Solid Freeform Fabrication 2022: Proceedings of the 33rd Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

THE IMPACT OF MEASUREMENT METHODOLOGY ON THE DIAMETER MEASUREMENT OF SIMPLE ADDITIVELY MANUFACTURED FEATURES

M. Praniewicz*, J. C. Fox*, C. Saldana†

* National Institute of Standards and Technology, Gaithersburg, MD 20899, United States
† George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, United States

Abstract

Dimensional qualification of additive manufacturing (AM) components is a continuing research problem. Different measurement techniques implemented on the same feature can yield different measurement results. While this can also be true for components made from more traditional manufacturing processes, the deviations between measurement techniques are often increased by an order of magnitude due to greater form and surface texture variations that occur on AM components. Understanding the origins of deviations and comparability of measurement processes is crucial to the measurement of AM components. In this work, identically designed components are produced using a laser powder-bed fusion process. The components are then measured using manual gaging and a coordinate measurement machine. The measurement of diameter is executed using various association criteria. A statistical analysis is performed to determine the comparability between the measurement techniques. Results indicate that the selection of different association criteria can provide statistically significant differences in the measurement result.

Introduction

Additive manufacturing (AM) technologies have progressed from limited applications in research and development to applications in industrial production. Both polymer and metallic AM processes are currently used to produce consumer products. However, these are typically in applications where there is low risk associated with component failure. Industries with highly stressed, high cycle, or dimensionally critical components, such as the consumer aerospace or automotive industries, have had a slower adoption rate of AM produced components. This is largely due to challenges in the qualification of component geometry and material properties [1]. The complex geometries afforded through the AM process create significant challenge for component inspection. Thus, the geometrical qualification of AM components has required a new, developing, area of research [2].

While the end goal of geometric qualification is providing measurements to document product quality, it requires input from all stages of the component development cycle. Without clear communication between the design, manufacturing, and inspection phases of the component, there is potential for the unnecessary production of initial components that don't comply with the component requirements and necessitates an altered design, manufacturing, or inspection to produce a second batch of components. This undermines the capability of additive manufacturing to rapidly produce complex components and adds additional development, labor, and material costs. Integrating these steps into the additive manufacturing process chain is critical to maximizing the potential of additive manufacturing [3].

Recent changes to the International Organization for Standardization (ISO) Geometric Product Specification (GPS) standards and the American Society of Mechanical Engineers' (ASME)'s product definition standards have sought to adapt product definitions to reflect technological developments in measurement systems, better relating product definitions to current inspection practices [4], [5]. There are two relatively new ISO GPS standards on linear sizes (ISO 14405-1:2016) and angular sizes (ISO 14405-3:2016) that have been introduced to support engineering requirements whose verification can

only be implemented using a coordinate measurement system (CMS) [6], [7]. The geometric qualification of AM components often necessitates the use of a CMS for feature measurement, as the vast design space allowed by AM enables features that are too complicated for manual gaging techniques. Furthermore, CMSs allow for the automation of complex measurement routines and provide excellent repeatability [8].

Several works have sought to characterize the effects of coordinate measurement machine (CMM) measurement parameters on AM components, including investigating the effect of stylus diameter and point sampling strategy [9]–[12]. These were both found to have significant impact on the measurement of AM components. Another influencing factor on measurements using any CMS is feature association. Association is defined in the ISO GPS system as a “feature operation used to fit ideal feature(s) to non-ideal feature(s) according to a criterion” [13]. An example of this would be fitting a plane to extracted CMM data via a least-squares method to determine the orientation of a surface. While this step in the measurement process is well known for the users of CMSs, it is often overlooked/unknown by those designing AM components. Without the specification of which association criterion to use, the measurement result could vary significantly. For instance, a designer may dimension the diameter of a component intending for it to be measured on a CMM. However, without assigning the association criterion, an inspector would likely only measure the component using calipers or a micrometer, depending on the tolerance requirement. This unnecessary ambiguity can lead to costly mistakes in the production cycle or lead to falsely approved components being used in service. This work seeks to demonstrate the use of several specification modifiers to convey the required association for a measurement.

In this work, AM components are evaluated using manual gaging and a CMM to investigate the effect of the association criterion on the measurement result. The manufacture of the AM components is first presented, including images of the as-built components. The measurement methodologies, including the different association criteria used, are detailed. The details of the individual measurement processes are first presented, followed by a statistical comparison of the different measurement methodologies. The results of this comparison indicate no statistical overlap between any of the association criterion chosen, indicating the importance of establishing consistency in this specification to minimize ambiguity in the qualification of AM components.

Methodology

The component investigated in this study was a single volume resembling the reference object described in Ref [14]. The component contains an array of nine 0.5 mm diameter, 2 mm long struts bookended by two 4 mm diameter by 2 mm tall endcaps. Figure 1 shows the component geometry with overall dimensions. The diameter of the top end cap is investigated in these experiments.

