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Dimensional Accuracy for Additive Manufacturing

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Abstract. *The Additive Manufacturing (AM) processes were developed to be a faster and easy way to prototype designs. Based on recent studies the layered based techniques are starting to become more predictable and their use for end parts is being developed along the academic researches and also being used in the industry for low volume productions. Nowadays the main goal of many studies is to provide knowledge of the process, to implement quality control of pieces and develop guidelines for design with additive manufacturing technologies. One of the issues in using additive manufacturing for final user products is the lack of control over dimensional accuracy. The standards for Geometric Dimensioning and Tolerancing (GD&T) are focused on materials that present uniformity of characteristics and based on bi-dimensional annotations, wich is not feasible to AM. This paper presents an evaluation of GD&T techniques, its limitations for AM and the proposed works to solve it. The study also presents an evaluation of accuracy for 3D printers, using an approach based on former studies for printers evaluation and analyzing the geometric accuracy for different process characteristics. Statistical methods are used to evaluate the influence of manufacturing parameters for AM in the final piece geometry, in an attempt to optimize settings according to the dimension tolerance obtained in each test specimen*

Keywords: Additive Manufacturing, Geometric Dimensioning and Tolerances, Design for Additive Manufacturing

1. INTRODUCTION

The Geometric Dimensioning and Tolerancing (GD&T) are regulated by the ASME Y14.5:2018 and ISO 1101:2017 (E) standards, the standards regulate the references, terminology, definition, symbolism, and indications for product specifications. The indications presented in those standards are well known for designers and manufacturers and they guide the manufacturing processes. With the dissemination of digital manufacturing processes, based on 3D models, these same practices are insufficient for providing the unambiguous definitions necessary to guide how an Additive Manufacturing (AM) part is manufactured and inspected (Witherell *et al.*, 2016). The indications are based on human interpretations for manufacturing and quality control of pieces, but they do not present data for machine and software's interpretation.

Series of studies introduce new ways to present GD&T, based on virtual models and readable data. Those studies show that regular GD&T guidelines and standards can be improved to suit new manufacturing processes, specially AM processes. The most relevant method for GD&T representations is Model-Based Definition (Witherell *et al.*, 2016),

The transfer of GD&T information from conventional processes to AM processes involves more than just a creation of new references and tolerances analysis. It is necessary to study the main process parameters in the final piece, such as layer thickness, build direction and location, support structures, heterogeneous materials and scan/track directions (Ameta *et al.*, 2015).

With the searching for the influences and new ways to present model data, another issue in AM processes involves the printer resolution and repeatability, those parameters will be evaluated for Fused Deposition Modelling (FDM). A commercial printer from XYZprinting, Inc., the DaVinci 1.0 Pro was used to print the test specimens.

2. GD&T IN ADDITIVE MANUFACTURING

According to Ameta *et al.* (2016), in a project, the definition for tolerances is based on a trade-off between tight tolerances, which usually result in better performance of the assembly, and loose tolerances, which result in lower cost to manufacture the individual parts but also in a lower probability of proper assembly and/or function. The ISO 1101 presents in its first basic concept that the geometrical tolerances are based on functional requirements, and the manufacturing process also influences it. Based on this statement, it is expected that the rules are applied to any manufacturing process, being the capacity of the process the limiting for its selection for the manufacturing of a specific piece.

The selection of manufacturing process is based on the evaluation of tolerances requirements, the designed tolerances need to be adapted to the manufacturing process. This analysis for the final tolerance at the manufactured piece based

on the manufacturing steps is called tolerance transfer. At tolerance transfer, the tolerance specifications and the steps of manufacturing are analyzed together, each step can create new data that needs to be referenced accordingly to the designed ones. At Ameta *et al.* (2016) the authors present an evaluation of the challenges for tolerance transfer in AM processes. Reaching the conclusion that for proper tolerance transfer based on AM technologies, the process planner needs to consider design intent, build direction process variation and data references.

The first requirement for manufacturing pieces trough AM technologies is the development of a 3D model. Based on the ISO/ASTM 52900:2015, that defines the terminology for AM, the STL file describes the surface geometry of an object as a tessellation of triangles used to communicate 3D geometries to machines in order to build physical parts. The building process is based on the layers generated by the slicing process and the material addition is controlled by G-codes generated directly from it. In that way, the AM technologies present model-driven manufacturing processes and the role of drawings in the life-cycle of products diminishes. Witherell *et al.* (2016) state that it is critical that the 3D model becomes the master data definition for a product produced with AM.

