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Measuring the Geometric Accuracy of CNC End Mill Manufacturing Process.

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Measuring the Geometric Accuracy of CNC End Mill Manufacturing Process.

by

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Abstract:

This paper presents a method and analysis for determining the geometric accuracy of CNC milling machines. The method measures the accuracy of five basic geometric values: straightness, circularity, size, angularity, and position. Tolerance prediction models are found using statistical analysis. The tolerance prediction models are used to find more complex tolerance values. The results of the paper will allow manufactures to measure the actual tolerance capabilities of their machines and no longer rely on guess work. The method and analysis can also be applied to other machining processes.

Introduction:

Until the twentieth century, the relationship between the designer and manufacturer has been very close. The designer would explain their design and how parts should fit together. The manufacturer, usually a skilled craftsman, would make the parts and refine them until they fit. Today however, designers and manufacturers are spread out all over the world. Designers need to be able to clearly and effectively convey design intent to a manufacturer even if they do not speak the same verbal language. On the other hand, manufacturers also need to tell the designer the capabilities of their manufacturing processes.

GDT is great for designers to communicate with manufacturers. GDT communicates how parts will be used by defining simple, geometric volumes [1, 3].

PCS COMPANY
www.pcs-company.com

STANDARD MACHINING TOLERANCES

PCS Company machining is performed to the tolerances stated below.

Should tighter tolerances be necessary submit requests for review.

Note: Unless otherwise noted on customer supplied final CAD drawings, and in writing on quote request, stated tolerances will apply. All Dimensions are in Inches

FINISHED INSERT POCKETS (MILLED):

Length and Width = (+.002/-0.000)

Parallel to bottom of plate = .001 per 8 inches

Position to Leader Pins and or Guide Bushings = (+/- .002)

Taper (±.0005) on plates or assemblies with thicknesses ≤ 4.000

Taper (±.001) on plates or assemblies with thicknesses > 4.000

Depth = (+0.000/-0.002) measured from parting line

Figure 1: This is an example of traditional coordinate tolerancing.

However, GDT is currently a one-way conversation. Most manufacturers cannot tell the designers what tolerance levels they can produce for each GDT feature. A manufacturer might provide a tolerance standard based on traditional coordinate dimensioning system for some manufacturing processes. After receiving the designs, the manufacturer then quotes a price based on how much time and resources it will take to make the part. If the manufacturer thinks that they will need advance processes to produce the requested tolerance, they will charge more money per part.

One of the most common manufacturing processes is CNC milling. CNC milling is a subtractive manufacturing process. The manufacturer starts with a block of material and removes material with the mill to form the part. CNC milling has a good balance between cost and accuracy. Unfortunately, manufactures usually determine their machining tolerances based on experience rather than testing.

The goal of this research is to determine the GDT values that a CNC mill can produce. If the GDT values for individual machines can be determined, then manufacturers can be confident in producing a higher level of accuracy. A manufacturer will charge much less if a part can be manufactured perfectly every time on a single machine. This will remove the need for large price safety factors by reducing the uncertainty of manufacturing. A designer could also avoid extra manufacturing processes by designing within the tolerances of a CNC mill.

Methods:

1. Part Design

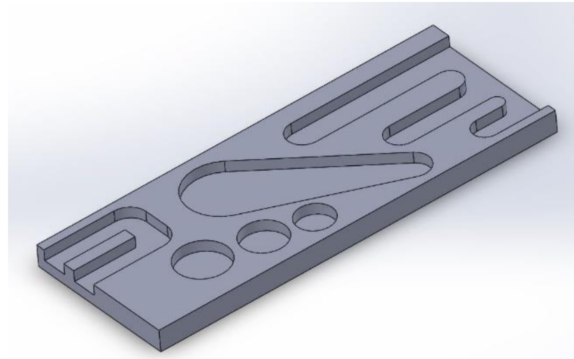

Figure 2: This is a SolidWorks model of the machined part.

A machined part was designed to have multiple straight edges, circles, features of size, and angles. The stock part is a 6061-T6 extruded aluminum block. The dimensions are 0.75x4x9 inches. The part was also designed to be made with only one end mill size. Multiple tools would increase time and cost to produce the part. To save more time, the part only requires one clamping position.

2. Machining

Figure 3: This is a photo of the machined part.

