Solid Freeform Fabrication 2016: Proceedings of the 27th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference

DIMENSIONAL ACCURACY OF TITANIUM DIRECT METAL LASER SINTERED PARTS

W. F. Mitchell*†, D. C. Lang†, T. A. Merdes†, E. W. Reutzel*†, and G. S. Welsh§

* Center for Innovative Material Processing through Direct Digital Deposition (CIMP-3D)
† Applied Research Laboratory at the Pennsylvania State University, University Park, PA 16801
§ Naval Air Systems Command, Patuxent River, MD 20670

Abstract

To address concerns regarding quality of production parts created using the Additive Manufacturing (AM) process, a study was conducted to quantify the dimensional accuracy of said parts. Fourteen AM builds were manufactured in Ti-6Al-4V material across two EOS DMLS machines (EOSINT M 280 and EOS M 290). In addition to studying the impact of machine-to-machine variability, other factors potentially impacting final dimensional accuracy were studied, including: powder state (virgin or reused); post-processing steps (heat treatment and part removal from substrate); location of part on substrate; and nominal part size. The results of the dimensional analysis showed that the individual machine itself was the dominant factor impacting dimensional accuracy. Also, a non-linear relationship between dimensional accuracy and nominal part size was identified, which would require a more complex machine calibration technique to correct.

Introduction

Manufacturing metal parts using the Additive Manufacturing (AM) process is of great interest to the aerospace industry [1]. The AM process has many potential advantages compared to conventional manufacturing processes including additional design freedom, creation of internal geometry, complex light-weighting of designs, consolidation of assemblies, and a reduced logistical supply chain [1]-[2]. In addition, certain titanium alloys are readily processed using AM, and the resultant parts offer potential to be incorporated into complex aircraft designs [1]. In order to begin using AM to produce production parts in these applications, an extensive effort must be undertaken to qualify and certify the process and final parts [2]. Dimensional accuracy must be a part of qualification and certification to ensure the parts being created on an AM machine match the final design intent. Also, to realize the economic benefits of AM [2], post processing must be minimized. Though many current applications require the use of conventional subtractive techniques to achieve the final part tolerances, particularly surface roughness [3], as more cost efficient techniques (e.g. batch surface finishing operations such as electrochemical polishing, Micro Machining Process, and Isotropic Superfinishing) become established to meet surface roughness limits, dimensional accuracy will be the next limiting factor in achieving final part tolerances. A combination of new surface finishing techniques and tighter, quantifiable dimensional control promises to reduce or possibly eliminate post-processing steps such as conventional machining, thereby significantly reducing final part cost.

Towards ultimately reducing final part cost and establishing part certification, a primary goal of our ongoing research is to investigate the dimensional accuracy that can be realized on commercially available AM machines. This paper covers the present state of that investigation. The research investigates Ti-6Al-4V parts that were produced on two EOS Direct Metal Laser Sintered (DMLS) machines located at different facilities. The final dimensional accuracy analysis includes an assessment of the overall dimensional accuracy realized; an investigation into variables possibly influencing the dimensional accuracy; and proposals for increasing the process accuracy.

Experimental Setup

Fourteen AM builds were produced for analysis. All builds used identical layouts, parameters, and procedures. Every effort was made to have consistency between each build and eliminate unintended sources of error. The builds were distributed across two machines and also encompassed virgin (previously unused) and reused titanium powder.

The build layout contained production components, mechanical test specimens, and so-called "witness coupons" (see Figure 1). The witness coupons were designed to assess various build characteristics, including dimensional accuracy. Both the mechanical test specimens and witness coupons were measured upon completion of each key manufacturing process which included the AM build, hot isostatic pressing (HIP), and part removal via submerged wire electrical discharge machining (EDM). In accordance with ASTM F2924-14 [4], the substrate with parts still attached was HIPed in an argon environment at 900 °C and 102 MPa for 4 hrs. A submerged wire EDM was then used to separate the parts from the substrate, cutting as close to the substrate as possible. In this application, the AM parts are ready for final finishing and/or machining upon completion of the three manufacturing processes listed above.

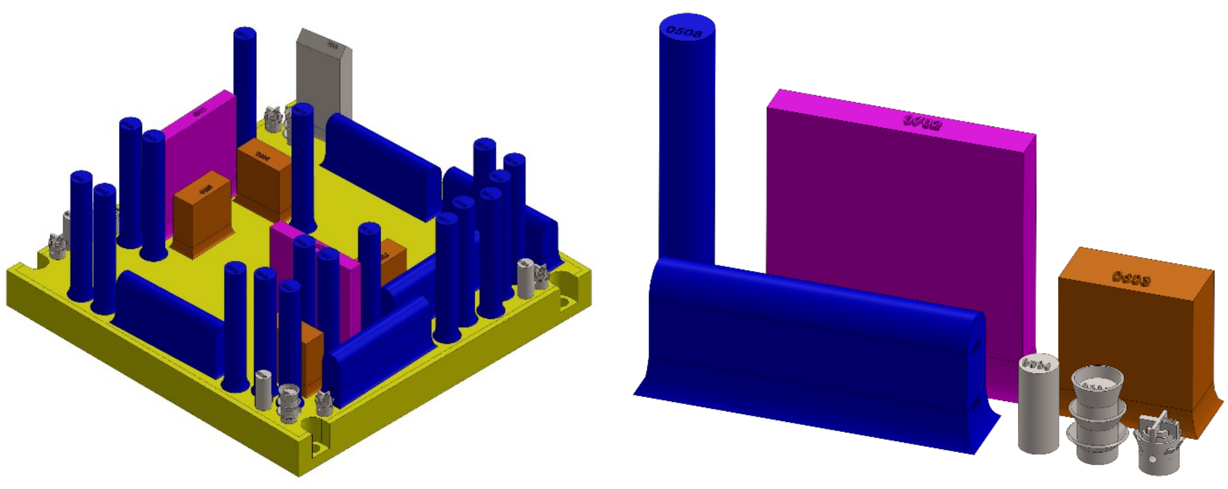

Figure 1: Part layout on AM build (left). Both mechanical test specimens and witness coupons measured for dimensional analysis (right).