Since the representation of tolerances is based on drawings and symbols for human interpretation and the AM processes is based on model files, the traditional GD&T needs to be altered to follow the digital manufacturing needs. To be applicable for AM processes the GD&T symbolism should be presented with readable data for computer-aided technologies, being based on the virtual model and not in human interpretations. A lot of effort is being made by researchers and standard associations to define proper representations for GD&T based on the part digital model, as represented by the ASTM F42 Committee for AM, ASME Y14 series committees and ISO TC 213 committees.

Witherell *et al.* (2016) introduce the concepts of Model-Based Engineering (MBE) and Model-Based Definition (MBD), where the product life-cycle data is presented in files related to the digital modeling of the piece. The Product and Manufacturing Information (PMI) are presented in computer-aided technologies to communicate the design intent. Feeney *et al.* (2015) also studied about the MBE, the authors reviewed the ISO STEP AP 242 standard, concluding that it contains several standardized information models that will enable 3D model-based engineering containing elements for human interpretations and machine-readable data, thereby satisfying some of the key requirements for a model-based enterprise. Both studies show that the MBD is a viable way to summarize all the information needed for a piece manufacturing, being able to be used for conventional processes and also digital manufacturing processes.

Sarigecili *et al.* (2014) developed a schematic interpretation process using the Standard for the Exchange of Product (STEP) model data to map a product's GD&T information and translate it content from STEP to OWL-based (Web Ontology Language) models and showed how this ontology-based model could be used for interpreting the semantics of GD&T needed for tolerance analysis.

The development of in-situ measurement techniques is discussed at Everton *et al.* (2016) and Mazumder (2015) for powder bed fusion and direct metal deposition for metal additive technologies. The industrial pull for measuring techniques while the manufacturing process is occurring in a way to prevent material discontinuities is also presented in the work, demonstrating again the need for solutions in the AM area regarding quality control. Hu and Mahadevan (2017) also researched in the metal additive area, presenting the current status and needs for uncertainty quantification and management. The authors investigated the developments for uncertainty and proposed an overall uncertainty quantification and management framework of the AM process. They reached the conclusion that the main developments need to be made in experiment design for model calibration and validation, and optimization under uncertainty of the AM process.

Regarding the influence of process parameters in uncertainties, Moges *et al.* (2019) studied the sources of inaccuracies for laser powder bed techniques in metal AM techniques. Analyzing the current models for describing the fusion process and also the influence of layer thickness, laser power, laser scan speed, absorptivity and temperature dependent properties at the tolerance of metal parts layered manufactured. In the polymers area, Turner and Gold (2015) studied the dimensional accuracy, resolution and surface roughness for FDM processes, According to the authors, the maximum feature resolution that is typically achievable on extrusion AM systems is on the order of 100 μm. Both resolution and dimensional accuracy are strongly dependent upon system parameters, in particular, ability to accurately regulate the flow rate of material trough the print nozzle. While there is a good basic understanding of how the parameters influencing resolution and accuracy, this needs to be translated to improved control algorithms, process monitoring capabilities and process and feedstock specifications.

3. FDM PROCESS

The FDM (also referred as Fused Filament Fabrication (FFF)) AM process is based on heating a filament feedstock to a semi-liquid state, pushing it against a heated nozzle and controlling the extrusion of the material through the nozzle. Most common feedstock filament materials include amorphous thermoplastics, in particular, acrylonitrile butadiene styrene (ABS) and the biodegradable polylactic acid (PLA) (Turner and Gold, 2015). Figure 1 presents an illustration for the process.

The FDM process have become the most popular AM technique along the years, its popularity came with two events that happened almost simultaneously, the expiration from the patents owned by Stratasys Corporation and the rising of self-replicate 3D printers, started with the RepRap project in 2005 and followed by commercial brands, such as Makerbot,
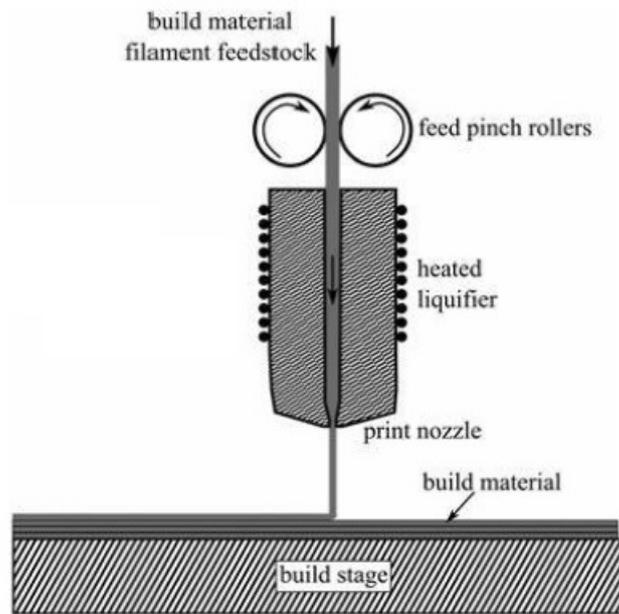
Figure 1. FDM process illustration (Turner and Gold, 2015)