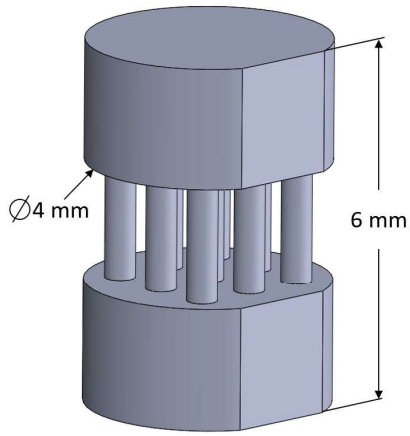

Figure 1: Component investigated

Thirty components in two different build orientations with this geometry were produced using an EOS M280 powder bed fusion system with EOS 316L powder at the manufacturer designated parameters for a 20 μm layer height. The components were manufactured in two different orientations to improve the likelihood of success in the build, due to small feature sizes. In the preferred vertical orientation, the component was oriented such that the cylinder axis of the end caps was parallel to the build direction. This orientation was preferred as there should be minimal form error in the struts. However, this orientation did have potential for failure, as the small diameter struts were susceptible to deformation during interaction with the recoater blade. Thus, the components were also printed in a horizontal orientation. This orientation had a much higher chance of a successful build, but had a higher potential for form error. Individual barriers were also built around each component to minimize the impact of the recoater blade on the delicate geometry. Figure 2 shows the completed build plate and details of the two different sets of components. One can see in Figure 2(b) that the vertical components did not build successfully. The build failed due to a recoater crash with one of the vertical components. The majority of vertical components appear to have failed prior to this crash. Since the struts do appear to have been fused, but were plastically deformed, the failure most likely occurred during the first layers of the top end cap. The small layer size deposited on top of loose powder most likely contacted the recoater blade and deformed upward, with the recoater blade dragging it in the direction of travel. For one component, the resistance to deformation must have been high enough to overcome the force of the recoater blade and jammed it in place. Fortunately, all horizontal components completed prior to the build halting, and can be seen in Figure 2(c).

Figure 2: Completed AM components before separation from build platform: (a) Build platform layout with vertical oriented components boxed in red and horizontal components boxed in green and unused components in-between. The direction of recoater travel is shown in the orange arrow. (b) Failed vertical orientation components (c) Successful horizontal orientation components

The components were then separated from the build plate using wire electrical discharge machining (EDM). Figure 3 shows an example completed component. The component was imaged using a Leica DVM6 10-megapixel digital microscope in two different orientations: (a) a top down view

of the component (along the build direction), (b) a side view (orthogonal to the build direction). An initial X-ray computed tomography scan of the component was completed and views identical to the digital microscopy were captured. These can be seen in Figures 3(c) and 3(d). There is a stark contrast in the apparent quality of the print between the top down and the side views. In the top view, the component appears to have been manufactured successfully judging by the straight cylindrical struts. However, significant form error can be seen in the downward facing surfaces in Figures 3(b) and 3(d).

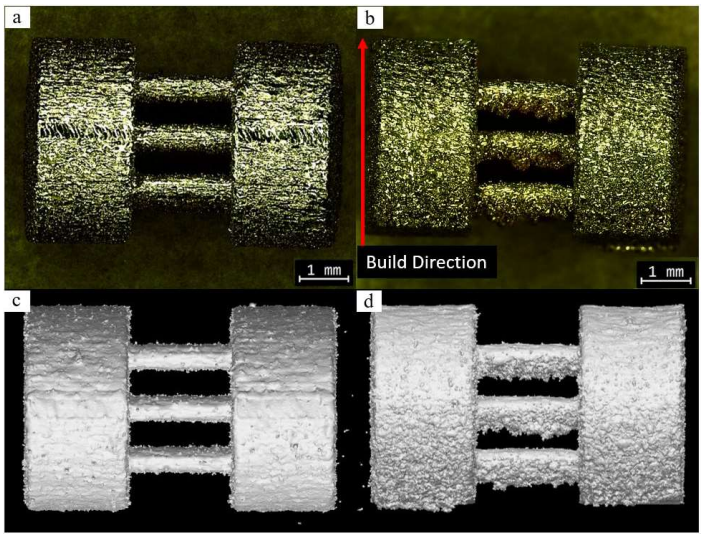

Figure 3: Optical and XCT images of a completed AM component: (a) and (c) show a top down view of the component using an digital microscope and XCT reconstruction respectively, (b) and (d) show the side view of the component with the build direction indicated

Unfortunately, three components were damaged during the wire EDM process, so 27 components were used in the remaining measurement processes. The components were first measured individually using a calibrated micrometer, which had a measurement resolution of 0.0025 mm. The components were then fixtured and measured individually on a CMM. The CMM measurements were completed using a Zeiss Micura with a maximum permissible error of length measurement ($E_{0,MPE}$) of (0.8 + L/400) µm, where L is the measured length in mm, according to ISO 10360-2 [15]. The CMM measurements used a 50 mN probing force, a 0.5 mm probe tip diameter, and thermal compensation active using a coefficient of thermal expansion of 16.2 µm/(m·K). The outer diameter of the top endcap was measured by probing 475 points on the surfaces. The fixtured component and the sampled points, shown as the green arrows, in the measurement can be seen in Figure 4(a) and (b), respectively.

