Title:
Application of Reference Part and Design of Experiments for Metrological Evaluation of AM Manufacturing Machine with FDM Technology

Authors:
Adão José Spíndola-Filho, spindola.arg@gmail.com, Universidade de Brasília - UnB
Antonio Piratelli-Filho, pirateli@unb.br, Universidade de Brasília - UnB
Rosenda Valdés Arencibia, arvaldes@mecanica.ufu.br, Universidade Federal de Uberlândia - UFU

Keywords:
Additive Manufacturing (AM), 3D Printing, Fractional Factorial Design, part tolerances.

DOI: 10.14733/cadconfP.2020.61-65

Introduction:
Additive manufacturing (AM) is one of the most widespread technologies today. Compared to traditional manufacturing by machining, there are some important advantages related to its characteristics of adding material. AM technology makes possible the manufacturing of parts having complex geometries, reducing material loss and costs. However, the available AM technologies still need to be evaluated when part tolerance limits are an important demand from designers [1-8].

Mahmood et al. (2016) verified through an experiment with three levels, that dimensional deviations increased when working with higher levels of extrusion speed, layer height and filling density, in addition to other variables. The authors used a 3D printer with FDM technology to analyze the dimensional and geometric deviations. They concluded that the size of the part, the extrusion temperature, the printing orientation and the layer height are factors that affect the dimensions and geometry of the parts. Lieneke et al. (2016) also assessed dimensional tolerances in the additive manufacturing process using FDM technology.

This paper presents a study related to the application of a reference part to evaluate AM manufacturing machines. The experimental work involved the part geometry definition and an investigation of the process variables by design of experiments. A Fractional Factorial Design was selected to investigate four variables: fill density, extrusion temperature, printing speed and layer height. The part was measured with a CMM and the dimensions, geometries and roughness of the manufactured surfaces were taken as reference to establish the AM machine performance.

Materials and Methods:
An AM machine, model Ender 3, with FDM (Fused Deposition Modeling) technology was used in the experimental investigation. A computer aided design (CAD) part was designed in Solid Edge software, having different shapes like cylinders, planes, half-sphere, freeform and rectangular rods, aiming to cover deviations like dimensional, geometric and roughness. Fig. 1 presents this artifact with respective geometries. The part maximum dimensions are 80 x 80 x 31 mm, (x, y, z). A polymeric ABS filament (Acrylonitrile Butadiene Styrene) was used to manufacture the parts.

An experimental design was generated to investigate the effect of the following factors over the dimensional, geometric and roughness deviations: fill density, extrusion temperature, printing speed and layer height. The 2^{4-1} fractional factorial design, with resolution IV and 8 runs, was used to carry out experiments without replication. This design is showed in tab. 1, having a defining relation equal to I = ABCD and generator D = ABC.

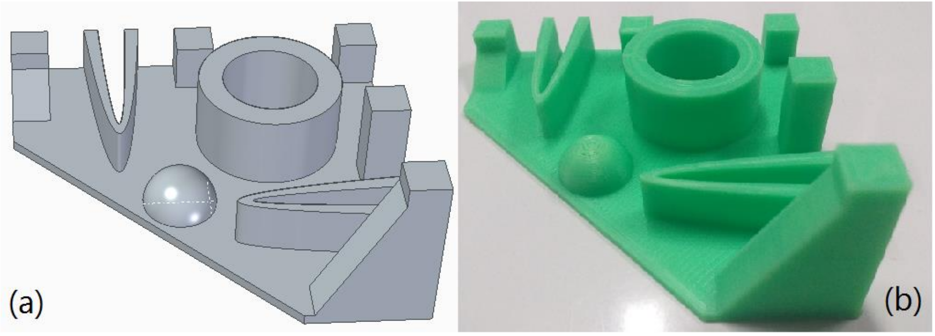

Fig. 1: Reference part (a) developed in CAD software and (b) manufactured in AM machine.

Runs (order)	*Fill Density (A)* (%)	*Extrusion Temperature (B)* (°C)	*Print Speed (C)* (mm/s)	*Layer Height (D)* (mm)
1 (4)	10	225	40	0.2
2 (5)	30	225	40	0.4
3 (8)	10	240	40	0.4
4 (7)	30	240	40	0.2
5 (3)	10	225	60	0.4
6 (1)	30	225	60	0.2
7 (6)	10	240	60	0.2
8 (2)	30	240	60	0.4

Tab. 1: Fractional factorial Design 2^{4-1}.