Ultimaker and Prusa (Minetola and Galati, 2018).

The manufacturing parameters influence the dimensional accuracy for printed parts, the main investigated properties are build direction, layer thickness, printing speed, raster angle and extrusion temperatures (Qattawi *et al.*, 2017).

4. EXPERIMENT

4.1 Objectives

According to Montgomery and Runger (2010) statistical methods are an important tool to provide both descriptive and analytical methods for dealing with the variability in observed data. In order to understand the effect of different variables on the dimensions and tolerances for the FDM process, a experimental planning was designed and analysed according to the theory of contrast, considering the variables and all interactions in pairs. The experiment will evaluate the influence of five variables from the FDM technology. The analysed variables are printing speed, layer height, extruder temperature, infill percentage and number of solid layers.

The printing speed is denoted by the movement speed of the carriage with the extrusion system. The carriage is controlled by electric motors and represent the deposition paths during printing. The layer thickness is represented by the height of the layers, translating to machine dynamics it represents the step in height used for each slice of the piece. The extruder temperature is the settled temperature for the printing nozzle during the manufacturing process, normally this setting is chosen according to the material thermal properties. The infill percentage is defined as the percentage of material at the internal volume of the printed piece, without considering the walls of it. The infill always present a pattern along the internal volume, for this experiment the honeycomb pattern was used in all specimens. The external features, such as side walls, bottom, and top surfaces are manufactured with solid layers, to ensure some stiffness to the model, the number of solid layers will be the last property evaluated in the study.

4.2 Experimental Planning

The 3D printing variables analyzed in this paper are presented in Tab. 1. Each one has two values tested, - and +. This notation was used because of the type of experimental design chosen for this work, the factorial design.

The tests were planned based on a factorial design of two levels and five factors, resulting in 32 experiments. Due to the high number of samples needed and the emphasis on factor screening presented by this study, it was decided to adopt a fractional factorial design, shown in Tab. 2 with its principal fraction, thus the defining relation is I=ABCDE (Montgomery and Runger, 2010). The choice to adopt a fractional design means that some aliased properties are present in the study. This property implies that the calculated effect for a factor will be in reality a addition of effects, from the factor it self and it aliased. Using the defining relation is possible to achieve all aliases factors, the factor or interaction multiplied by the defining relation will give it aliased factor. The aliased property is extended for all interactions presented in the experimental planning, the design resolution is the property that defines the interactions and its aliased. This study

Table 1. 3D printing variables.

Index	Variable	Value	
		-	+
A	Printing Speed [mm/s]	40	50
B	Layer Height [mm]	0.15	0.3
C	Extruder Temperature [ºC]	235	245
D	Infill Percentage [%]	15	25
E	Number of Solid Layers	3	6

presents a resolution V in which no main effect or two-factor interaction is aliased with any other main effect or two-factor interaction, but two factor interactions are aliased with three-factor interactions (Montgomery and Runger, 2010).

Factor E (Number of solid layers) was defined by the interaction ABCD, reducing by half the number of tests. The definition means that the factor E is denoted by a multiplication of the signs of A, B, C and D. Hence its estimate value is not changed if we consider that the interaction between four factor have small or none effect at the result.

Table 2. Fractional factorial design (2^{5-1})

Run Number	A	B	C	D	E (ABCD)
1	-	-	-	-	+
2	+	-	-	-	-
3	-	+	-	-	-
4	+	+	-	-	+
5	-	-	+	-	-
6	+	-	+	-	+
7	-	+	+	-	+
8	+	+	+	-	-
9	-	-	-	+	-
10	+	-	-	+	+
11	-	+	-	+	+
12	+	+	-	+	-
13	-	-	+	+	+
14	+	-	+	+	-
15	-	+	+	+	-
16	+	+	+	+	+

4.3 Test Specimens

The definition of the test specimens format was mainly based on (Moylan *et al.*, 2014), in the study, the authors evaluated several artifacts used to evaluate machines and technologies performances. Concentrating on the GD&T aspects, an evaluation of the test specimen proposed by Moylan *et al.* (2014) was performed. The proposed artifact was used to evaluate several features, including tolerances, the authors highlighted thirteen characteristics related to GD&T. To appraise this experiment design and the methodology applied, a simpler version was conceived to investigate less characteristics and with complex shapes, like small features, being ignored at this point. For the development the circular features were used because they would present the worst case for manufacturing, when the most motors are operating. The final specimen is presented in Fig.2.