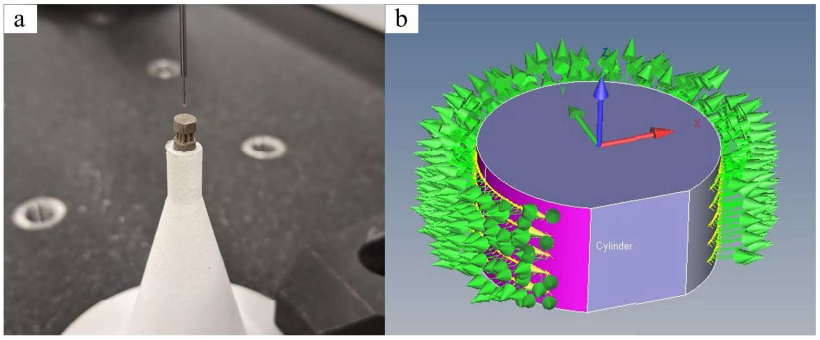

Figure 4: (a) Component CMM measurement setup and (b) points sample in CMM measurement

After the data was captured using the CMM, it was imported into GOM Inspect software [16] as a point cloud and the diameter of the feature was calculated using different association criteria. These different association methodologies are depicted in Figure 5, using the nomenclature defined in ISO

14405-1:2016 [6]. Commonly, dimensions of components in product definition data are often listed without modifiers, as in Figure 5(a). This then implies the default specification of two-point size. A two-point size is the distance separating the two points composing an opposite point pair taken simultaneously on the extracted feature (see ISO 17450-3) [17]. A two-point measurement also can be specifically designated using the (LP) modifier, as in Figure 5(b). Two-point measurements are representative of mechanical gauging processes, such as measurements with calipers, micrometers, and comparators, where a measurement is taken across two opposing parallel faces. However, measurements executed using a CMM often do not use this measurement specification. CMM measurements are often executed by extracting data points from the surface and fitting features using a least-squares criterion. The least-squares association (or global gaussian) can be designated by using the (GG) modifier, as shown in Figure 5(c). Another common association criterion used is the Chebyshev (or minimax), which can be designated using the modifier (GC), as shown in Figure 5(d). An additional commonly used association criterion for cylindrical bosses is the minimum circumscribed cylinder, which can be specified using the modifier (GN), as in Figure 5(e).

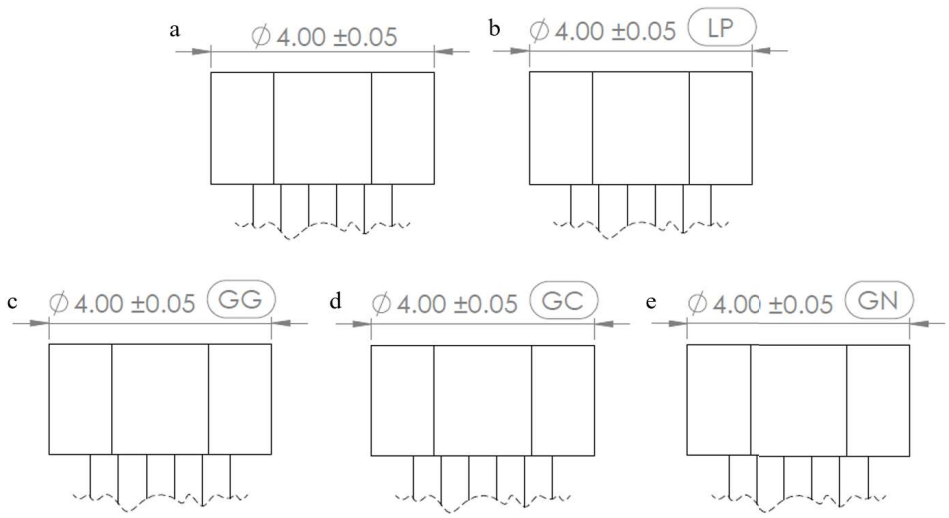

Figure 5: Drawing depiction of measurement specification modifiers used for the different association criterion: (a) Default (two-point measurement), (b) Two-point measurement, (c) Least-squares, (d) Chebyshev, (e) Minimum circumscribed cylinder

The AM components were assessed using all of the specification modifiers shown in Figure 5. The no modifier case and (LP) specification are identical and were assessed using the micrometer measurements. The (GG), (GC), and (GN) specifications were assessed by changing the fitting algorithm used on the extracted measurement data for each sample. This then created four unique diameter measurement results for each sample. Statistical analysis was then performed on the measurement results to discern differences in the measured diameter. Initial normality tests were conducted on each of the measurement specifications using an Anderson-Darling test using the null hypothesis of normality and a confidence value of $\alpha = 0.05$. An analysis of variance (ANOVA) was then conducted with the null hypothesis that there is no significant difference between the means of the measurement methods with a confidence value of $\alpha = 0.05$. If the null hypothesis was rejected, a Tukey-Kramer pairwise comparison was then conducted to determine if there were any overlaps in the confidence intervals of the various groups with a confidence value of $\alpha = 0.05$ to test if the means of the two data sets compared are very similar.

