of melting pool, the material deposition of the FDM process is sufficiently slow and steady under optimized parameters that no significant global effect should be expected at different feature dimensions. Another issue worth noting is the infill value used for this part. The infill function is intended to reduce the amount of materials that need to be deposited so that the part could be built faster and cheaper. However, the selection of infill would likely have significant effect on the accuracy and resolution of the features as a result of the modified boundary thickness. The knowledge about the effect of infill level on the processability and geometrical characteristics is generally lacking, therefore the parameters used in this study could be considerably off from the optimal values, e.g. best practice. However, this was not expected to affect the validity of the discussion.

After analysis, it was concluded that the current NIST standard test part design could be further improved for process capability evaluation purpose.

(a) SLS (b) EBM (c) FDM

Fig.4 Samples of NIST test part

| Geometrical characteristics | Measurement # | Description | Tolerance –SLS (mm) | Tolerance – EBM (mm) | Tolerance –FDM (mm) |
|---|---|---|---|---|---|
| Straightness | 1 | Datum surface F | 0.028 | 0.022 | 0.432 |
| | 4 | Datum surface G | 0.043 | 0.024 | 0.087 |
| | 5 | Datum surface D | 0.041 | 0.099 | 0.025 |
| | 8 | Datum surface E | 0.057 | 0.074 | 0.046 |
| | 9 | Datum surface H | 0.076 | 0.064 | 0.224 |
| | 15 | Substrate surface perpendicular to H | - | - | - |
| | 17 | Substrate surface parallel to H | - | - | - |
| Parallelism | 2 | Vertical wall of negative Z feature parallel to datum F | 0.043 | 0.064 | 0.650 |
| | 3 | Vertical wall of negative Z feature parallel to datum G | 0.048 | 0.076 | 0.070 |
| | 6 | Vertical wall of positive Z feature parallel to datum D | 0.112 | 0.087 | 0.202 |
| | 7 | Vertical wall of positive Z feature parallel to datum E | 0.161 | 0.079 | 0.091 |
| | 18 | Substrate surface parallel to datum H | 0.192 | 0.189 | 0.358 |
| Perpendicularity | 16 | Substrate surface perpendicular to datum H | 0.225 | 0.194 | 0.099 |
| Roundness | 10 | Center cylindrical hole | 0.032 | 0.083 | 0.170 |
| | 12 | Smaller center cylindrical platform | 0.070 | 0.121 | 0.231 |
| | 14 | Larger center cylindrical platform | 0.045 | 0.143 | 0.298 |
| Concentricity | 11 | Smaller center cylindrical platform to center hole | 0.036 | 0.053 | 0.078 |
| | 13 | Larger center cylindrical platform to center hole | 0.116 | 0.129 | 0.124 |
| True position | 19-23 | Pin extrusions along diagonal directions of the part | 0.038 | 0.296 | 0.257 |
| True position | 24-28 | Thickness of the positive Z features | 0.136 | 0.153 | 0.658 |
| | 29-33 | Thickness of the negative Z features | 0.082 | 0.079 | 0.167 |

Table 2 GD&T measurements of the NIST standard test part

## Standard test part redesign

The redesigned part is shown in Fig.5, and the features are described in details in Table 3. The primary considerations that were incorporated into the redesign process were the different orientations and feature dimensions. In addition to the dimensional accuracies of the features, the primary geometrical characteristics investigated are straightness/flatness, parallelism, true position, surface finish and minimum feature resolution. Note that the minimum feature resolution in the z direction (e.g. the build direction) is represented by the minimum step effect. As shown in Fig.5, most of the geometrical characteristics could be evaluated at a number of different feature sizes (x-y plane and z direction), as well as tilt angles. Furthermore, most of the features were designed to facilitate easy access with regular metrology methods including calipers, micrometers, CMM machines, profilometers and optical microscopes. For example, in order to enable measurement probe to reach the under-facing surfaces of the overhanging features with different angles (Measurement 2 in Fig.5), the low angle features were designed to be attached on top of the high angle features. The surface roughness of overhanging features and sloped features might pose some difficulties for measurement, and with the design shown in Fig.5, cutoff operations might be needed for these characteristics. It was also suggested that post-process support removal could potentially affect the measurement results [15]. However, under “best practice”, the support generation would be integral to the part manufacturing, therefore the geometrical characteristics on the features and surfaces that involve support would still be informative even if the results might be compromised by the standard post-process practice.