4.4 Methodology

The test specimens were manufactured using the same printer and same settings, the differences between each sample are the factors presented at the experimental design. To reduce the influence of external factors the order for the experiments was randomized and all 3D parts were printed in the same machine, the DaVinci 1.0 Pro from XYZprinting, Inc. The printer uses FDM technology, with a building volume of 200 mm x 200 mm x 200 mm, layer resolution from 20 to 400 µm, X/Y position precision of 12.5 µm and Z position precision of 0.4 µm. The material used for the parts was ABS filament with 1.75 mm of nominal diameter and yellow pigmentation, to prevent external influences all the pieces were manufactured with the same cartridge and in sequence. The steps for each specimen manufacturing were: 1) clean
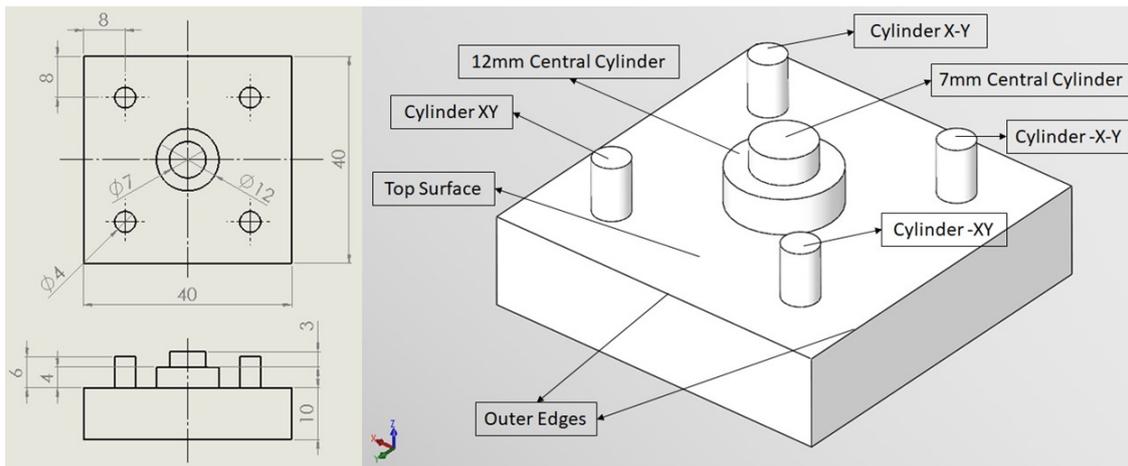
Figure 2. Test Specimen

the printing bed, 2) apply a thin layer of glue on the building platform, 3) upload the codes for manufacturing from the computer to the machine trough its commercial software, 4) print the specimen, 5) remove the piece from the printing bed with a spatula, and 6) measure.

All the measures were made using an analog vernier caliper, witch has a resolution of 0.05 mm. The test specimens manufactured were compared against the original CAD model in the dimensions presented in Tab.3. The dimensions measured at the test specimen represents ways to put to the proof the characteristics available for control in GD&T standards, using at least one characteristic per type of tolerance presented in ISO 1101:2017 (E).

Table 3. Investigated characteristics

Investigated Characteristic	Analysed Feature	Analysed Dimension
Straight features	Outer edges	Outer edge length
Circular or arced features	Central cylinders	Circularity for central cylinders
Concentric circles	Central cylinders	Central revolution axis
Bosses	4 mm pins	Diameters for the 4mm pins
Location	4 mm pins and central cylinders	Center point location
Alignment errors	Top surface	Four distinct points in top surface
Errors in beam size	4 mm pins	Cylinders XY, -XY, X-Y and -X-Y heights

To compare the measurements from the test specimens and the CAD model, several distances had to be taken from each piece. The method used to obtain the final value for each desired characteristic is presented at Tab.4. The true values described at the methods are obtained from the CAD model as presented in Fig.2.