Results

Figure 6 shows the results of the micrometer diameter measurements of the components. As previously described, these measurements used a two-point measurement technique to measure the diameter. The AM components appear, on average, within the specification. The average diameter for

these components was measured to be 4.014 mm, with a standard deviation of 14 µm. The left side of Figure 6 shows the histogram of the measured values. The vertical black dashed line indicates the mean of the measured values. The vertical red dashed line indicates three standard deviations away from the mean, indicating close to where the limits of a normal distribution would lie. Examining this, the data does appear to follow a normal distribution. The right side of Figure 6 displays the quantile-quantile (q-q) plot using a Gaussian distribution to analyze the normality of the diameter measurements. The Anderson-Darling test failed to reject the null hypothesis of normality and the data appears to closely follow the normal distribution with the exception of two outliers at approximately 3.99 mm.

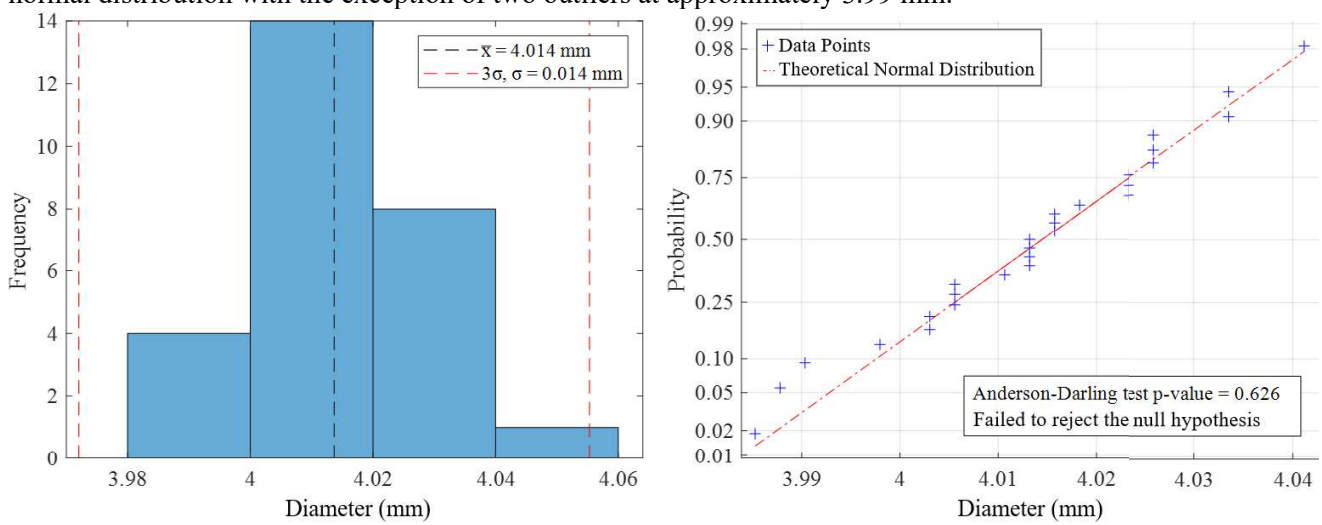

Figure 6: Diameter measurement using the micrometer, (LP) two-point size modifier

Figure 7 displays the results of the CMM measurements using the least-squares association criterion (GG). The average for these measurements is 3.989 mm. This is in contrast to the two-point measurements conducted with the micrometer, as the two means are 25 µm apart. The standard deviation of these measurements was calculated to be 16 µm. However, unlike the two-point measurements, the histogram of the measurements does not appear to follow a normal distribution, as the measurements are skewed toward larger diameters. The Anderson-Darling test rejects the null hypothesis that the measurements come from an underlying normal distribution. Significant departures from the underlying distribution can be seen in the q-q plot. This confirms that two different measurement techniques performed on AM components can not only shift the mean of the measured values, but also yield significantly different underlying distributions of the results.