The two AM machines used in this research included an EOSINT M 280 and an EOS M 290. Both machines are based on Direct Metal Laser Sintering (DMLS) technology, the EOS M 290 being a newer version of the EOSINT M 280 with some enhancements [5]. The typical achievable part accuracy in Ti-6Al-4V material is stated as equivalent between the M 280 and M 290 machines [6], and they were treated as equal in this study. Both machines were calibrated by EOS technicians for laser power, focal distance, and galvanometer accuracy during installation.

Six AM builds were completed on the EOSINT M 280 machine and eight AM builds were completed on the EOS M 290 machine.

Ti-6Al-4V metal powder was used for all AM builds. The raw material was sourced directly from the machine manufacturer [6]. Half of the builds from each machine (three for the M 280 and four for the M 290) used powder which had never undergone AM processing, otherwise known as virgin powder. After successful completion of each virgin powder build, the remaining unsintered powder was reclaimed and sieved according to the manufacturer's recommendations. The reclaimed powder, now designated as "reused," was then used to complete another round of AM builds on both the M 280 and M 290 machines. The effect of powder state, virgin vs. reused, on dimensional accuracy is analyzed in the results section.

For dimensional accuracy assessment, the aforementioned mechanical test specimens and witness coupons were measured with calibrated calipers after each key manufacturing process, as described above. Exceptions where measurements were unable to be collected included M 280 builds 5 and 6, post part removal and all M 290 builds, post build. The same technician measured all parts to eliminate user variability from influencing the measurement results. The measurements were recorded into a database for storage and future analysis. The machine, powder state, and manufacturing step were all analyzed for their influence on dimensional accuracy. Additionally, the final part measurements (after part removal) were analyzed for correlations to part location on the substrate and nominal part size.

Results

Once all fourteen AM builds were completed and part measurements collected, the part measurement data was normalized for dimensional analysis. By subtracting the nominal part size (see Figure 2) from the actual measurements as shown in the equation below, the measurement data could be compared across the various part sizes.

$$Dimensional\ Accuracy = (Measured\ Size) - (Nominal\ Part\ Size)$$

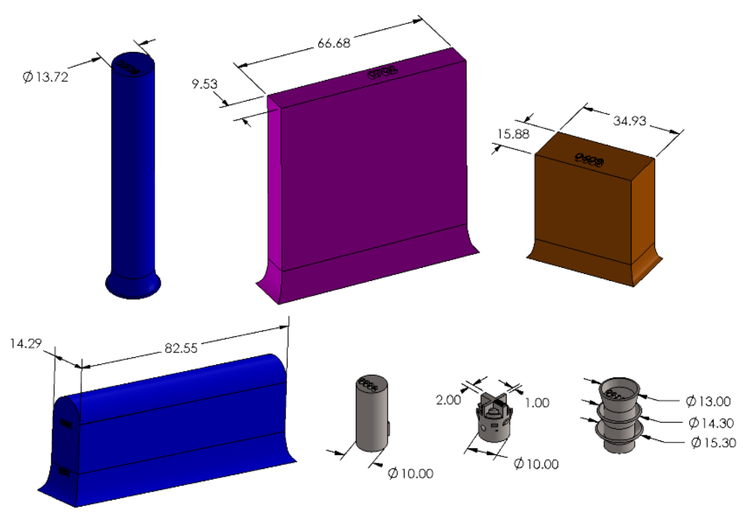

Figure 2: Nominal part sizes (diameters, lengths, and widths) of mechanical test specimens and witness coupons.

The calculated values for dimensional accuracy, or deviation from nominal, were then analyzed to assess four factors that could have a systematic effect on the results: build number, machine type, powder state (virgin vs. reused), and post-processing step. The dimensional accuracy data was also analyzed for trends with respect to part location on the substrate and nominal part size. The two regression analyses were used to characterize changes in dimensional accuracy caused by build quality variations or machine calibration settings (e.g., laser beam offset and X-direction or Y-direction scaling errors).

The build-to-build variation was analyzed first. For comparison, the data was restricted to measurements taken after part removal. Also note-worthy, builds 1-3 on the M 280 machine and builds 1-4 on the M 290 machine were completed using virgin powder. The remaining builds were completed with reused powder.

Utilizing a box and whisker plot, Figure 3 visually summarizes the dimensional accuracy variability from build-to-build on both the M 280 and M 290 machines. In box and whisker plots, the upper and lower extremes of the boxes represent a given population's interquartile range (25th percentile to the 75th percentile); the whiskers extending from the interquartile boxes represent the upper and lower quartiles; and the asterisks represent outliers in the data. Within the interquartile box, the population's median is shown as a horizontal line and the population's mean is shown as a filled diamond. The means are connected from build-to-build within each machine to highlight dimensional accuracy changes with respect to build number.