The part model was then imported into Mastercam to generate the G-codes. Dynamic 2D milling tool path was used for all features in the part. The part was manufactured in the Haas TM-1P CNC milling machine in the PSU machine shop. No finishing cuts were used for the tool path. A 3/8-inch end mill was used to cut the features. Spindle speed was set to 5000 RPM and very light cuts were used for each layer. Each depth of cut was a max of 0.075 inches. This made the total machining time over 2 hours. However, the amount of tool wear was extremely minimal. No post processing was performed on the machined part.

3. Measuring

The part dimensions were measured on a Tesa Micro-hite coordinate measurement machine (CMM). Eight features of straightness, circularity, size, angularity and position were measured. For location measurements, sides 10 and 6 were chosen as the datums.

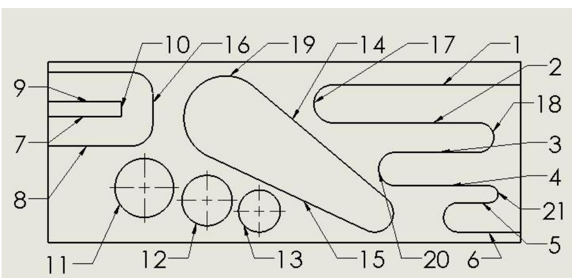

Figure 4: The measured features are labeled with numbers.

Results:

Table 1: This table shows the tolerance statistics for each measured tolerance.

Tolerance (mm)	Average	Max	Min	Standard Deviation
Straightness	0.005	0.008	0.003	0.002
Circularity	0.006	0.008	0.003	0.002
Size	-0.012	-0.007	-0.021	0.005
Orientation	0.004	0.013	-0.003	0.005
Position	0.030	0.056	0.017	0.012

Straightness:

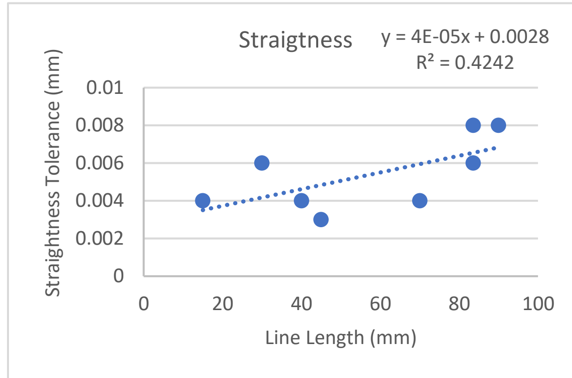

Figure 5: This graph shows the measured straightness tolerance and best fit line.

The CNC mill produced very straight lines with precise tolerance. The average straightness tolerance was only 5 microns. The tolerance increased as the size of the feature increased. A longer measured line had a larger tolerance. The R-squared value for the best fit line was 0.4242.

Circularity:

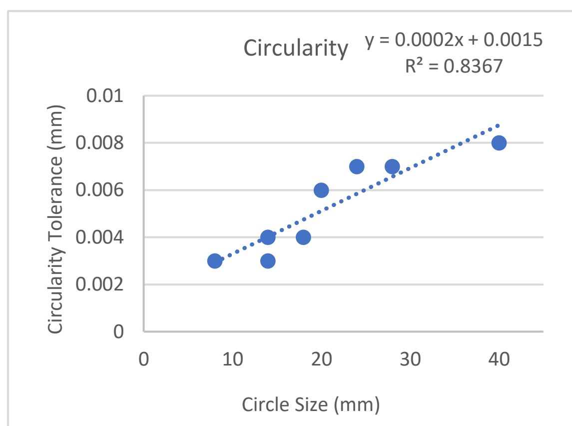

Figure 6: This graph shows the measured circularity tolerance and best fit line.

The circles had very similar tolerance characteristics as the lines. They were very precise and the tolerance increased as the size of the circles increased. The correlation between the size and tolerance was much stronger as the R-squared value was 0.8367.

Size:

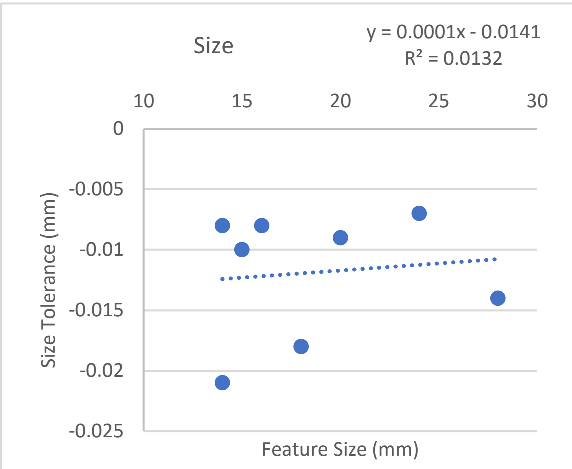

Figure 7: This graph shows the measured size tolerance and best fit line.