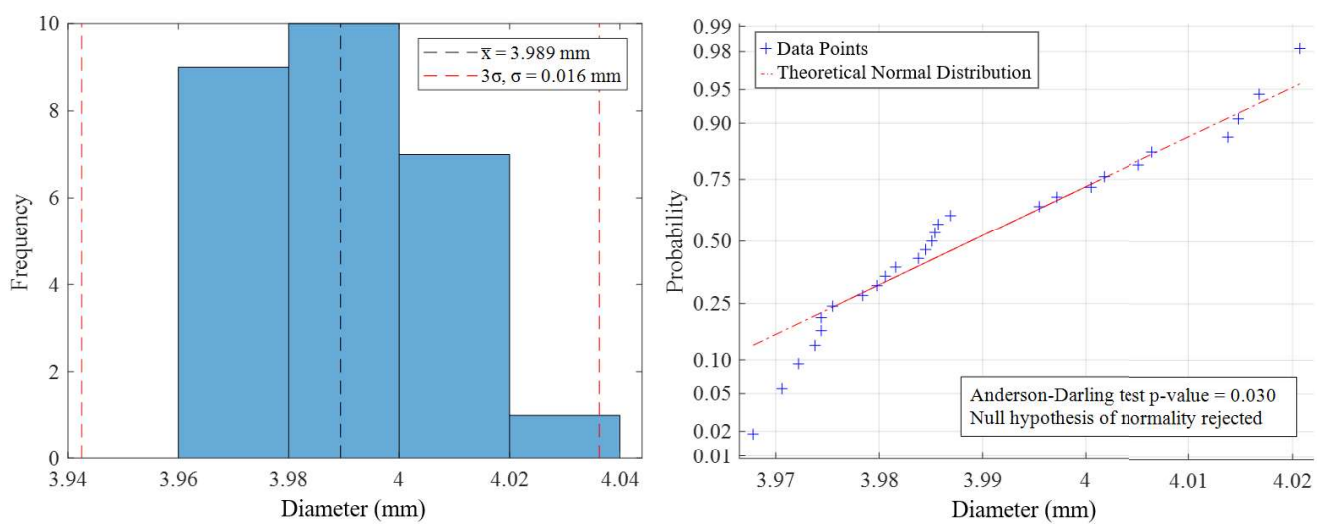

Figure 7: Diameter measurement using the leas-squares association criterion on the CMM data, (GG) modifier

Figure 8 displays the results of the CMM measurements using the Chebyshev association criterion (GC). The average for these measurements was 4.029 mm, which is larger than both the LP and GG measurement methodologies. The standard deviation of these measurements was 25 µm, which is also larger than the two previously discuss methodologies. The distribution of the data is clearly one sided toward larger diameter measurements. As expected, the null hypothesis of normality is rejected in the Anderson-Darling test and the q-q plots show poor conformance to the underlying distribution throughout, not only at the tails of the distribution.

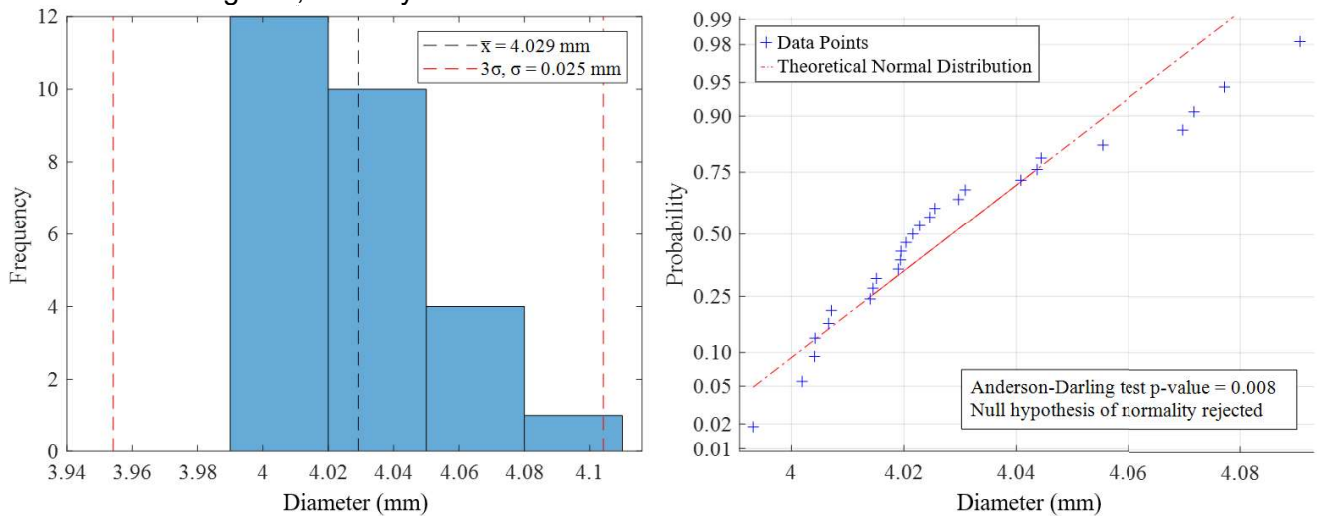

Figure 8: Diameter measurement using the Chebyshev association criterion on the CMM data, (GC) modifier

