

25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0653

EXPERIMENTAL STUDY ON DIMENSIONAL DEVIATIONS IN HOLES PRODUCED BY FUSED DEPOSITION MODELING

Leonardo Miranda dos Santos
Mateus Francisco Ferreira de Paula
Givan Martins Macedo Junior
Lucas Barreiros Robatto
Isabel Beatriz Prestes
Amanda Silva de Deus
Anderson Vicente Borille

Instituto Tecnológico de Aeronáutica. Department of Mechanical Engineering. São José dos Campos, SP, Brazil.
miranda@ita.br, mateus.mec2017@gmail.com, givan@ita.br, robatto@ita.br, isabel@ita.br, amdeus@ita.br, borille@ita.br.

Abstract. Additive manufacturing is a set of techniques that produce components by adding successive layers of material. Due to the versatility that additive manufacturing presents compared to other manufacturing processes, it has been widely used for the production of complex geometry parts. In the fused deposition modeling (FDM) process, layers of material are deposited from a heated extruder head and fed by a filament. Several variables interfere in the quality of the product obtained by FDM. The choice of material, workpiece positioning and the deposition parameters directly interfere on the volume of material used, surface finish, dimensional deviations and mechanical strength. This experimental study focused on the identification of the influence of the deposition parameters on the geometric deviations in holes produced by FDM, using PLA as material. For the manufacturing, the influences of three factors on hole diameter and circularity were analyzed: print speed, infill percentage and shell thickness. Analyses of variance were performed and showed that there are significant correlations between all the deposition parameters and the dimensional responses, which were discussed in terms of thermal effects.

Keywords: additive manufacturing, dimensional deviation, FDM

1. INTRODUCTION

Additive manufacturing is a set of techniques that produce components by adding successive layers of material. In order to design a part by additive manufacturing, the component must be modeled using a CAD software interface or through the scanning of an existing product, for later converting the generated file to the STL (Standard Triangle Language) format, which represents the three-dimensional models as a mesh of triangles.

Due to the versatility that additive manufacturing presents compared to other manufacturing processes, it has been widely used for the production of complex geometry parts in automotive and aerospace industries. This technology provides freedom of development for engineers and designers and can be used as a mean for visualizing products functionality through prototypes, facilitating decisions and the detection of possible errors. However, the additive manufacturing techniques need to be analyzed in terms of the knowledge of the mechanical and thermal limits of the materials in each application area (BORILLE, 2009; KOLOSSOSKI, 2014).

The fused deposition modeling (FDM) is an additive manufacturing process that consists on the deposition of layers of material from a heated extruder head fed by a filament. The main advantages of this technology include: a good variety of non-toxic available material, low material and maintenance costs, low temperature operation, quick production of thin parts, and very compact size machines with low cost (DURGAN and ERTAN, 2014).

Dimensional deviations directly affect the functionality and adjustment of components. Therefore, it becomes an important task to ensure the quality of the manufactured part with the proper selection of process parameters (MOHAMED et. al., 2015). Several variables interfere in the dimensional deviations of the product obtained by FDM, such as the choice of material, the manufacturing positioning and the deposition parameters. The present study focuses on the identification of the influences of the deposition parameters on the dimensional deviations of holes in components obtained by means of FDM.

2. MATERIALS AND METHODS

The FDM tests were performed on a Sethi3D® FDM machine S3 model, with a maximum deposition volume of 270 mm x 270 mm x 300 mm in a temperature-controlled environment (23 ± 1 °C). The workpiece used for the tests consisted of a parallelepiped (75 mm x 75 mm x 25 mm) with a central hole of 25 mm diameter, whose model was created in the SolidWorks® CAD software interface, as shown in Fig.1.

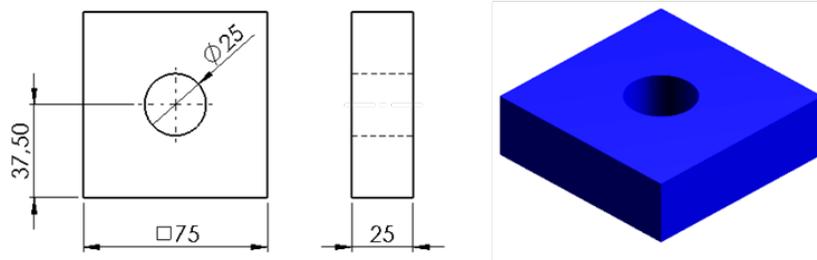


Figure 1. Dimensions and 3D model of the workpieces of the study.