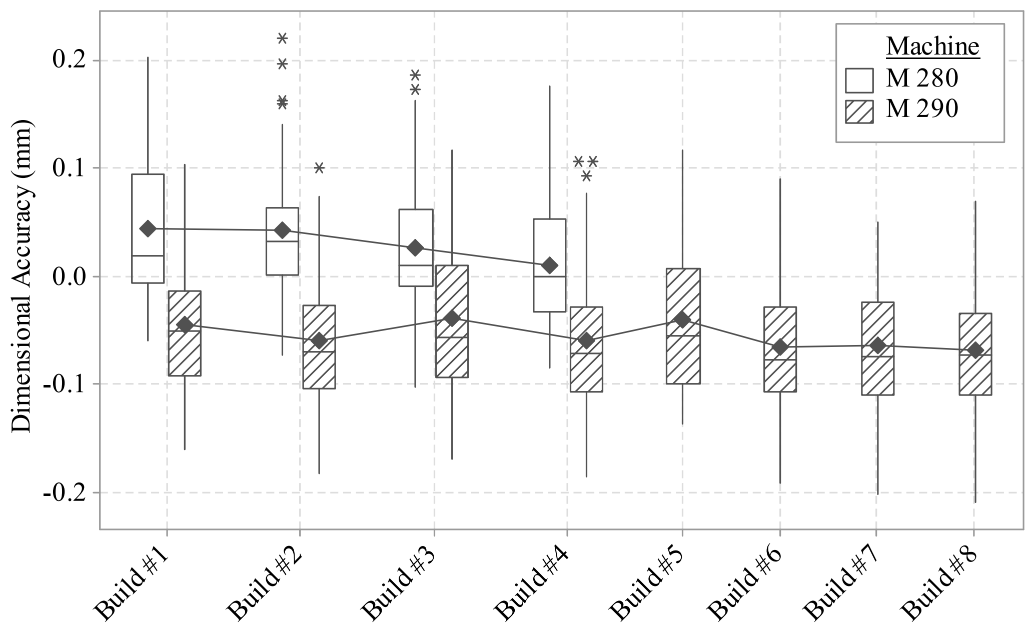

Figure 3: Box and whisker plot comparing dimensional accuracy across multiple AM builds and two AM machines.

An analysis of variance (ANOVA) was performed on the build-to-build data to quantify any statistical difference between each build. Results from a pairwise comparison using Tukey's method at 95% confidence level showed that there was no statistical difference between the means of all builds, when restricted to each machine separately. Both the M 280 and M 290 machines produced parts on a build-to-build basis that were dimensionally equivalent at 95% confidence. Therefore, the data suggests there was no statistically significant drift of the dimensionally accuracy from build-to-build on either machine. [7]

As is suggested in the build-to-build data (Figure 3) and build-to-build pairwise comparison results, the builds completed on the M 280 machine produced dimensional accuracy results that differed from builds completed on the M 290 machine. To statistically assess this study's second potential factor, machine-to-machine variability, the dimensional accuracy data were segregated into separate populations for each machine. A comparison of each machine's dimensional accuracy distribution can be seen in the histogram below (Figure 4). The histogram shows that the two machines produced dimensional accuracy populations with similar variance (σ^2), but different means [7]. The M 280 and M 290 data's standard deviation was $\sigma = 0.061$ mm and $\sigma = 0.062$ mm respectively. However, the data's means were $\mu = 0.038$ mm and $\mu = -0.050$ mm respectively, a total difference of 0.088 mm.

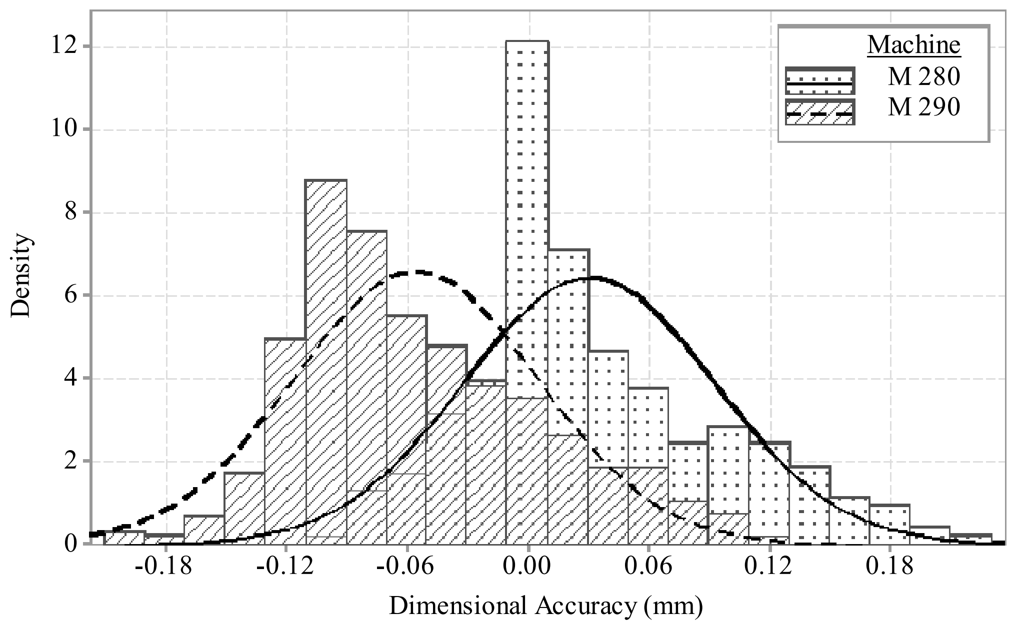

Figure 4: Histogram of dimensional accuracy differences between two AM machines.

Using the two-sample *t*-test for equal means, the M 280 and M 290 dimensional accuracy means were statistically compared. At a 95% confidence level, the *t*-test rejected the null hypothesis signifying that the each machine's mean dimensional accuracy was statistically different. From the two-sample *t*-test, the test statistic (*t*-value) was computed to be 15.30 and the calculated probability (*p*-value) was computed to be less than 0.000. Though standard deviations for both machines were nearly identical, both calculated *t*- and *p*-values exceed the limits to accept the null hypothesis at 95% confidence (less than 1.96 for *t*-value and greater than 0.05 for *p*-value), validating that the means between each machine are different with statistical significance. [7]

Powder state was the third factor analyzed for its effect on dimensional accuracy. An equal number of AM builds were completed on the M 290 machine for each case: four utilizing virgin powder and four utilizing reused powder. To assess the effect of powder state on the dimensional accuracy while limiting extraneous influences, the data was restricted to include measurements captured after part removal, from M 290 AM builds only. The machine type and manufacturing processes are excluded from the analysis, thereby eliminating their possible influence on the results.