Figure 9 displays the results of the CMM measurements using the minimum circumscribed cylinder association criterion (GN). The average of these measurements is significantly larger than the other measurement methods, 4.139 mm. The dispersion of data is also larger, with a standard deviation of 35 µm. The histogram of the measurement results appears gaussian. This is confirmed by the Anderson-Darling test which fails to reject the null hypothesis that the data comes from an underlying normal distribution. The q-q plot shows some minor departures from the underlying distribution around the tails, but the majority of the data appears to conform well. The (GN) data by far indicates the largest diameters measured. This is not unexpected as the minimum circumscribed feature is only influenced by the highpoints on the surface. However, it is important to note that the minimum circumscribed criterion generally does not give an ideal normal curve from the theoretical perspective, but provides a truncated normal distribution bounded by the maximum deviation of the measurement or manufacturing process [18]. A non-truncated normal distribution is used here for simplicity and for comparison.

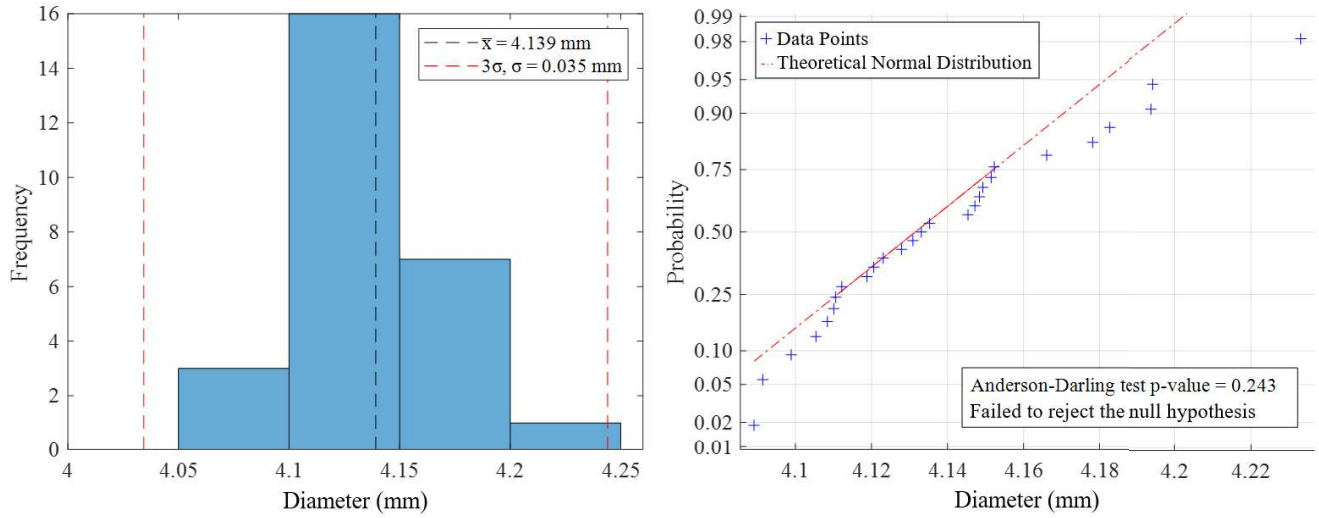

Figure 9: Diameter measurement using the minimum circumscribed association criterion on the CMM data, (GN) modifier

Table 1 displays the results of the ANOVA between the four different measurement procedures. Clearly, the null hypothesis that the four data sets all come from one underlying distribution is rejected. Figure 10 displays a box plot comparing the four different data sets. The red line in each data set represents the median value. The top and bottom edges of the blue box indicate the 25th and 75th percentiles of the data, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' marker symbol. The (GN) data is clearly larger than the other three data sets showing no overlap at all with the exception of one outlier in the (GC) data set. This separation clearly contributed to the rejection of the null hypothesis in the ANOVA. The other three measurement methods are much closer and have overlap at the extreme values. However, the (GG) measurements do appear lower than the rest, but it is difficult to discern from these results. It is important to note that one of the underlying assumptions of an ANOVA is the normality of data, but it has been shown that, generally, ANOVA is robust to violations of the normality assumption [19].

Table 1: ANOVA results for the comparison of the association criterion

Source	SS	df	MS	F	P-Value
Groups	0.3558	3	0.1186	388.22	8.92e-47
Parts	0.0355	26	0.0014	4.47	1.45e-07
Error	0.0238	78	0.0003		
Total	0.4152	107			

