euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015

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A predictive model for dimensional errors in Fused Deposition Modeling

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Abstract

This work concerns the effect of deposition angle (α) and layer thickness (L) on the dimensional performance of FDM parts using a predictive model based on the geometrical description of the FDM filament profile. An experimental validation over the whole α range from 0° to 177° at 3° steps and two values of L (0.254 mm, 0.330 mm) was produced by comparing predicted values with external face-to-face measurements. After removing outliers, the results show that the developed two-parameter model can serve as tool for modeling the FDM dimensional behavior in a wide range of deposition angles.

Additive Manufacturing (AM), Fused Deposition Modelling (FDM), Predictive model, Tolerance

1. Introduction

Fused deposition modeling (FDM) is an Additive Manufacturing (AM) technology that makes possible the fabrication of complex shapes and geometrical features in 3D. Although FDM technology shows interesting advantages such as fabrication of functional parts, minimal wastage, and ease of support removal, certain drawbacks such as slow process, restricted accuracy, and shrinkage [1] still limit a wider industrial expansion. This work first presents a predictive model for dimensional errors based on FDM parameters and, afterwards, its experimental validation.

2. Model

Boschetto et al. [2] presented as the FDM filament geometry can be approximated as a sequence of circumference arcs where both the radius and the spacing are described as a function of deposition angle (α) and layer thickness (L). In the current work, the theory of filament geometry is modified taking into account L_{min} that corresponds the filament cross-section at α = 0 and a new analytical description for the radius of the filament. Under the hypothesis that the contact between measuring equipment and profile occurs only at the top of asperities, the model can be expressed as follows:

$$D_{max} = D_{nom} + y_{max} = D_{nom} + L_{min}(1-\cos(2\alpha)) \quad (1)$$

where D_{nom}, y_{max} and α are the nominal value, the maximum deviation obtained from the model, and the deposition angle expressed in radiant, respectively. In order to quantify the goodness of the model, an experimental investigation was carried out by using two values of L (0.254 mm, 0.330 mm) and 59 levels of α, using an angular sampling at 3° steps.

3. Item design and manufacture

The design of test parts was based on a few constraints to limit the number of the parts, make them easy to handle, and produce all the parts within the same FDM batch. In order to satisfy the constraints, a hexagonal specimen was selected. The shape was devised with a nominal side length of 20 mm and a thickness of 15 mm. Because of the different orientation of its sides, every specimen allowed to measure three different face-to-face lengths (which represent the selected measurands) oriented at three different deposition angles. Therefore, the number of specimens was reduced by three times. Furthermore, attention was given to increasing the robustness of the investigation by using STL-native objects developed in Mathematica Wolfram, which made it possible to delete potential errors due to the conversion from CAD-file to STL-file and by randomizing the positioning of specimens within the FDM volume, which seemed to be a reasonable way for neglecting the effect due to FDM deposition head drift (see Figure 1). For each L-α combination, two specimens were manufactured. A total of 80 specimens were prototyped on adopting a Stratasys Dimension BST 768 FDM machine with solid scaffold. All parts are made of ABS.

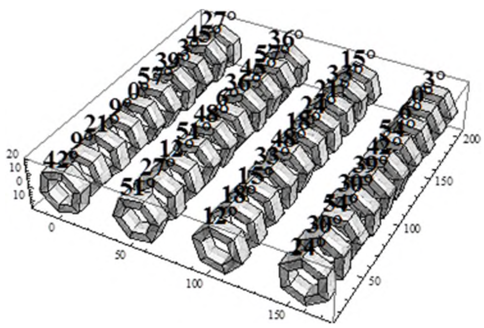


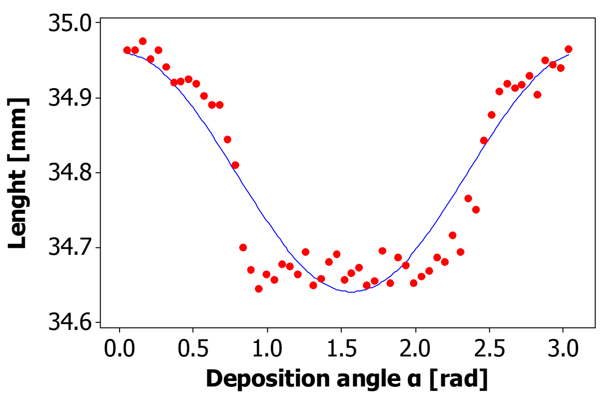
Figure 1. 3D Virtual specimens and their random position on the FDM machine table.