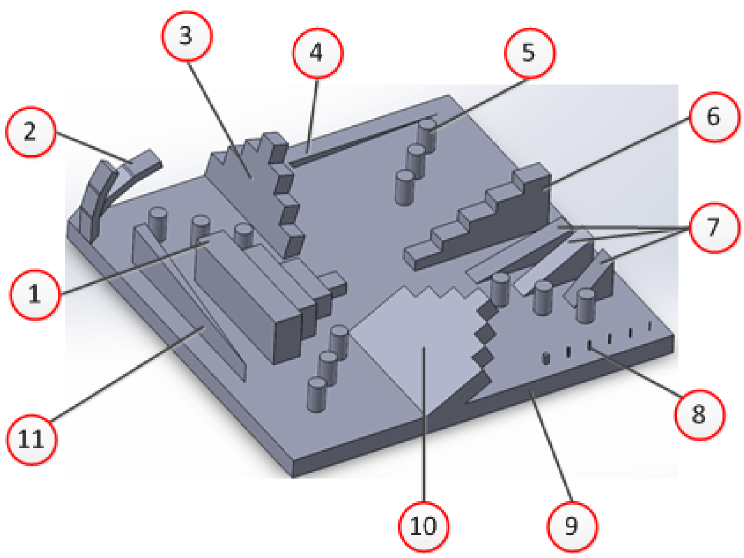
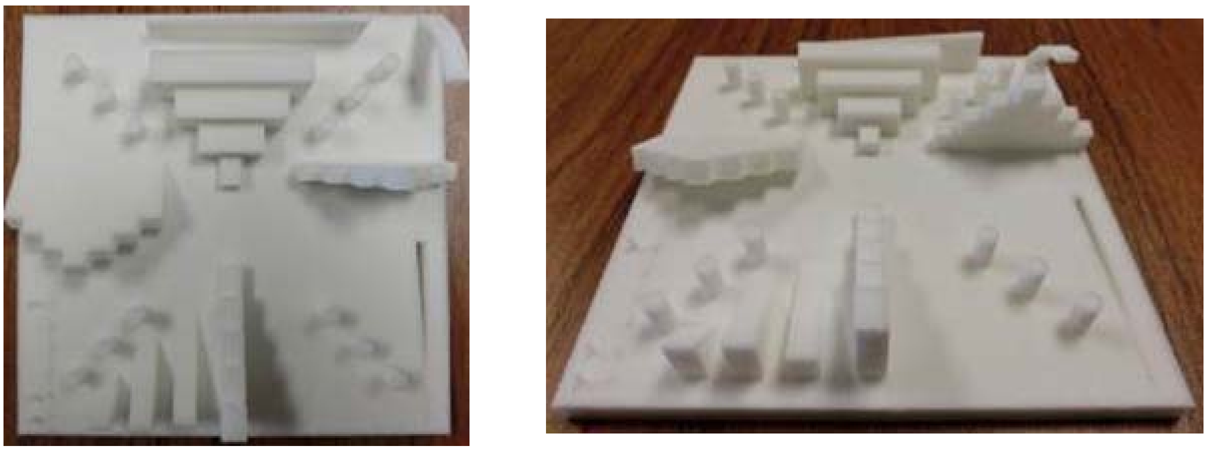