4.5 Identifying the impact of variables

To identify the main factors the sparsity of effects principle was applied, considering that the system is dominated by the main effects and order two interactions. Given that the experiment has sixteen samples to be manufactured and measured, a simple replication was performed for each specimen.

To numerically obtain the impact of each variables a analysis of contrast was performed. The contrast method is defined by (Montgomery and Runger, 2010) as a rough but very effective multiple comparison technique. As result for the methodology we obtain effects for each factor and also the order two interactions. The values for the effects obtained by the contrast method represent the multiple regression model coefficients multiplied by two.

The second method is a graphical analysis, the effects obtained in the first method are compared to each other to identify which are the most significant. The effects that are negligible are normally distributed, with mean zero and will tend to fall along a straight line on this plot, whereas significant effects will have nonzero means and will not lie along the straight line (Montgomery and Runger, 2010).

5. RESULTS AND DISCUSSION

For the first analysis, the effects calculated using the contrast method are shown in Tab.5. The effects for factors present small values because the variations in responses are from the first decimal order, causing a small difference between each response. Even with the small values presented it is possible to identify factors with higher impacts for each experiment.

Table 4. Measurements

Analysed Dimension	Measurement Description
Outer edge length	Sum up the length of the four outer edges from base, divided by 4 to get the mean value as response.
Circularity for central cylinders	Measurement of the diameter for the central cylinders taken in 4 different directions (X, Y, 45o+ and 45o-), divided by four and divided by the true value. The mean for the two central cylinders are taken to make a unique answer.
Central revolution axis	Measurement of the distances from the border of the test piece to the border of the cylinder. The distance was added with the radius of the cylinder, found with the measurements for the last feature. The values for X and Y were added and divided by two, the mean was after divided by 20 to put it as a value round 1.
Diameters for the 4mm pins	Measurement of the 4 diameters in two directions divided by 2 to get the mean value for each feature and later divided by 4 to get a mean value for the piece as result.
Center point location	Measurement of the difference between the pin and the walls in four directions (X+, X-, Y+, Y-), the measurement for the center points were based in the diameters calculated in the previous analysis. The location error was calculated dividing the experimental value for the coordinates by the true value.
Four distinct points in top surface	The height of each corner, denoted by the lower and higher values in the directions X and Y, was measured and subtracted by the true value individually, the final result was the subtraction of the four values encountered.
Cylinders XY, -XY, X-Y and -X-Y heights	Measured the four pins heights, summed up and divided by four to get the mean value.

Table 5. Effects of factors

Variable	Straight Features	Circular or arced features	Concentric circles	Bosses	Location	Alignment errors	Errors in beam size
Mean	40,0953	1,5317	0,9974	4,1281	0,9999	0,09375	5,9773
Temperature (A)	0,0406	0,0083	-0,0023	0,1109	0,0039	-0,175	-0,0109
Layer Height (B)	0,2219	0,0310	0,0012	0,1469	0,0025	-0,4375	0,0828
Solid Layers (C)	0,0313	0,0140	0,0008	0,0500	-0,0013	-0,2375	-0,0609
Infill Percentage (D)	-0,0406	0,0003	-0,0004	-0,0656	-0,0021	0,65	0,0266
Speed (E)	0,0063	0,0171	0,0023	0,1422	0,0013	0,1875	-0,0453
AB	0,0156	0,0026	0,0012	0,0609	0,0016	-0,225	0,0172
AC	-0,0125	-0,0062	0,0017	-0,0109	0,0012	-0,175	0,0297
AD	0,0219	0,0147	0,0017	0,0266	0,0021	-0,0375	-0,0391
AE	0,0062	0,0100	0,0008	0,0375	-0,0032	-0,225	-0,0109
BC	0,0062	-0,0043	-0,0010	0,0219	-0,0013	-0,1375	-0,0391
BD	-0,0156	0,0022	0,0019	0,0219	0,0006	0,175	-0,0453
BE	-0,0062	0,0034	0,0022	0,0391	0,0009	-0,5875	-0,0047
CD	-0,0250	-0,0056	0,0008	-0,0062	-0,0002	-0,175	0,0297
CE	0,0281	0,0010	0,0024	0,0109	0,0047	-0,2375	-0,1359
DE	-0,0187	-0,0019	-0,0013	-0,0172	-0,0012	0,25	-0,0234

Table 6. Factors with higher impacts

Response	High effect factors
Straight Features	Layer Height (B)
Circular or arced features	Layer Height (B)
Concentric Circles	CE, Speed (E), Temperature (A), BE
Bosses	Layer Height (B), Speed (E), Temperature (A)
Location	Temperature (A), AE
Alignment errors	Infill Percentage (D), BE
Errors in beam size	CE, Layer Height (B)

Considering the magnitude of the impacts the most relevant for each response are presented in Tab.6.