4. Measuring equipment and strategy

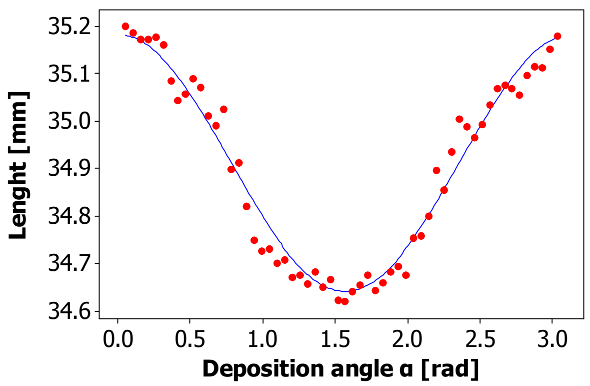
Due to lack of standards that combine metrology and AM, a surface characterization was undertaken to make a decision on both the measuring instrument and strategy. Hexagons with different combinations of *L* and *α* were inspected by employing a contact profilometer (Taylor-Hobson Talysurf Super) using an evaluation length of 4 mm. Afterwards, the surface information was filtered with a λs filter of 2.5 µm and with a Gaussian filter using a cut-off length of 0.8 mm. The analysis revealed as the profiles change not only for different *L*-*α* pairs but also along the same side. These occurrences can be due to a thermal gradient during the FDM deposition process. Taking into account the results, the decision-making, over the measuring instrument and strategy, veered to the use of external micrometer and 9 measurements face-to-face. The advantage of the external micrometer was that it ensured the contact on the top of the asperities due to the large anvils (Ø = 6.5 mm). Concerning the chosen measurement strategy, it permitted to take into account any local difference and, also, produced measurements with a moderated grade of overlapping.

5. Experimental validation and results

After performing 2124 measurements, results were divided in 59 subgroups, as many as α investigated, and treated using Chauvenet's criterion. Three interactions were sufficient for replacing discordant observations with the average of their subgroup. Because this procedure introduces variations on the distribution shape, but not on the average value, the validation of the model was carried out taking into account exclusively the average value for each α-subgroup. In figure 2 are displayed the data and compared to the model.



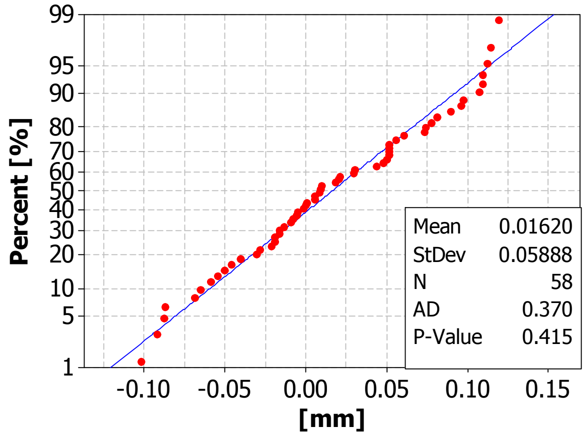
(a)



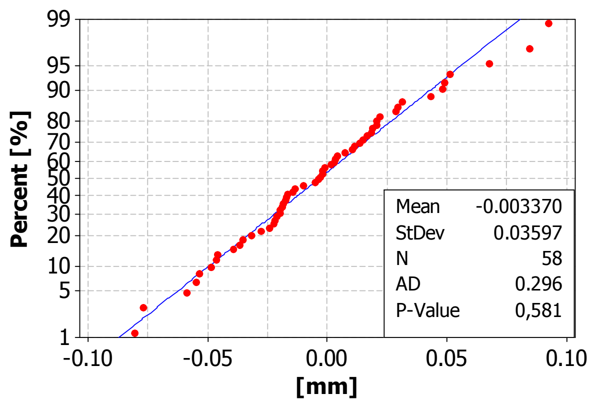
(b)

Figure 2. Comparison between model and experimental result the data set from L = 0.254 mm (a) and L= 0.331 mm (b).

At first glance, the two-parameter appears in accordance with the data. Such suggestion is confirmed by an Anderson-Darling test, which is a quantitative measure of how well the residuals from a regression model are described by a normal distribution [3]. The 5% critical value of the Anderson-Darling test is widely exceeded in both the experimental validation as shown in figure 3.



(a)



(b)

Figure 3. Anderson-Darling test of the data set from L = 0.254 mm (a) and L= 0.331 mm (b).

6. Conclusion

A two-parameter model for dimensional behavior and its experimental validation were presented. The residual analysis indicated the reliability of the model for describing the dimensional behavior of FDM artefacts. The work may be further extended taking into account different raw materials and FDM machines.

7. Acknowledgements

The paper presented here is based on an earlier study undertaken by the author at Sapienza University of Rome, Italy.

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