Fig.5 Re-design of the standard test part

| Feature | Description | Geometrical characteristics |
|---|---|---|
| 1 | Extrusions with different feature dimensions (35mm, 25mm, 15mm, 5mm) in both the x-y plane and the z direction | Straightness on vertical planes<br>straightness on z-planes<br>parallelism on vertical planes<br>parallelism on z-planes<br>surface roughness on vertical planes<br>surface roughness on z-planes |
| 2 | Overhanging features with varying angles (15°, 30°, 45°, 60°, 75°, 90°) | Straightness of planes at different overhanging angles<br>Surface finish of surface at different overhanging angles |
| 3 | 75° overhanging features with different feature dimensions (35mm, 25mm, 15mm, 5mm) | Flatness of vertical walls<br>Parallelism of vertical walls<br>Surface roughness of sloped sides |
| 4 | Slots with changing dimensions from 0-2mm for 2D negative feature resolution evaluation at x-y plane | Minimum negative line feature size in x-y plane |
| 5 | Cylindrical extrusion pins aligned across the part | True position in x-y plane |
| 6 | Extrusions with different z step heights and the same feature dimensions in x-y plane | straightness on z-planes<br>parallelism on z-planes<br>surface roughness on z-planes |
| 7 | 15°, 30° and 45° sloped surfaces for step effect in z direction | Straightness of sloped surface<br>Step effect in z direction at various angles |
| 8 | Thin extrusions for 1D feature resolution evaluation at x-y plane | Minimum point feature size in x-y plane |
| 9 | Overall geometry of the standard test part with the largest feature dimensions (100mm) | Straightness on vertical planes<br>parallelism on vertical planes<br>surface roughness on vertical planes |
| 10 | 30° overhanging features with different feature dimensions (35mm, 25mm, 15mm, 5mm) | Flatness of vertical walls<br>Parallelism of vertical walls<br>Surface roughness of sloped sides |
| 11 | Extrusion with changing dimensions from 0-2mm and a low angle slope for 2D positive feature resolution evaluation at x-y plane and step effect in z direction with different feature dimensions | Minimum positive line feature size in x-y plane<br>Step effect in z direction at different locations |

Table 3 Features and geometrical characteristics of redesigned standard test part

One sample of the redesigned part was fabricated by the SLS system with the same parameters as used for the NIST standard test part for quick check of the improved design. The final part is shown in Fig.6. Most of the features were fabricated successfully. However, one of the overhanging features was broken during the post-process. This might be caused by the small thickness of the feature (1mm), which likely needs to be redesigned. Metrology was performed following the guideline listed in Table 3 using caliper and CMM. Due to the limitation of the test equipment, surface finish and the characteristics that involve the under-facing surfaces were not measured. Also, the true position was not evaluated since there was no difference in design made for these features. The results of the other geometrical characteristics are shown in Table 4.



(a) Top overview (b) Angled overview

Fig.6 Redesigned standard test part fabricated by SLS

From the results listed in Table 4, the effect of feature dimension appeared to be more significant on vertical features (Measurement 1), which became less obvious for tilted features, which could be reasonably attributed to the more pronounced step effect with tilted features. It was also shown that the quality (flatness and parallelism) of the surface in x-y plane as the z height increases (Measurement 1 and 6). As expected, the step effect is more pronounced for low angle features (Measurement 2 and 7), which justified the inclusion of these features in the test part. Overall, the redesigned test part revealed some extra information about the geometrical tolerances of the SLS process with different features. It's worth noting that the selection of the feature size in this study was rather rough, and the smallest feature dimension evaluated was 5mm. This might not be small enough to reveal all the information related to the dimensional effect for some processes. Also, the relatively small surface area for the features also made the metrology less convenient, which could be further improved in the future studies.

## Conclusion

It was suggested in this study that a standard test part design that attempts to achieve both geometrical tolerance characterization and process development might be inefficient. On the other hand, when process optimization is not concerned, the current standard test part design might not be sufficiently efficient in providing essential information for users to make comparison among AM processes as well as between AM and traditional processes. In the feature design, due to the limitless possibility of the feature geometries that could be used in AM part design, it was suggested that the characteristic feature size and orientation are two critical factors that need to be evaluated for each geometrical characteristic.

The standard test part proposed by NIST was analyzed, and it was suggested that some of the feature designs could be further improved. A redesign part was proposed, and preliminary experiment found that this part could provide more information about the process tolerances that accounts for the feature size and orientations. This redesign was not intended to be final, and one of the objectives of this study is to inspire more research in this subject with a potentially new and useful guideline.