The influences of three factors on the responses of diameter and circularity (Tab. 1) were analyzed: print speed, infill percentage and shell thickness. Each factor was analyzed in two levels, resulting in eight deposition conditions. Two repetitions were performed in two different machines each, in order to check the reproducibility of the results. The machines were of the same model, and the FDM parameters such as layer height, infill pattern, extrusion width, and temperatures were fixed, as described in Tab. 2.

Table 1. Variable parameters.

Parameters	Level 1	Level 2
Print speed (mm/s)	40	80
Infill Percentage (%)	20	80
Shell thickness (mm)	1	4

Table 2. Fixed parameters.

Parameters	All conditions
Layer height (mm)	0.3
Infill pattern	Rectilinear
Infill angle (°)	45
Extrusion width (mm)	0.48
Extruder temperature (°C)	200
Bed temperature (°C)	65

The software Repetier Host® was used to set up the deposition parameters. For all deposition conditions, a blue color PLA Acccreate® filament was used as the material. The material was fixed aiming to eliminate variations related to this factor.

A coordinate measuring machine (CMM), Mitutoyo® model Beyond Crystal C 7106 was used for the measurements of diameter and circularity of the holes. The procedure consisted in first defining one of the upper vertices of the part as reference (workpiece origin). Then, for the geometric analysis of the hole, 48 points were selected, arranged in 4 height levels, corresponding to circles at heights of 5, 10, 15 and 20 mm, with 12 measurement points each. From the measurements, the arithmetic means of circularity and diameter were obtained. Figure 2 shows the hole measurement procedure.

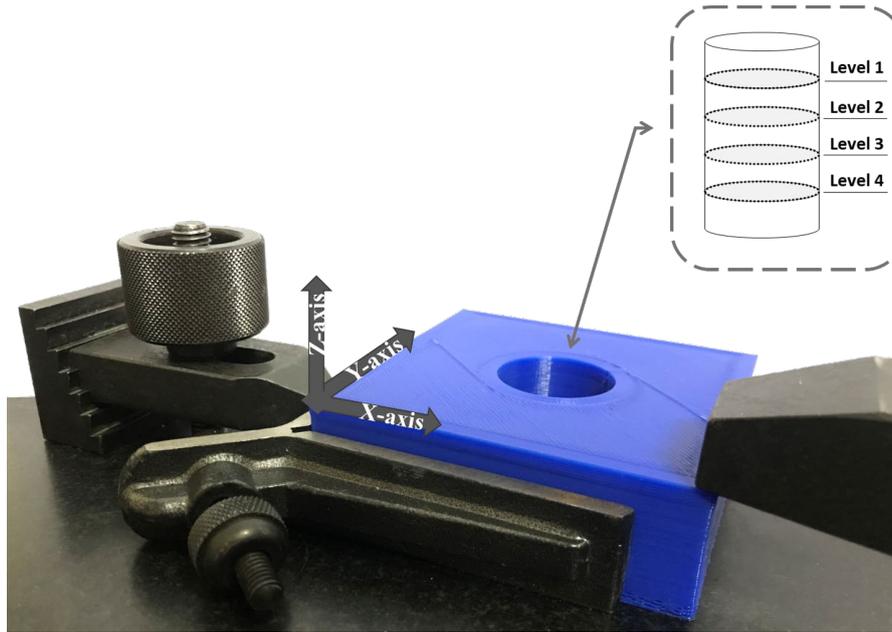


Figure 2. Location of the workpiece origin and hole measurement procedure.

In order to validate the deposition tests results, a factorial analysis of variance (ANOVA) was performed adopting a 90% confidence interval. Experimental residues of the responses were analyzed to validate the normal distribution assumption, which allowed the factors behavior comprehension.

3. RESULTS AND DISCUSSION

The ANOVA showed that there are significant correlations between the factors and responses of the study. For the hole diameter (Tab. 3), all the factors, speed, infill percentage and shell thickness, presented significant influence individually (P-Value < 0.1), considering machine 1. For machine 2, all the factors, except the speed, were significant, which could be due to calibration differences. No interactions between the factors were significant for both machines.

Table 3. Results of the ANOVA for diameter.

Source	P-Value Machine 1	P-Value Machine 2
Speed	0.017 ^(*)	0.558
Infill	0.010 ^(*)	0.000 ^(*)
Shell	0.011 ^(*)	0.004 ^(*)
Speed*Infill	0.415	0.793
Speed*Shell	0.123	0.271
Infill*Shell	0.723	0.188

^(*)influencing factors

It could be observed in the main effect plots (Fig. 3) that parts with high speed and high infill tended to present results closer to the nominal diameter. Regarding the shell thickness, lower values were associated to better diameter accuracy.