The virgin and reused powder dimensional accuracy results can be seen in Figure 5. The standard deviation of each population was $\sigma = 0.062$ mm and $\sigma = 0.059$ mm for virgin and reused powder respectively. The population means were $\mu = -0.050$ mm and $\mu = -0.060$ mm respectively. Again using the two-sample *t*-test for equal means, the virgin powder and reused powder populations were statistically compared. The resulting test statistic and calculated probability were computed to be *t*-value = 1.77 and *p*-value = 0.077. Both values fall within the limits to accept the null hypothesis, H_0, at a 95% confidence level. Therefore, the two-sample *t*-test for equal means indicates that there is no statistical difference in dimensional accuracy between the virgin powder and reused powder population means.

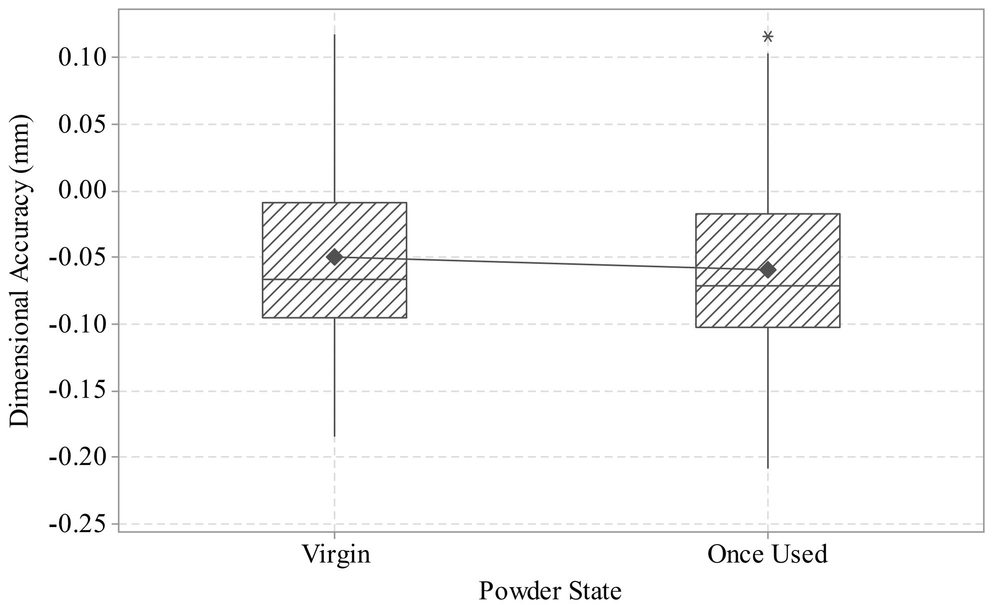

Figure 5: Box and whisker plot comparing dimensional accuracy between virgin and reused powder. Statistical testing indicated no difference between the two population means.

The fourth and final statistical comparison assessed the effect of each manufacturing process on dimensional accuracy. Understanding the effect, if any, caused by HIP or part removal on dimensional accuracy would allow the initial AM part design to be compensated accordingly. For this analysis, the data was filtered to include measurements taken on M 280 AM builds using virgin powder only. Filtering in this manner limits any extraneous effects from machine-to-machine and powder state variability.

The dimensional accuracy results can be seen in Figure 6 below. The three box and whisker groups represent the dimensional accuracy measurements taken after each manufacturing process. An ANOVA was completed on the three data groupings, the results of which indicated no statistical difference in the variances and means when comparing "Post Build" to "Post HIP" and "Post HIP" to "Post Part Removal". The *t*-test calculated the *t*-values to be 1.51 and 1.49 respectively while the *p*-values were calculated to be 0.285 and 0.296 respectively. However, the ANOVA results did indicate a statistical difference of the variances and means between the "Post Build" and "Post Part Removal" groups, with the *t*-test calculating a *t*-value of 3.03 and a *p*-value of 0.007. This appears to indicate that the part size is systematically reduced once processed through HIP and part removal via wire EDM. Since the total difference between the "Post Build" and "Post Part Removal" means was 0.032 mm while the precision uncertainty of the measurement device was calculated to be 0.010 mm, collecting more data is desired before drawing definitive conclusions.

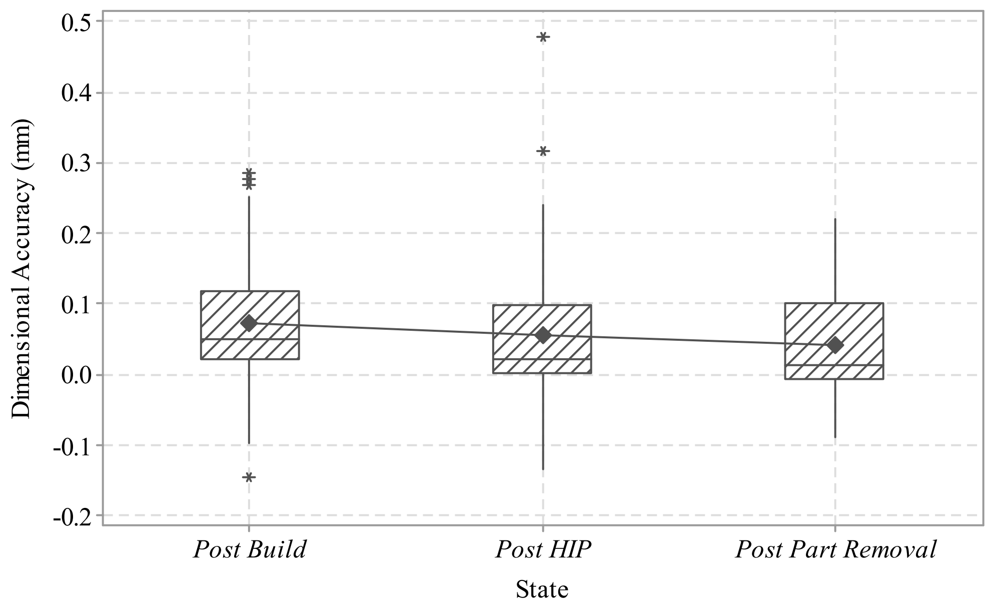

Figure 6: Box and whisker plot comparing the dimensional accuracy across three key manufacturing processes.