A Coordinate Measuring Machine (CMM), Mitutoyo QM-Measure 353 with touch trigger probe, and a roughness tester, Mitutoyo SJ-201, were used to perform the measurements of the geometries and the roughness, respectively. These instruments are presented in Fig. 2. The software MCOSMOS was used to determine the dimensional deviations (length, diameter), geometric form deviations (flatness, cylindricity, sphericity), geometric orientation deviations (perpendicularity, parallelism and angularity) and geometric location deviation (concentricity and coaxiality) were determined. The surface roughness and the printing time were also measured. Five measurements were taken of each characteristic investigated. The most significant variables were determined by Analysis of Variance (ANOVA), Normal Probability Plots (NPP) of the effects and NPP of residuals to verify the assumptions of residuals Normally, independent and identically distributed (NIID), based on results of design of experiments [9].

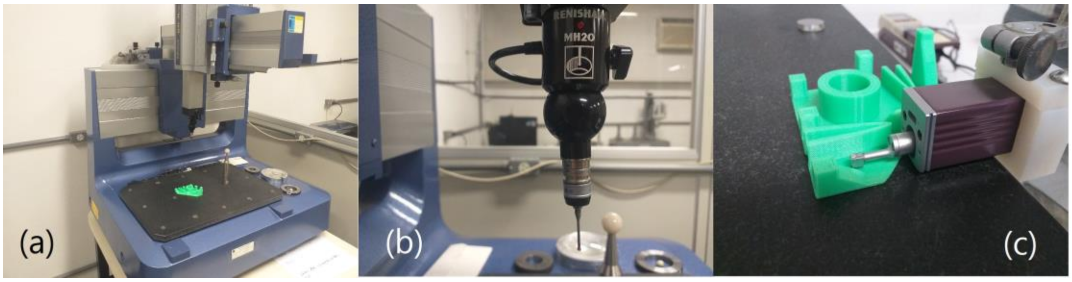

Fig. 2: (a) Coordinate Measure Machine – MMC; (b) CMM probe; (c) roughness tester.

Results and Discussion:
First, the mean and standard deviation of each sample were calculated to analyze the results. Error bars were determined considering a confidence interval of 95% for the mean and two standard deviation for variability limits. Analysis was carried out with dimensional, geometric and roughness deviations.

Dimensional deviations
Fig. 3 presents the results of the deviations in length for the eight parts manufactured according to runs 1-8 of the experimental design. As observed, it is not easy to compare all eight parts. So, the analysis of variance (ANOVA) was performed and Tab. 2 presents the results for length in z axis. Based on experimental plan, the main effects for each response variable and interactions were determined using the Yates' algorithm and are presented by the probability paper in Fig. 4.a for the length in z axis. As observed, the factors C (print speed), D (Layer height) and the AB interaction (confounded with CD) were significant (with 95% probability) to z-axis length. The analysis of the residuals showed that it was not possible to reject the normality of the residuals, Fig. 4.b.

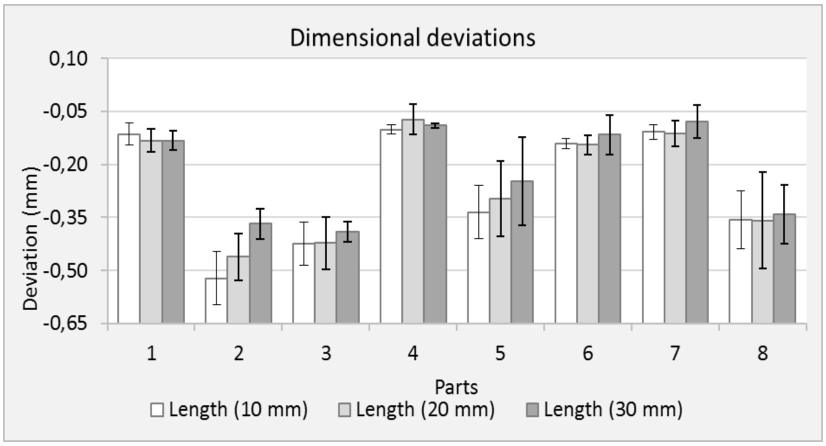

Fig. 3: Average and error bars of dimensional deviations, length 10, 20 and 30 mm.