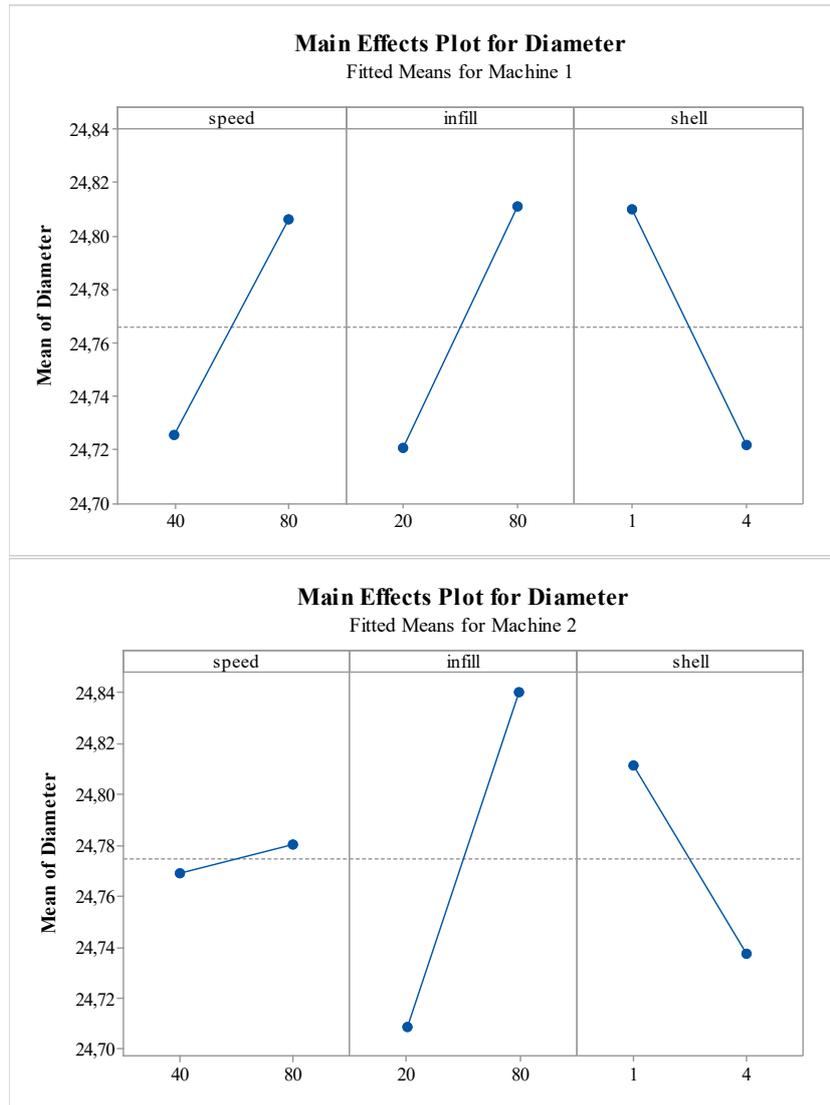


Figure 3. Main effects plot for diameter results of machines 1 and 2.

A possible explanation for these results can be based on the factors effects on the contraction of the material, which reduces the hole diameter. Higher speeds may reduce the time for the filament to contract before a new layer is added, and the final effect is less overall hole contraction. The higher infills can also act as holding diameter filaments, making the contraction more difficult. Regarding the shell, higher thickness should enhance the contraction, because more filaments are subjected to diameter reducing forces.

Furthermore, due to the contraction it could be noticed that the diameter results were always smaller than the nominal value. Hence, compensations in the diameter specified in the CAD file are necessary for reaching the desired diameter. However, as the results showed, these compensations may depend on the parameters selected.

For the analysis of hole circularity, the ANOVA showed that for machine 1 the influencing factors were print speed, infill percentage, shell thickness, and the combinations of the speed with infill and shell thickness, as described in Tab. 4. For machine 2, speed, infill and the combination of infill and shell thickness were identified as influencing factors.

Table 4. Results of the ANOVA for circularity.

Source	P-Value Machine 1	P-Value Machine 2
Speed	0.002 ^(*)	0.058 ^(*)
Infill	0.095 ^(*)	0.003 ^(*)
Shell	0.011 ^(*)	0.115
Speed*Infill	0.044 ^(*)	0.519
Speed*Shell	0.043 ^(*)	0.346
Infill*Shell	0.852	0.014 ^(*)

^(*)influencing factors

By analyzing the main effects plot in Fig. 4, it could be observed a trend that parts manufactured with higher speeds, higher infill percentages and lower shell thicknesses present lower circularity deviations. These results can be associated to distortion effects similar to those of contraction used to explain the diameter findings.