This method represent a numerical analysis for the experiment. It shows the direct relationship between the response and each factor, as lower the value is, the minor influence it has at the expected values. This analysis is absolute, and does not present a way to visualize the data or identifying the overall results or even identify outliers or bad data points. To complete the analysis the effects are plotted with the cumulative probability. To identify the differences for the average values and perform a screening of factors we identify as described in the last section. The plots for each analysis is presented in Fig.3 and Fig.4. The comparison between both results are presented in Tab 7.

The experimental method presented in this study was based on the necessity to discover the parameters that needs to be controlled to achieve best performances relative to aspects of GD&T. The characteristics investigated here are presented in standards and regulations, and the statistical analysis performed the screening of five factors that influences the FDM process according to the analysis of specific features. Since a experimental design was performed, the number of test specimens was already defined and even optimized using the fractional factorial design. The manufacturing of the test specimen took a considerable amount of time. Each test specimen was fabricated separately to avoid external factors of influence, so before and after each manufacturing there was a necessity to remove the piece and repeat all the process for the next one.

The part that took most time to be complete was measuring all the features analyzed, since the measuring method used for the study was analogical, each measuring had a time to be taken, considering method and reading. Even further, the FDM process can present some local errors, similar to deformed grains, that makes the readings inaccurate, each part that presented any failures like that had some loss in presenting the real value. The operator for the measures needed to choose between touch or not the defect with the probe from the vernier caliper, but this was overcome by the techniques to reach the value, described in Tab. 4, making operations to reach means or even normalized responses. The magnitude for the effects presented small values, but this is explained by the small difference between the values in responses, always with variations in decimal parts only, sometimes not even in the first decimal order. With that the factors are short in magnitude, but was still possible to distinguish differences in values and perform a screening of most important factors
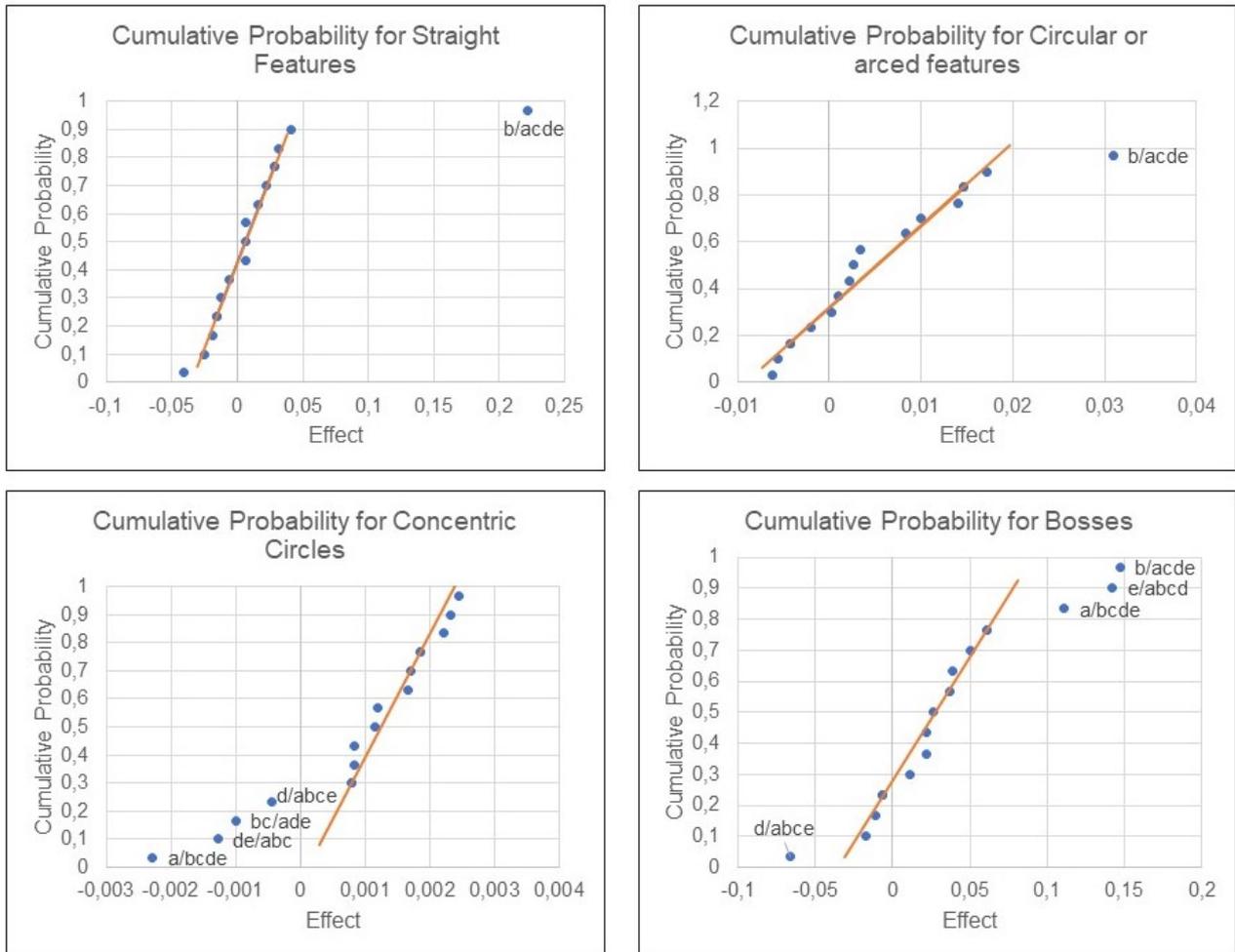
Figure 3. Graphical Analysis for Responses 1 to 4