Source	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	*F-Value*	*P-Value*
A	0,005245	1	0,005245	1,921465	0,184711
B	0,002843	1	0,002843	1,041386	0,322683
C	**0,022034**	**1**	**0,022034**	**8,071850**	**0,011796**
D	**0,547224**	**1**	**0,547224**	**200,466465**	**0,000000**
AB (CD)	**0,039043**	**1**	**0,039043**	**14,302635**	**0,001634**
AC (BD)	0,000013	1	0,000013	0,004946	0,944807
AD (BC)	0,001517	1	0,001517	0,555677	0,466818
Error	0,043676	16	0,002730		
Total	0,661595	23			

Tab. 2: Analysis of Variance (Length in Z axis).

The same analysis was performed to all other measured characteristics or response variables. Table 3 shows a summary with all tolerance types and design variables (factors) and interactions. The factors and interactions significant (95% probability) are marked for each response variable. It can be observed that variables C and D are significant for most of investigated characteristic.

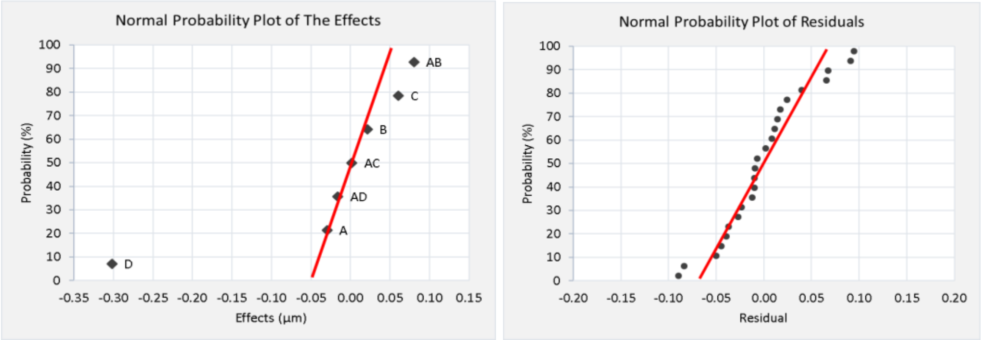

Fig. 4: Normal Probability Plot for (4.a) main effects in z-axis length (10 mm) and (4.b) residuals.

Tolerance Type	*Characteristic*	*Factors* A	B	C	D	*interactions* AB(CD)	AC(BD)	AD(BC)
Dimensional	Length (Z axis – 10 mm)			◇+	◇-	◇+		
	Length (Z axis – 20 mm)				◇-	◇+		
	Length (Z axis – 30 mm)			◇+	◇-			
	Internal diameter				◇-			◇-
	External diameter	◇+	◇-					
Geometry / Form	Flatness				◇+			
	Cylindricity (Internal)	◇-						
	Cylindricity (External)			◇+	◇+			◇-
	Sphericity			◇-	◇+			
Geometry / Orientation	Perpendicularity (XY axes)			◇+				
	Perpendicularity (XZ axes)			◇+				
	Perpendicularity (YZ axes)	◇+						
	Parallelism (X axis)					◇+	◇+	
	Parallelism (Y axis)			◇+	◇+	◇+	◇+	
	Parallelism (Z axis)						◇+	
	Angularity (30°)			◇+	◇+			
	Angularity (60°)			◇+	◇+			
Geometry / Localization	Concentricity/Coaxiality			◇+		◇-		
Roughness	Roughness (X axis)				◇+			
	Roughness (Y axis)				◇+	◇-		
	Roughness (Z axis)				◇+			

Tab. 3: Significant factors and interactions for dimensional and geometric deviations and roughness.

Printing Time
It was verified through the experiment that factors C and D are significant (95%) for printing time, as shown in Fig. 5. For both factors, the increase in levels values cause reduction in response produced (negative effect).

Conclusions:

The proposed investigation was suitable to evaluate the effect of AM process variables over the quality of the manufactured parts. It was observed that the variables print speed (C) and layer height (D) were very important as they influence dimensional, geometric and roughness tolerances in the machine studied. In the case of length in Z axis, changing C level from 40 to 60 mm/s results in an increase in average part length of 0.05 mm and changing D level from 0.2 to 0.4 mm results in a decrease in average part length of 0.27 mm.