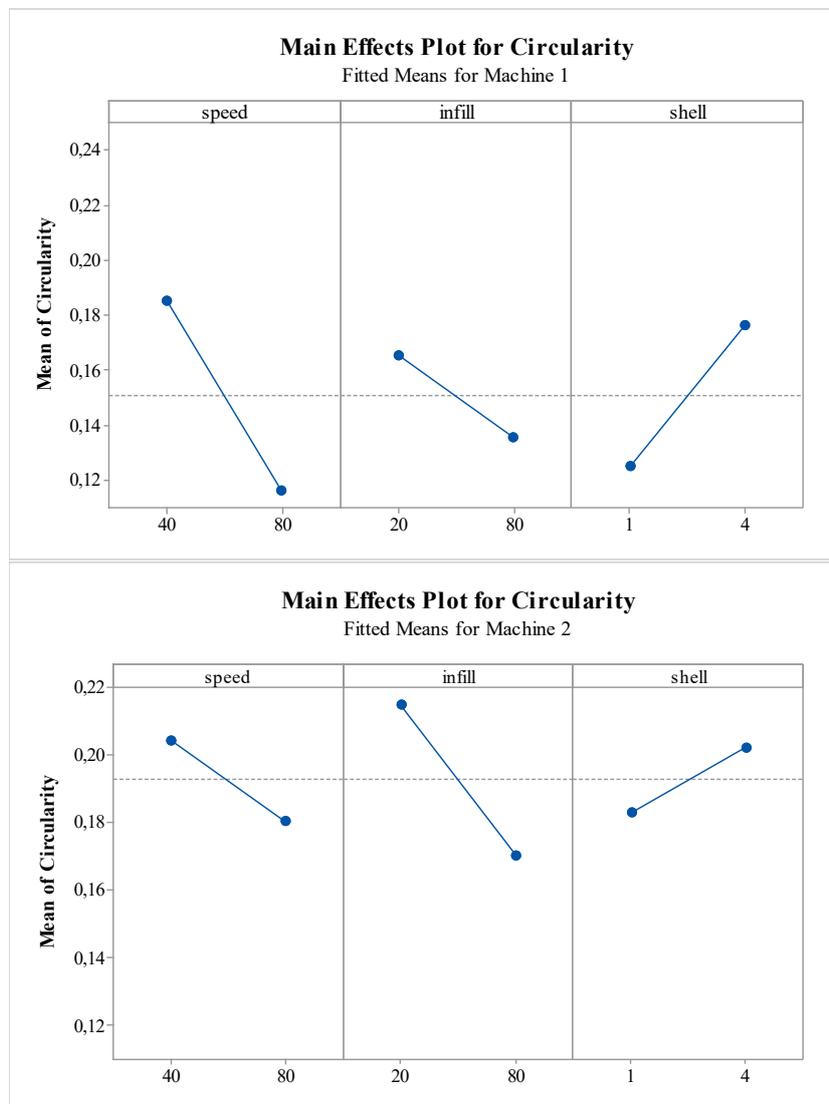


Figure 4. Main effects plot for circularity results of machines 1 and 2.

The combined influence of the deposition parameters on the circularity results was verified, as shown in Fig. 5. The interaction between the speed and shell thickness, and speed and infill percentage could be observed for machine 1. For the machine 2, only the interaction between the infill and shell thickness was significant.

In spite of the significant interactions found, no general trend could be observed because the two machines presented opposite behaviors. Thus, the interaction between the factors may be sensitive to machine calibration.