| Feature | | Description | Tolerance value (mm) |
|---|---|---|---|
| 1 | Flatness-1 | x-y plane, 35mm feature size | 0.029 |
| | Flatness-2 | x-y plane, 25mm feature size | 0.109 |
| | Flatness-3 | x-y plane, 15mm feature size | 0.116 |
| | Flatness-4 | x-y plane, 5mm feature size | 0.092 |
| | Flatness-5 | Vertical plane, 35mm feature size | 0.187 |
| | Flatness-6 | Vertical plane, 25mm feature size | 0.120 |
| | Flatness-7 | Vertical plane, 15mm feature size | 0.127 |
| | Flatness-8 | Vertical plane, 5mm feature size | 0.099 |
| | Parallelism-1 | x-y plane, 35mm feature size | 0.095 |
| | Parallelism-2 | x-y plane, 25mm feature size | 0.136 |
| | Parallelism-3 | x-y plane, 15mm feature size | 0.159 |
| | Parallelism-4 | x-y plane, 5mm feature size | 0.134 |
| | Parallelism-5 | Vertical plane, 35mm feature size | 0.313 |
| | Parallelism-6 | Vertical plane, 25mm feature size | 0.689 |
| | Parallelism-7 | Vertical plane, 15mm feature size | 0.391 |
| | Parallelism-8 | Vertical plane, 5mm feature size | 0.424 |
| 2 | Flatness-1 | Flatness of 45° feature | 0.123 |
| | Flatness-1 | Flatness of 30° feature | 0.155 |
| | Flatness-1 | Flatness of 15° feature | 0.347 |
| | Angle-1 | Actual angle of 45° feature | 0.667 |
| | Angle-2 | Actual angle of 30° feature | 0.399 |
| | Angle-3 | Actual angle of 15° feature | 0.693 |
| 3 | Flatness-1 | Vertical plane, 35mm feature size | 0.143 |
| | Flatness-2 | Vertical plane, 25mm feature size | 0.112 |
| | Flatness-3 | Vertical plane, 15mm feature size | 0.250 |
| | Flatness-4 | Vertical plane, 5mm feature size | 0.164 |
| | Parallelism-1 | Vertical plane, 35mm feature size | 0.234 |
| | Parallelism-2 | Vertical plane, 25mm feature size | 0.125 |
| | Parallelism-3 | Vertical plane, 15mm feature size | 0.340 |
| | Parallelism-4 | Vertical plane, 5mm feature size | 0.196 |
| 4 | Dimension | Minimum feature size in x-y plane | 0.640 |
| 6 | Flatness-1 | x-y plane at z height of 15mm | 0.040 |
| | Flatness-2 | x-y plane at z height of 12mm | 0.038 |
| | Flatness-3 | x-y plane at z height of 9mm | 0.024 |
| | Flatness-4 | x-y plane at z height of 6mm | 0.056 |
| | Flatness-5 | x-y plane at z height of 3mm | 0.162 |
| | Parallelism-1 | x-y plane at z height of 15mm | 0.056 |
| | Parallelism-2 | x-y plane at z height of 12mm | 0.050 |
| | Parallelism-3 | x-y plane at z height of 9mm | 0.064 |

| | | | |
|---|---|---|---|
| | Parallelism-4 | x-y plane at z height of 6mm | 0.111 |
| | Parallelism-5 | x-y plane at z height of 3mm | 0.210 |
| 7 | Flatness-1 | Sloped surface with 15° angle | 0.143 |
| | Flatness-2 | Sloped surface with 30° angle | 0.165 |
| | Flatness-3 | Sloped surface with 45° angle | 0.096 |

Table 4 Measured geometrical characteristics of the redesigned standard test part made by SLS

| | | | |
|---|---|---|---|
| 8 | | | |
| 10 | Flatness-1 | Vertical plane, 35mm feature size | 0.194 |
| | Flatness-2 | Vertical plane, 25mm feature size | 0.105 |
| | Flatness-3 | Vertical plane, 15mm feature size | 0.130 |
| | Flatness-4 | Vertical plane, 5mm feature size | 0.182 |
| | Parallelism-1 | Vertical plane, 35mm feature size | 0.540 |
| | Parallelism-2 | Vertical plane, 25mm feature size | 0.384 |
| | Parallelism-3 | Vertical plane, 15mm feature size | 0.305 |
| | Parallelism-4 | Vertical plane, 5mm feature size | 0.498 |
| 11 | Dimension | Minimum feature size in x-y plane | 0.460 |

Table 4 Measured geometrical characteristics of the redesigned standard test part made by SLS (cont.)

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