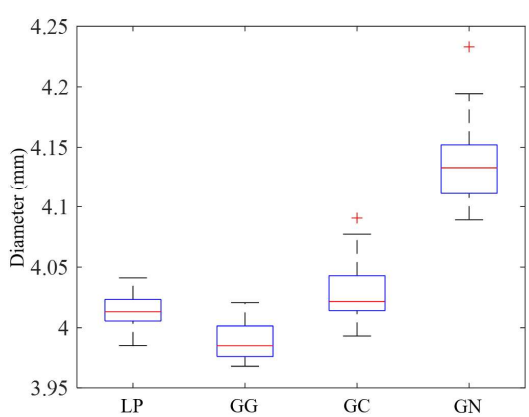

Figure 10: Box plot comparing the different measurement methods

Table 2 shows the results from the Tukey-Kramer pairwise comparison test. Each difference column indicates the difference between the mean of the “Group” and “Control Group” in the individual comparison. The P-Values indicate the results of the comparison and show no overlap between the six pairs tested at a confidence value of α = 0.05. Figure 11 graphically displays the results of the test. The circles for each data set indicate the mean value, while the horizontal lines indicate the 95% confidence interval for each data set. It is clear that none of the six pairs investigated have statistical overlap, as reflected in the P-Values of the test. Similar to ANOVA, the Tukey-Kramer analysis has been shown to be relatively robust to non-normality, but Type I and Type II errors are certainly possible [20]–[22]. Clearly, each of these different association criteria has had a significant impact on the diameter measurement of these AM components.

Table 2: Results from Tukey-Kramer pairwise comparison

Group	Control Group	Lower Limit (mm)	Difference (mm)	Upper Limit (mm)	P-Value
LP	GG	0.0073	0.0243	0.0413	0.0
LP	GC	-0.0325	-0.0155	0.0015	0.0088
LP	GN	-0.1425	-0.1255	-0.1085	0.0
GG	GC	-0.0568	-0.0398	-0.0228	0.0
GG	GN	-0.1668	-0.1498	-0.1328	0.0
GC	GN	-0.1270	-0.1100	-0.0930	0.0

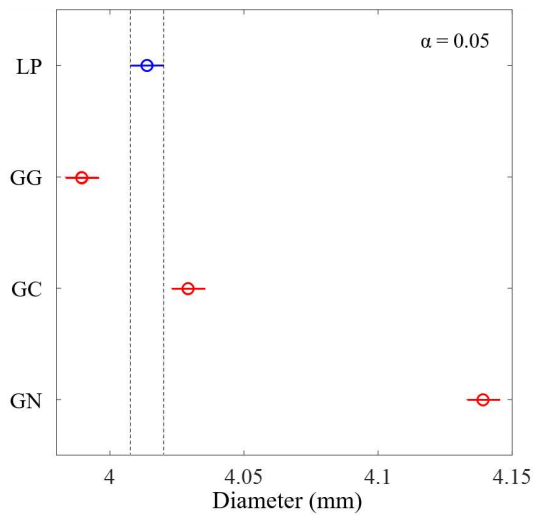

Figure 11: Graphical display of the Tukey-Kramer analysis

It is important to note that the magnitudes and statistical findings of the results in this work are specific to the components analyzed. While measurements using the (GG) method will likely be smaller than measurements using the (LP) and (GN), the deviations between the results may not always be at the magnitude observed in this work. The values will depend on the component size, component form, and surface texture. An increase in form errors will directly impact the (GN) measurements and will likely impact the (LP) measurements, since these methods are heavily influenced by the extreme values of the surface. However, these errors will have a lesser impact on the (GG) method since the least-squares method seeks to minimize the error from all points to the associated feature. For instance, if the axis of the cylinder had been aligned along the build axis, as described in the methodology, we may have seen very different results as the form errors on the cylinder surface would be less likely to occur. Furthermore, if the components were larger, component form would also change, as a greater number

of layers would be able to form the cylindrical geometry. Future work should investigate the effect of varying component geometry and build orientation on these measurement methodologies.

These results show that significant differences in the measurement of AM components can occur depending on the measurement methodology implemented, specifically the choice of association criterion. It is critical for designers, manufacturers, and inspectors of AM components to understand the differences in these methodologies and their potential impact on the measurement result. Designers should seek to provide specifications using the intended inspection methodology, specifically by using the specification modifier appropriate for their application, in order to minimize ambiguity in the product requirements. Likewise, this onus also falls on the inspector to report the measurement procedure used to produce the results.

Conclusions

This work examined the use of different measurement methods in the qualification of diameter on a simple AM feature. The results from this investigation showed that the choice of the association criterion can have a significant impact on the measurement result. The use of different association criteria was found to produce different mean values, different dispersions of values, and different distributions of data across the measurement of 27 components. The different association criteria were found to produce statistically significant measurement results, with differences in means up to about 0.15 mm. Further investigations should examine the impact of these specifications over a wider range of geometric features, sizes of features, and orientations within the AM build volume to gain a better understanding of the potential impact of association criterion on the measurement of AM components.

Disclaimer

Certain commercial entities, equipment, or materials may be identified in this document to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

References

[1] "Roadmap for Automotive Additive Manufacturing," United States Council for Automotive Research LLC, 2021.

[2] R. K. Leach, D. Bourell, S. Carmignato, A. Donmez, N. Senin, and W. Dewulf, "Geometrical metrology for metal additive manufacturing," *CIRP Annals*, vol. 68, no. 2, pp. 677–700, 2019, doi: https://doi.org/10.1016/j.cirp.2019.05.004.