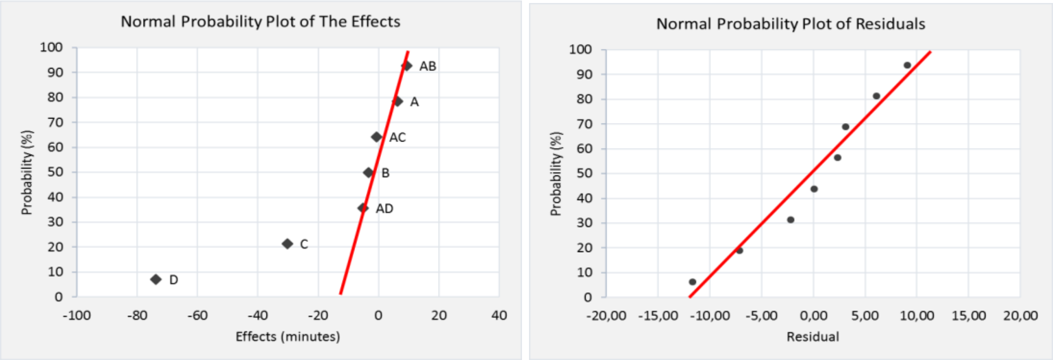

Fig. 5: Normal Probability Plot of (5.a) main effects and (5.b) residuals of printing time.

The variables A (fill density) and B (extrusion temperature) were less significant (95%) as they only had effect over a few dimensional and geometric tolerances. The same was observed for the interactions of variables. For printing time, it was observed that variables C and D had a negative effect, e.g., increasing the levels produced decrease in time spent. The total time spent to carry out all experiment was 17 h 27 min. Future work are required to propose objects and methods to reduce the time spent in machine evaluation.

References:

[1] Dilberoglu, U. M.; Gharehpapagh, B.; Yaman, U.; Dolen, M.: The role of additive manufacturing in the era of Industry 4.0, Procedia Manufacturing, 2017, 545-554. https://doi.org/10.1016/j.promfg.2017.07.148

[2] Galantucci, L. M.; Bodi, I.; Kacani, J.; Lavecchia, F.: Analysis of dimensional performance for a 3D open-source printer based on fused deposition modeling technique, Procedia CIRP, 28, 2015, 82-87. https://doi.org/10.1016/j.procir.2015.04.014

[3] Griffiths, C. A.; Howarth, J.; Rowbotham, G. A.; Rees, A.: Effect of build parameters on processing efficiency and material performance in fused deposition modeling, Procedia CIRP, 49, 2016, 28-32. https://doi.org/10.1016/j.procir.2015.07.024

[4] Lieneke, T.; Denzer, V.; Adam, G. A. O.; Zimmer, D.: Dimensional tolerances for additive manufacturing: Experimental investigation for Fused Deposition Modeling, Procedia CIRP, 43, 2016, 286-291. https://doi.org/10.1016/j.procir.2016.02.361

[5] Mahmood, S.; Talamona, D.; Goh, K. L.; Qureshi, A. J.: Fast Deviation Simulation for 'Fused Deposition Modeling' process, Procedia CIRP, 43, 2016, 327-332. https://doi.org/10.1016/j.procir.2016.02.004

[6] Montgomery, D. C.: Design and analysis of experiments, Wiley, 9th edition, Hoboken, NJ, 2017.

[7] Piratelli-Filho, A.; Silva-Junior, J.; Anwer, N.; Mehdi-Souzani, C.; Arencibia, R. V.; Vianna, D. M.: Circularity Compensation by CAD Modeling in Rapid Prototyping of Cylindrical Parts. Computer-Aided Design and Applications, 16, 2018, 1063-1069. https://doi.org/10.14733/cadconfP.2018.392-396

[8] Villamil, C.; Nylander, J.; Hallstedt, S. I.; Schulte, J.; Watz, M.: Additive manufacturing from a strategy sustainability perspective, International Design Conference – Design 2018. https://doi.org/10.21278/idc.2018.0353

[9] Zanetti, V.; Cavalieri, S.; Pezzotta, Z.: Additive manufacturing and PSS: a solution life-cycle perspective, IFAC-PapersOnLine, 2016,1573-1578. https://doi.org/10.1016/j.ifacol.2016.07.804