With all categorical factors analyzed, the study was expanded to characterize dimensional accuracy variation as a function of two continuous variables: part location on substrate and nominal part size. For both analyses, only measurements taken after part removal were used.

First, a linear regression was performed on the data with dimensional accuracy as the dependent variable and linear distance from the substrate center to part location as the independent variable (see Figure 7). A scatter plot of the data and regression analysis results can be seen in Figure 8. Prior to analysis, the dimensional accuracy was hypothesized to change as the part under measurement increased in distance from the substrate center due to expected variations in laser spatial energy distribution across the build area. The largest laser variation should occur in the corners of the building area, therefore those areas have the highest probability of large dimensional deviations.

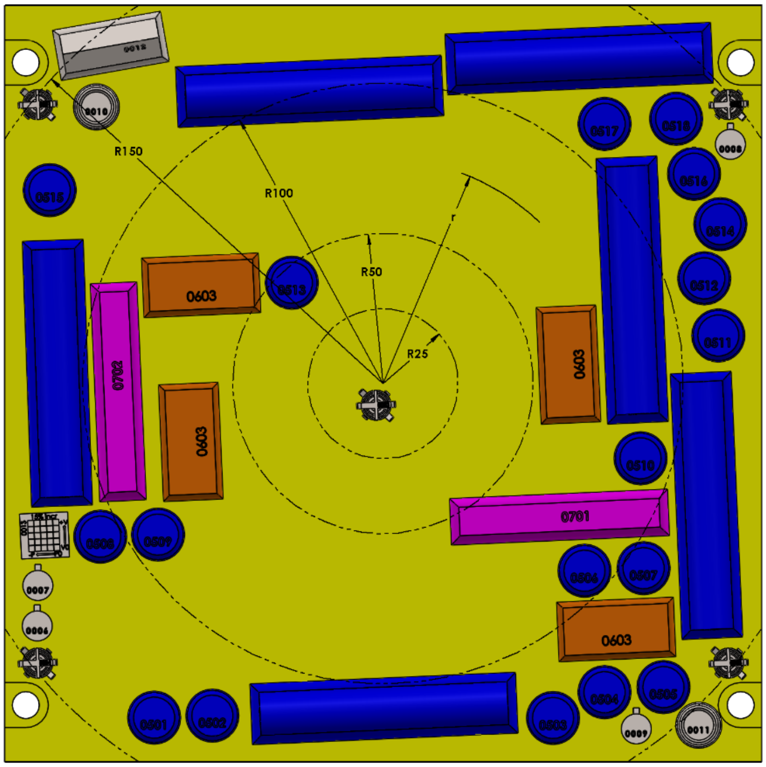

Figure 7: Illustration of various distances from the center of substrate. Dimensional accuracy measurements were analyzed according to the distance from the center of the substrate to the centroid of the part under measurement.

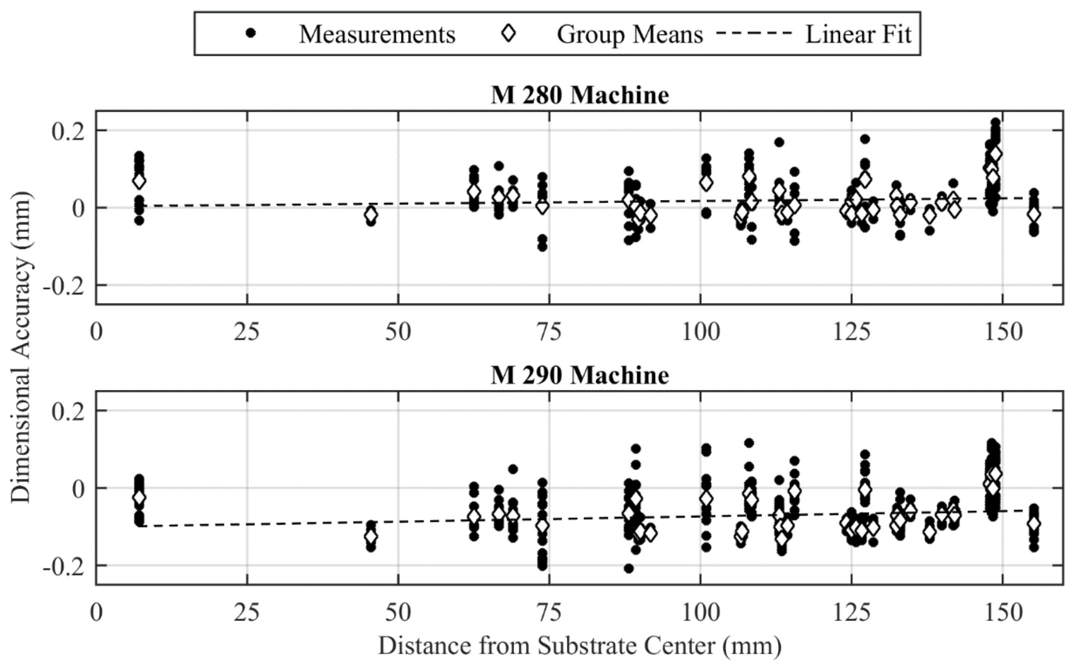

Figure 8: Dimensional accuracy plotted as a function of distance from substrate center to part measurement location.