for each characteristic. To overcome this the study could be made in a different scale, like changing from millimeters to micrometers.

The graphical analysis has also proven efficient, supplementing the contrast analysis with a qualitative test. The responses for each method are connected, since the plots are from the effects established at the contrast method with a statistical theory of cumulative probabilistic. As presented at results, both methods have intersections in the screening results. The final screening was performed as the factors presented in both methods. The most important factors were layer height and temperature, with four and three appearances as a factor with considerable influence, respectively. Others factors that were presented as considerable in one appearance were speed, infill percentage and the interaction of temperature with speed, layer height with speed and solid layers with speed. According to the analysis the factors that are most important to achieve good performances for GD&T parameters are the layer height and temperature. The feature that presented most factors with high influence was the analysis for bosses, that measured the diameters for the pins in the test specimen, this can be explained by the already presented difficult of consider or not the local defects.

6. FINAL CONSIDERATIONS

The GD&T field for AM is inefficient as presented nowadays, the digital manufacturing needs a reformulation for standards and quality assurance techniques. All the manufacturing processes data are already digital, without need for human interpretation for decision making or any intervention during fabrication. The quality management systems also needs to adapt to this new era of manufacturing, having less processes as human interpretative data or at least presuming a digital way to do it. As presented here, many studies are already trying to develop news methods and systems that manage to put all the information for quality control in digital data readable by machines, making possible a "real time" quality control. An automated inspection for the manufactured part could be used to generate a virtual model of the actual manufactured part. Managing to achieve a robust system to generate the virtual model make it possible to perform quality control over manufactured parts that could be used in-situ operation and to evaluate parts.