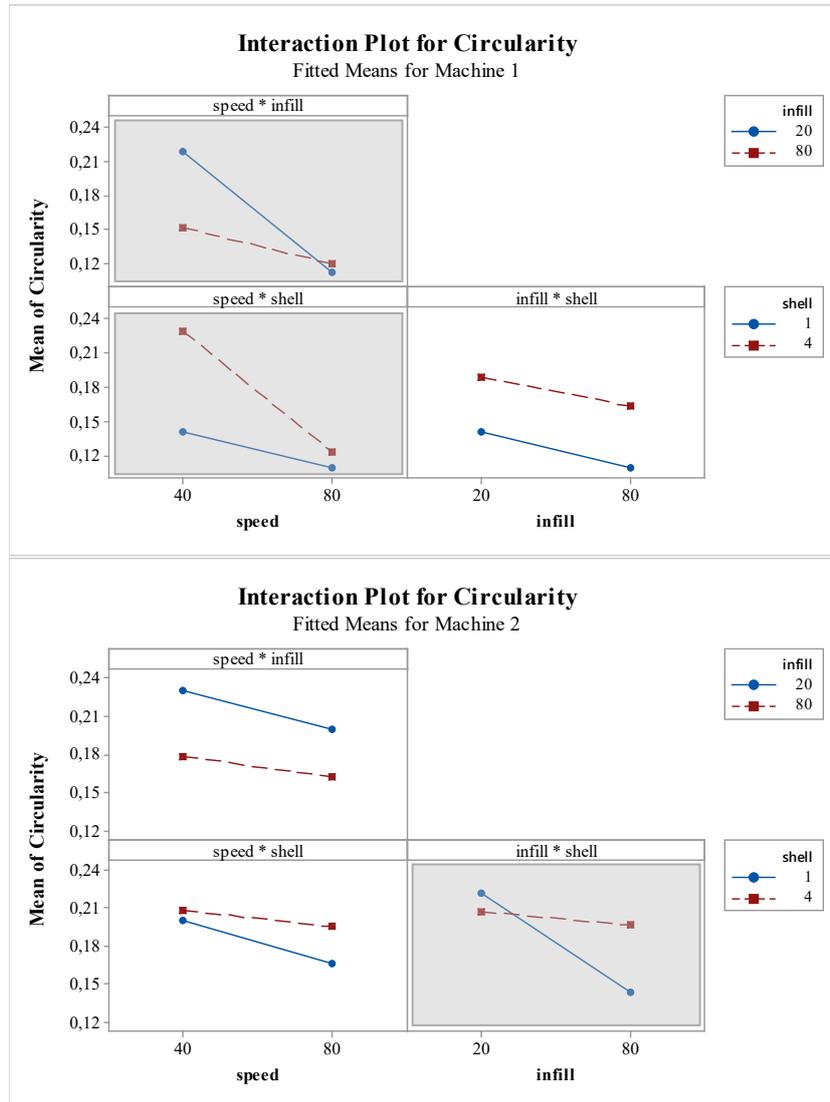


Figure 5. Interaction plot matrix for circularity results of machines 1 and 2. The interactions that showed significant influence on the circularity are highlighted in gray.

Table 5 summarizes the factors effects on the geometric deviations and the hypotheses for the observed results.

Table 5. Summary of results and hypotheses of the study.

Source	Diameter and Circularity deviation effect	Explanation
↑ Print speed	+	Shorter deposition times lead to less thermal distortions
↑ Infill percentage	+	Higher density, more difficult to contract and distort
↑ Shell thickness	-	More hole filaments subjected to distortion forces

(+) positive effect, (-) negative effect

4. CONCLUSIONS

From the analyses, all the factors influenced the diameter and circularity responses of holes, individually. The combination of the factors did not influence the diameter, but for the circularity, the interaction seems to be sensitive to machine calibration. Increasing the print speed and infill percentage and reducing the shell thickness can result in holes with diameter closer to nominal and with smaller circularity deviations.

The responses behaviors found were explained in terms of the effects of the factors on contraction and thermal distortions. The compensations which were identified as necessary for reaching desired hole diameters, due to contraction, were found to be dependent on the print parameters. These observations are based on physical phenomena that could also be valid for other additive manufacturing processes. The knowledge generated in the present study, therefore, can be useful for the prediction of additive manufacturing dimensional deviations and assist on the definition of proper parameters to ensure parts dimensional quality.

5. ACKNOWLEDGEMENTS

The authors acknowledge the financial support of CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), and of the Center of Competence in Manufacturing (CCM-ITA).

6. REFERENCES

BORILLE, Anderson Vicente. **Decision support method to apply Additive Manufacturing Technologies for plastic components in the aircraft industry**. 2009. 173f. Thesis of doctor of sciences – Aeronautics Institute of Technology, São José dos Campos.

DURGAN, Ismail; ERTAN, Rukie. Experimental investigation of FDM process for improvement of mechanical properties and production cost. *Rapid Prototyping Journal* 20 (2013) p. 228-235.

KOLOSSOSKI, George. **Considerações geométricas para a fabricação de componentes aeronáuticos pelo processo Fused Deposition Modeling – FDM**. 2014. 147f. Dissertação de Mestrado Profissional em Engenharia Aeronáutica – Instituto Tecnológico de Aeronáutica, São José dos Campos.

MOHAMED, Omar A.; MASOOD, Syed H.; BHOWMIK, Jahar L. Optimization of fused deposition modeling process parameters: a review of current research and future prospects. *Advances in Manufacturing* 3 (2015) p.42-53.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.