The fitted coefficients for the linear equation of the form $y = mx + b$ are shown in Table 1. Table 1 also summarizes the goodness of fit value (coefficient of determination or R^2 value) and results from the F-test (F-value and p-value). The F-test compares the linear regression model against the regression model one degree lower, in this case a constant model. The F-test outputs a test statistic, the F-value. If the F-value exceeds a threshold value established by the number of degrees of freedom and confidence level, the linear regression model is said to fit the data better than the constant model. The p-value is an indicator associated with the F-value and when it is below the desired significance level (in this case, $\alpha = 0.05$), the regression model is considered to be a better fit to the data, with statistical significance, than a regression model one degree lower.

Visually, the data presented in Figure 8 appears random with no correlation between dimensional accuracy and part location. The regression analysis confirms these visual observations. For both machines, coefficient of determination (R^2) values associated with the linear regression model were very low indicating that the model had high residual errors. Also, the p-values associated with the F-test statistic exceeded $\alpha = 0.05$ significance level for both the M 280 and M 290 machines. Therefore, the linear regression model did not provide a statistically significant fit that was better than a constant model and it can be concluded that dimensional accuracy is not linearly related to part location.

Table 1: Regression analysis results for dimensional accuracy as a function of part location

Machine	*b*	*m*	R^2	*F-value*	*p-value*
M 280	0.003	1.38×10^{-4}	0.01	0.45	0.56
M 290	-0.101	2.71×10^{-4}	0.04	1.42	0.24

EOS machines require the completion of a "fine-tuning" AM build (see Figure 9) for every processing parameter set (material type and layer thickness). The fine-tuning build is used for calibration of the beam offset, X scaling factor, and Y scaling factor. These three values are used to account for the melt pool geometry and material shrinkage during laser sintering. The factors are recognized as an approximation, since the actual melt pool geometry and material shrinkage are dependent upon part size, geometry, and distortion. As a potential solution to the calibration factors' variation, EOS recommends calibrating the machine using actual parts when possible. In many instances, this is impractical as the AM process lends itself to produce one-off parts and implement frequent part-to-part design changes. Therefore, measurements and calibrations calculated on one build would not necessarily apply to the next build.

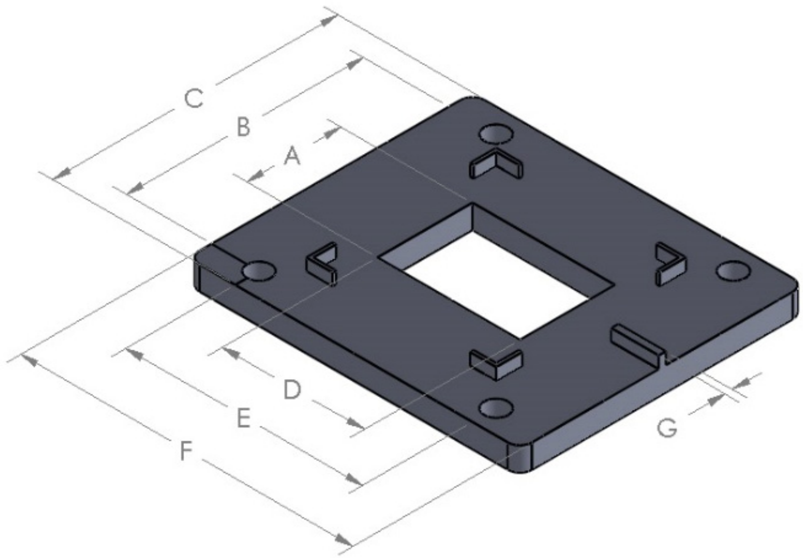

Figure 9: EOS recommended calibration artifact created during "fine-tuning" build. Measurements collected from the artifact are used to generate beam offset, X scaling, and Y scaling values.

Before the start of this research, both machines manufactured a fine-tuning build, measured the resulting geometry, and generated calibration factors for use on all AM builds thereafter. A regression analysis was performed to estimate the correlation between dimensional accuracy and nominal part size, assessing the effectiveness and accuracy of the calculated beam offset, X scaling, and Y scaling factors.

The dimensional accuracy data was first plotted as a function of nominal part size (see Figure 10) with both the machine type, M 280 and M 290, and the measurement direction, X and Y, analyzed separately. Then, both linear and quadratic regression models were fit to the dimensional accuracy data. The data and regression analysis results can be seen in Figure 11.