Table 7. Comparison between results

| Response	Screening for contrast analysis	Screening in graphical analysis
Straight Features	Layer Height (B)	Layer Height (B)
Circular or arced features	Layer Height (B)	Layer Height (B)
Concentric Circles	CE, Speed (E), Temperature (A), BE	Temperature (A), DE, BC, Infill Percentage (D)
Bosses	Layer Height (B), Speed (E), Temperature (A)	Infill Percentage (D), Layer Height (B), Speed (E), Temperature (A)
Location	Temperature (A), AE	AE, CE, Temperature (A)
Alignment errors	Infill Percentage (D), BE	Infill Percentage (D), BE
Errors in beam size	CE, Layer Height (B)	CE, Layer Height (B)
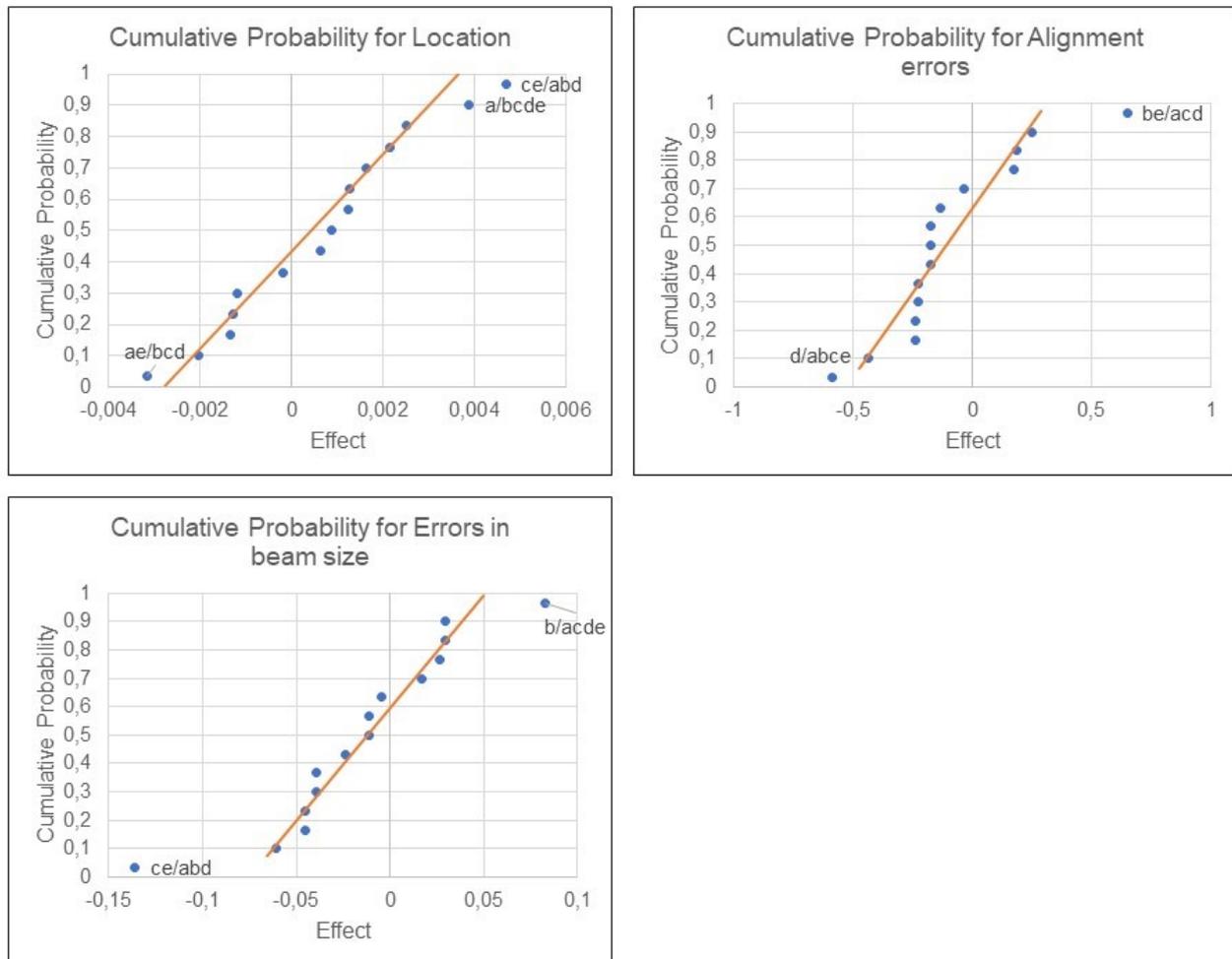
Figure 4. Graphical Analysis for Responses 5 to 7

To experiment the full potential for digital manufacturing processes and systems the GD&T standards regulators, such as ASME and ISO, are developing new standards to be released soon. For now only assumptions can be made about revisions, but the achievement of digital quality control is one of the concerns already discussed by its committees, specially the ones relative to additive manufacturing.

For further studies an investigation of layer height and temperature influences must be taken into account, like a surface responses, this experimental designs manage to find optimal regions of values for both factors and try to guarantee best performances regarding geometrical dimensions and tolerances. Considering the large number of manufacturing parameters in FDM process, another screening methodology should also be consider for further works, with parameters that were not presented in this study such as material, pigmentation, machine design, build platform temperature, among others. With the statistical theory is possible to present tolerance values for the FDM process and adapt guide lines for Design for AM regarding the GD&T. Analysing the process and with the experience from the authors the five analysed

parameters were pre-selected, but by any means are considered the most important parameters, neither for the process in general or the GD&T characteristics.

Adapting these study for other AM technologies is also another suggestion for further works, the process needs to be studied in a first moment to understand the parameters that influences the manufacturing and the screening technique can be applied to identify the most important and later try to find regions of optimization.

7. ACKNOWLEDGEMENTS

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