The FOS that were measured in this research were circles, rails, and slots. The tolerance for FOS were about twice as large as the straightness and circularity tolerance. The average tolerance for FOS was -12 microns. No correlation was found between the size of a feature and the tolerance. The R-squared value for the best fit line was 0.0132.

Angularity:

Angularity was very similar to FOS in tolerance. While the average was closer to zero than the average of FOS, the standard deviation was the same. Once again, there did not seem to be any correlation between the angle and the tolerance value. The R-squared value for the best fit line was 0.0361.

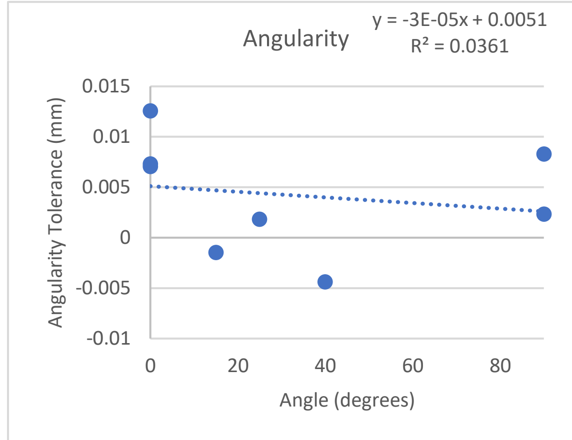

Figure 8: This graph shows the measured angularity tolerance and best fit line.

Position:

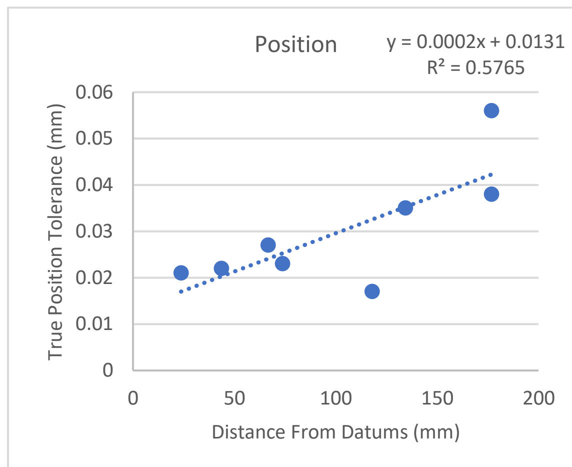

Figure 9: This graph shows the measured position tolerance and best fit line.

Position had the largest tolerance value out of all the measured tolerances. It had both the highest average and standard deviation. The amount of tolerance did correlate to the distance from the datums. The R-squared value was 0.5765 for the best fit line.

Discussion:

Toolpath Distance:

The straightness and circularity seemed to be very similar in tolerance average, range, and standard deviation. However, the slope of the models for straightness and circularity were different. When the circularity characteristic length was converted from the diameter of the circle to the circumference of the circle, the slopes lined up very well. The common factor between the circumference and the line length is the toolpath distance traveled by the end mill.

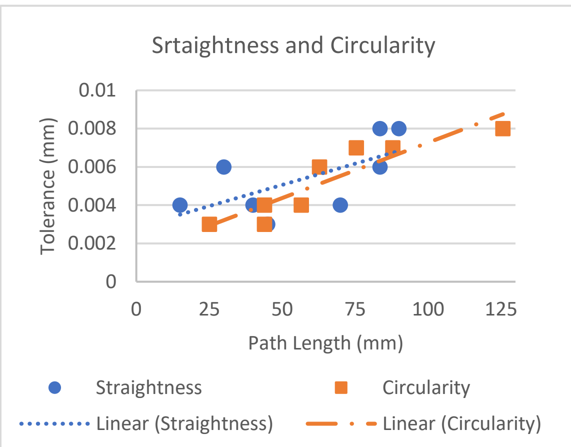

Figure 10 This graph demonstrates the similarity between the straightness and circularity models.

Because the toolpath distance seems to equally affect straightness and circularity, the data was combined to form a single model for straightness and circularity. This increases the sample size of the model and reduces uncertainty. It also simplifies the equations for finding the advanced GDT values.