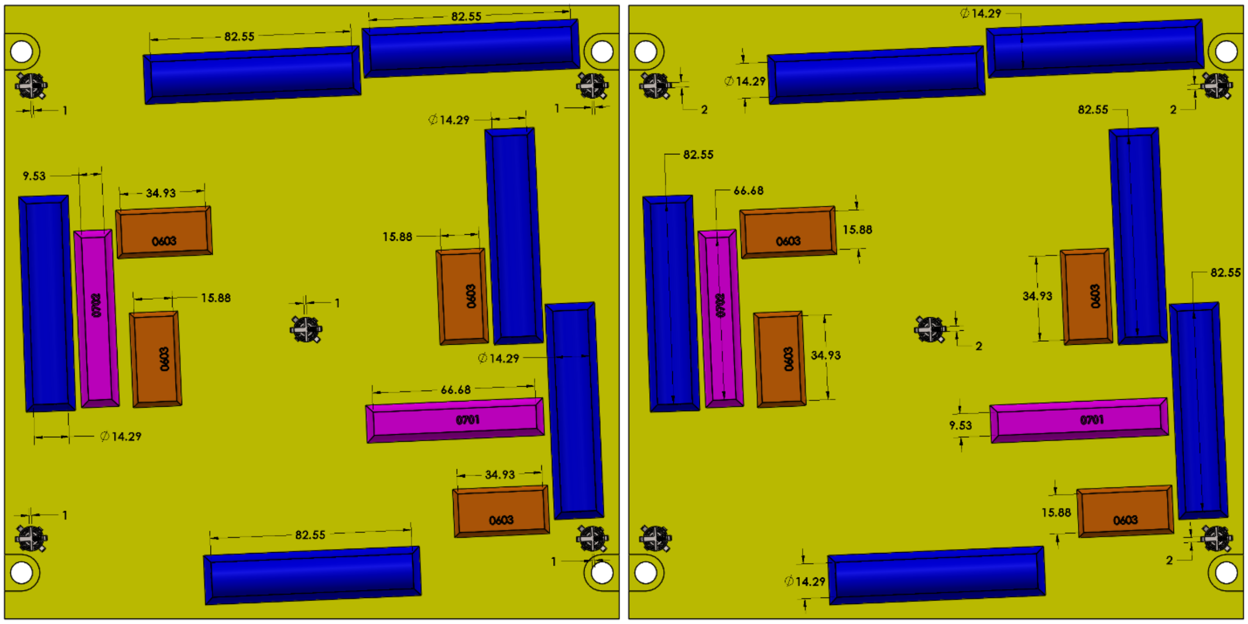

Figure 10: Nominal part sizes shown in the X measurement direction (left) and Y measurement direction (right).

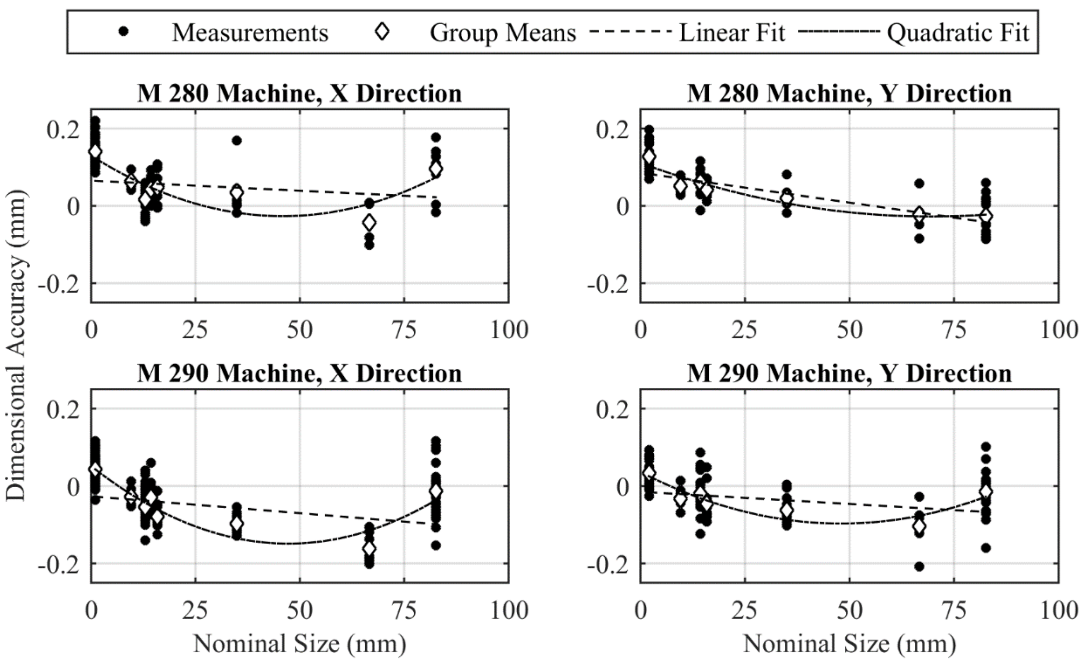

Figure 11: Dimensional accuracy plotted as a function of nominal part size with linear and quadratic regression models fitted to the data. [7]

Table 2 summarizes the linear and quadratic regression analyses for comparison. The model coefficients, b, m_1, and m_2, correspond to the equation of form $y = m_1x + b$ for the linear regression model, and $y = m_2x^2 + m_1x + b$ for the quadratic regression model. In all cases, a quadratic relationship more closely represents the actual dimensional accuracy data. As a result, the quadratic fit produces lower residual errors and therefore a larger coefficient of determination. Also, only the linear regression model on the M 280 machine in the Y direction produced a *p*-value of less than α = 0.05 significance level for the F-test. Therefore, a linear regression model does provide a better fit to the data than a constant model in that case, but it does not provide a better fit in the other three cases. In contrast, the quadratic regression model produces *p*-values of less than α = 0.05 significance level on all but one case: the M 280 machine in the Y direction. That specific case does not correlate dimensional accuracy to nominal part size at a 95% confidence level. The other three cases demonstrate statistically significant correlations: the dimensional accuracy data exhibits a quadratic relationship to nominal part size.

Table 2: Regression analysis results for dimensional accuracy as a function of nominal part size. The model coefficients and goodness of fit values are compared between linear and quadratic regression models.

Machine	Direction	*b*	m_1	m_2	R^2	*F-value*	*p-value*
		Linear Regression Model					
M 280	X	0.065	-5.21×10^{-4}		0.08	0.53	0.49
M 280	Y	0.086	-1.54×10^{-3}		0.81	21.90	0.01
M 290	X	-0.027	-8.72×10^{-4}		0.18	1.29	0.30
M 290	Y	-0.015	-6.31×10^{-4}		0.21	1.32	0.30
		Quadratic Regression Model					
		b	m_1	m_2	R^2	*F-value*	*p-value*
M 280	X	0.130	-6.82×10^{-3}	7.43×10^{-5}	0.64	4.40	0.08
M 280	Y	0.111	-3.98×10^{-3}	2.86×10^{-5}	0.91	19.79	0.01
M 290	X	0.052	-8.49×10^{-3}	8.98×10^{-5}	0.81	10.48	0.02
M 290	Y	0.036	-5.56×10^{-3}	5.79×10^{-5}	0.80	7.91	0.04

Since the dimensional accuracy data did not correlate linearly with nominal part size in three of the machine and measurement direction cases, the errors cannot be corrected with more accurate derivation of the beam offset, X scaling, and Y scaling values. One case, the M 280 machine in the Y direction, did exhibit a linear correlation between dimensional accuracy and nominal part size. Therefore, the linear regression model could be used to calculate new beam offset and Y scaling values to increase accuracy for this particular scenario. However, correcting the scaling factor in only one direction of the build area is impractical, as AM parts require accuracy in both X and Y directions.