[3] D. W. Rosen, "Design for the Additive Manufacturing Process Chain," presented at the 2021 International Solid Freeform Fabrication Symposium, Austin, TX, 2021. doi: 10.26153/tsw/17534.

[4] E. P. Morse, C. M. Shakarji, and V. Srinivasan, "A Brief Analysis of Recent ISO Tolerancing Standards and Their Potential Impact on Digitization of Manufacturing," *Procedia CIRP*, vol. 75, pp. 11–18, 2018.

[5] ASME, "ASME Y14.5 - 2018: Dimensioning and Tolerancing," Standard, 2018.

[6] International Organization for Standardization, "ISO 14405-1:2016 Geometrical product specifications (GPS) - Dimensional tolerancing - Part 1: Linear sizes," International Organization for Standardization, 2016.

[7] International Organization for Standardization, "ISO 14405-3:2016 Geometrical product specifications (GPS) - Dimensional tolerancing - Part 3: Angular sizes," International Organization for Standardization, 2016.

[8] E. Trapet, E. Savio, and L. De Chiffre, "New advances in traceability of CMMs for almost the entire range of industrial dimensional metrology needs," *CIRP Annals*, vol. 53, no. 1, pp. 433–438, Jan. 2004, doi: 10.1016/S0007-8506(07)60733-1.

[9] S. Lou, S. B. Brown, W. Sun, W. Zeng, X. Jiang, and P. J. Scott, "An investigation of the mechanical filtering effect of tactile CMM in the measurement of additively manufactured parts," *Measurement*, vol. 144, pp. 173–182, 2019.

[10] L. Schild, A. Kraemer, D. Reiling, and H. Wu, "Influence of surface roughness on measurement uncertainty in Computed Tomography," presented at the 8th Conference on Industrial Computed Tomography (iCT 2018), 2018.

[11] J. Berez, M. Praniewicz, and C. Saldana, “Assessing laser powder bed fusion system geometric errors through artifact-based methods,” *Procedia Manufacturing*, vol. 53, pp. 395–406, Jan. 2021, doi: 10.1016/j.promfg.2021.06.042.
[12] M. Praniewicz, G. Ameta, J. Fox, and C. Saldana, “Data registration for multi-method qualification of additive manufactured components,” *Additive Manufacturing*, vol. 35, p. 101292, 2020, doi: https://doi.org/10.1016/j.addma.2020.101292.
[13] International Organization for Standardization, “ISO 17450-1:2011 Geometrical product specifications (GPS) - General concepts - Part 1: Model for geometrical specification and verification,” International Organization for Standardization, 2011.
[14] M. Praniewicz, J. C. Fox, and C. Saldana, “Toward traceable XCT measurement of AM lattice structures: Uncertainty in calibrated reference object measurement,” *Precision Engineering*, May 2022, doi: 10.1016/j.precisioneng.2022.05.010.
[15] International Organization for Standardization, “ISO 10360-2:2009 Geometrical product specifications (GPS) — Acceptance and reverification,tests for coordinate measuring machines,(CMM) —Part 2: CMMs used for measuring linear dimensions,” International Organization for Standardization, Geveva, Switzerland, 2009.
[16] GOM GmbH, “GOM Inspect 2021”.
[17] International Organization for Standardization, “ISO 17450-3:2016 Geometrical Product specifications (GPS) - General concepts - Part 3: Toleranced features,” International Organization for Standardization, 2016.
[18] A. L. Sweet and J. F. Tu, “Evaluating tolerances and process capability when using truncated probability density functions,” *International Journal of Production Research*, vol. 44, no. 17, pp. 3493–3508, Sep. 2006, doi: 10.1080/00207540500521576.
[19] E. Schmider, M. Ziegler, E. Danay, L. Beyer, and M. Bühner, “Is it really robust? Reinvestigating the robustness of ANOVA against violations of the normal distribution assumption,” *Methodology: European Journal of Research Methods for the Behavioral and Social Sciences*, vol. 6, no. 4, pp. 147–151, 2010, doi: 10.1027/1614-2241/a000016.
[20] J. Jaccard, M. A. Becker, and G. Wood, “Pairwise multiple comparison procedures: A review,” *Psychological Bulletin*, vol. 96, no. 3, pp. 589–596, 1984, doi: 10.1037/0033-2909.96.3.589.
[21] G. C. Ramseyer and T.-K. Tcheng, “The Robustness of the Studentized Range Statistic to Violations of the Normality and Homogeneity of Variance Assumptions,” *American Educational Research Journal*, vol. 10, no. 3, pp. 235–240, May 1973, doi: 10.3102/00028312010003235.
[22] H. J. Keselman, “A Power Investigation of the Tukey Multiple Comparison Statistic,” *Educational and Psychological Measurement*, vol. 36, no. 1, pp. 97–104, Apr. 1976, doi: 10.1177/001316447603600108.