Tolerance Prediction Model Statistics:

To find the upper and lower tolerance limit predictions for each measured tolerance, the following equations were used [1]:

$$T = \pm t_{n-1} s \sqrt{1 + \frac{1}{n}} \quad (1)$$

$$T = \pm t_{n-2} s \sqrt{1 + h_i} \quad (2)$$

$$h_i = \frac{1}{n} + \frac{(X - \overline{X})^2}{\sum (X_i - \overline{X})^2} \quad (3)$$

Eq. 1 finds the margin of error for the tolerance confidence interval of an independent variable. The FOS and angularity tolerances are both independent. Eq. 2 finds the margin of error for the tolerance confidence interval of a dependent variable. Straightness and circularity are both dependent on the toolpath length, while the position is dependent on the distance from the datums.

Eq. 3 accounts for potential uncertainty in the model if the predictor value is outside of the measured value range. The margin of error is then added to the model for the upper tolerance prediction and subtracted from the model for the lower tolerance prediction. For straightness, circularity and position, the lower tolerance predation is not useful for GDT and therefore is not calculated.

Tolerance Predictions:

All predictions were calculated at a 99.9% confidence level. This means that 99.9% of all the features produced on the Haas TM-1P CNC milling machine in the PSU machine shop will be more precise than the tolerance prediction lines.

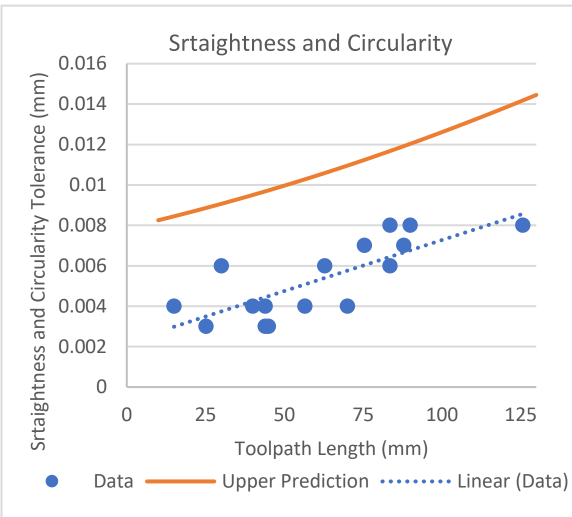

Figure 11: This graph shows the upper tolerance prediction model for straightness and circularity.

For example, using the graph, the straightness tolerance of a line that is 40 mm long would be under 9.5 microns. For a circle, one would multiply the diameter of the circle by π to find the circumference of the circle. A circle with a diameter of 20 mm would have a circularity tolerance under 10.5 microns.

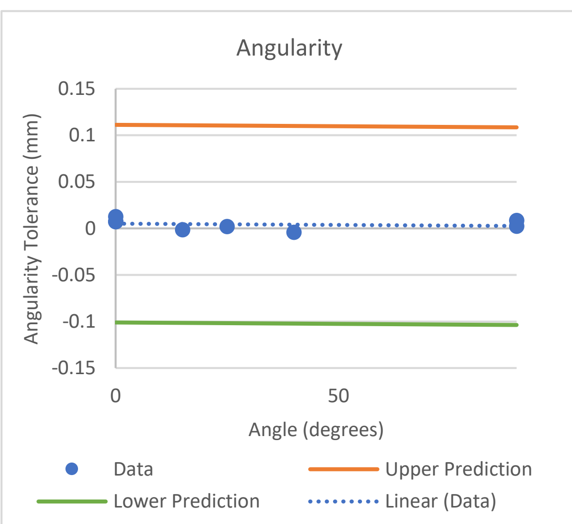

Figure 12: This graph shows the upper and lower tolerance prediction model for angularity.

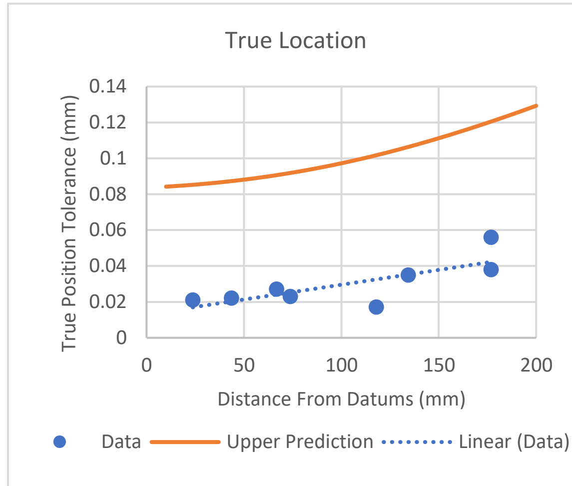

Figure 13: This graph shows the upper tolerance prediction model for position.