Ultimately, a more robust technique must be developed and implemented to correct the non-linear errors seen. A better galvanometer calibration technique [8], application of material shrinkage factors on a part-to-part basis, or a pre-processing algorithm to scale parts based on their size could all potentially improve the dimensional accuracy.

Conclusions and Future Work

The requirements of additively manufactured parts are driven by each individual application. For some applications where dimensional control is not critical or the parts require post-processing such as finish machining, the dimensional accuracy presented in this work is adequate. However, other applications will require tighter dimensional control or the parts will undergo more cost efficient post-processing such as batch finishing. To meet the design intent in these applications, the existing dimensional accuracy control as presented in this work will require improvements. [7]

To assess the root cause of existing dimensional accuracy error in the two EOS machines tested, the build number, machine type, powder state, and manufacturing steps were all analyzed as influencing factors. The statistical results indicated there was no correlation between dimensional accuracy and build number. The machine type however indicated the largest dimensional accuracy variation at 0.088 mm. Since each machine undergoes its own calibration and material shrinkage factor calculations, there is a lot of variability that could cause this difference. The third factor, powder state, did not exhibit any statistically significant effect on dimensional accuracy. Finally, the manufacturing step showed no statistically significant difference between each subsequent step, but did reveal a statistically significant difference from the very beginning of the manufacturing process (post build) to the end (post part removal). The overall difference was 0.032 mm. Since measurement device's precision uncertainty was calculated to be 0.010 mm, collecting more data with a more accurate measurement device is desired to confirm the results presents.

The effect of part location and nominal part size on dimensional accuracy were also analyzed using a regression analysis. There was no correlation between part location and dimensional accuracy; the data varied randomly across multiple part location distances. The dimensional accuracy data did exhibit a strong quadratic relationship to nominal part size. The non-linear errors resulting from such a relationship make them difficult to correct with the current machine calibration strategy. The root cause is unknown at this time, however, improved galvanometer calibration, implementation of the material shrinkage factors on a part-to-part basis, or predictive modeling and compensation of the shrinkage prior to build could all correct the error.

In continuation of this research, it would be advantageous to independently verify the individual machines' accuracy, including the galvanometer calibration. The machine qualification could build upon existing efforts to create a standard test artifact [9] by using the artifact for machine accuracy assessment and calibration. Also, collecting and analyzing additional data from more AM builds will improve the accuracy of the statistical tests and regression models generated thus far. This may help to develop an understanding of the underlying root cause affecting dimensional accuracy, a necessity to improve the results. The inclusion of more and varied part geometries should also be considered on new AM build layouts. Nominal part sizes should be selected to fill in the existing data's gaps and also extend range of measurement size past the current maximum. Parts of varying cross sectional area are also important to investigate as they could potentially reveal new trends that would need to be characterized. In parallel to the actual AM builds and build measurements, thermo-mechanical modeling of the AM build layout should be conducted. The models may be able to predict dimensional accuracy changes and could be used in the future to improve dimensional control before an AM build.

Acknowledgements

This work would not have been possible without the contributions of several individuals. We would like to thank Naval Air Systems Command personnel Dr. Venkat Manivannan, Mr. John Schmelzle, and Mr. Eric Kline for their contributions. We would also like to thank Mr. Michael Geyer, Ms. Gabrielle Gunderman, and Mr. Mason Jacoby from ARL Penn State for their efforts designing, measuring, and recording data.

This material is based upon work supported by the Naval Air Systems Command (NAVAIR) under Contract No. N00024-12-D-6404, Delivery Order 0321. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Naval Air Systems Command (NAVAIR).

References

[1] Campbell, I., Bourell, D., and Gibson, I., 2012, "Additive Manufacturing: Rapid Prototyping Comes of Age," *Rapid Prototyping J.*, 18(4), 255–258.

[2] Frazier, W. E., 2014, "Metal Additive Manufacturing: A Review," *Journal of Materials Engineering and Performance*, Volume 23, Issue 6, 1917-1928.

[3] McClelland, M. J., 2016, "'Additive is not an Island' – A Renishaw Solution Approach to the Control of AM Part Quality," *ASPE 2016 Summer Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing Proceedings*, Volume 64, 33-37

[4] ASTM F2924-14 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion, ASTM International, West Conshohocken, PA, 2014, http://dx.doi.org/10.1520/F2924

[5] Datasheet: EOS M 290. 04/2014. EOS GmbH. 17 Jul 2016. http://www.eos.info/m-solutions/download/datasheet_EOSINT_M290.pdf

[6] Datasheet: EOS Titanium Ti64. 05/2014. EOS GmbH. 17 Jul 2016. http://www.eos.info/fe8d0271508e1e03

[7] Mitchell, W.F., Reutzel, E.W, Merdes, T.A., Lang, D.C, 2016, "Dimensional Accuracy and Machine Variability of Titanium Parts Manufactured using the EOS Direct Metal Laser Sintered (DMLS) Process," *ASPE 2016 Summer Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing Proceedings*, Volume 64, 211-215

[8] Land, W., II., 2014, "Effective Calibration and Implementation of Galvanometer Scanners as Applied to Direct Metal Laser Sintering," *ASPE 2014 Spring Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing Proceedings*, Volume 57, 151-156

[9] Moylan, S., Slotwinski, J., Cooke, A., Jurrens, K., Donmez, M.A., 2014, "An Additive Manufacturing Test Artifact," *Journal of Research of the National Institute of Standards and Technology*, Volume 119.17, 429-459