Using all of the tolerance prediction models, a GDT callout calculator was created based on previous models used for finding the GDT values for 3D printers [1]. The models were simplified slighlty because straightness and ciccularity share the same tolerance prediction model. The calculator allows a designer to know the tolerance value that can be produced for a given GDT callout and feature dimentions on a specific endmill. A machine shop could send this GDT calculator, that is calibbrated to their machines to designers to indicate the tolerance level that they can producing.

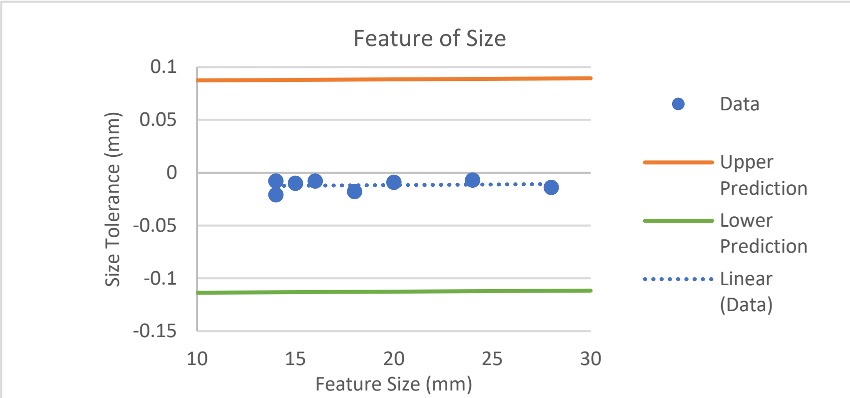

Figure 14: This is a graph that shows the upper and lower tolerance prediction model for features of size.

Table 2: This table is an example of the GDT calculator. Dimensions are in millimeters and angles are in degrees.

GDT Callouts Calculator	User Input 1	User Input 2	User Input 3	Tolerance Upper	Tolerance Lower
Straightness (line length)	40			0.009503243	
Circularity (diameter)	20			0.010588001	
Flatness (diagonal length)	80			0.011482635	
Cylindricity (diameter, axis depth)	10	30		0.018191009	
Feature of Size (feature size)	20			0.088359091	-0.112559091
Perpendicularity-Axes (axis length)	50			0.012127172	
Perpendicularity-Surface (projection length)	75			0.013650347	
Parallelism-Axes (axis length)	30			0.011082503	
Parallelism-Surface (diagonal length)	60			0.012771805	
Angularity-Surface (diagonal length, projected length, angle)	20	25	45	0.010595159	
Profile of a Line (largest profile length)	25			0.088859091	-0.112059091
Profile of a Line with Datum (largest profile length, distance from datum)	10	20		0.172316103	-0.028602078
Profile of a Surface (largest profile length, profile depth)	25	30		0.097924246	-0.102993935
Profile of a Surface with Datum (largest profile length, distance from datum, profile depth)	10	20	30	0.181381259	-0.019536923
Runout (diameter, distance from datum)	40	20		0.099132121	
Total Runout (diameter, length from end to end, distance to datum)	35	60	100	0.120909357	
True Position (distance to datum)	42			0.0871312	

Conclusion:

In this paper, the GDT tolerance capabilities, that a specific end mill machine can produce, have been determined. Using the methods and analysis presented in this paper, anyone can find the GDT values for their own CNC endmill. The process has already been applied to other manufacturing processes such as 3D printing [1, 2]. Future research could focus on verifying the models used to calculate the more complex GDT callouts. This method should also be applied to lathe machining, laser cutting, broaching, grinding boring, and honing.

Citations:

Citation 1

F. Etesami and T. Griffin, 2013 "Characterizing the Accuracy of FDM Rapid Prototyping Machines for Machine Design Applications", *Syst. Des.*, vol. 12, p. V012T13A060

Citation 2

K. Kempen, F. Welkenhuyzen, J. Qian, and J. Kruth, 2014, "Dimensional Accuracy of Internal Channels in SLM Produced Parts," 2014 ASPE Spring Topical Meeting: Dimensional Accuracy and Surface Finish in Additive Manufacturing

Citation 3

P. Witherell, G. Herron, and G. Ameta 2016 "Towards Annotations and Product Definitions for Additive Manufacturing." *14th CIRP Conference on Computer Aided Tolerancing (CAT), Procedia CIRP*. Vol. 43. 339–344.