FDM 3D Printing Parameters Optimization: The Key Role of Line Width

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Abstract

Additive manufacturing technologies have evolved rapidly and steadily over the last decade and they become widely used not only in large, high-level companies, but also in medium-sized industries for both the production of prototypes, mockups, and the production of finished components. Stratasys' patented fused deposition modelling (FDM) technology, or more generally Fused Filament Fabrication (FFF), is by far the most cost-effective additive manufacturing (AM) technology especially if compared to powder technologies such as selective laser melting. It offers an extremely wide range of materials from nowadays mainstream, low-cost polylactic acid to the more advanced carbon fiber PEEK. The use of this technology is usually finalized on the production of prototypes and few case studies of end-use components can be found in the literature. This is due to the difficulties in predicting the final behavior of the resulting component and the presence of defects that can cause unpredictable premature failures in the component. This study focuses on describing how it is possible to reduce the defects present in the component with a careful choice of printing parameters and in particular focus on the effect of the parameter called "line width" and its correlation with the geometry of the printable part. The results would help to make FFF a more reliable process that could be used for obtaining a reliable, industrial production as well as prototype manufacture.

Keywords
Optimized FFF, FDM defects, printing parameters, line width

1. Introduction
The Fused Filament Fabrication (FFF) process was first introduced by Stratasys, a leading company in AM technologies, under the name of FDM®. It was patented as a mouldless technique for the fabrication of solid objects. Nowadays it is the most widespread AM technology because it offers a versatile choice of thermoplastic materials such as low cost polylactic acid (Rajpurohit et al. 2019) up to engineering plastic like Nylons (Guessasma et al., 2021). It consists in a continuous deposition of lines of extruded material up to the formation of an entire layer (Shahrubudin et al. 2019). Moreover, the component is built layer by layer and is possible to obtain solid object having complex shapes, as reported by the studies of (SAVU et al. 2019), (Mahamood et al. 2019), and (Brian et al. 2014). Furthermore, research by (Tofail et al. 2018) stated that FFF can create fully complete parts in series production.

1.1 Defects in 3d printed parts
Defects plays a key role in 3D printing since they are responsible for the degradation in mechanical properties with respect to injection molded parts. As suggested by (Gordeev et al. 2018). Voids of molten material found between lines and layers in the printed structure leads to a reduction in the final density of the component. These voids are strictly correlated with the values of slicing parameters. Moreover, the chosen printing strategy can also generate voids in the structure for example where perimeter lines joined infill lines. The presence of pores can be observed in a nondestructive way using CT (Computed Tomography) scans on the specimens (Damon et al. 2019) or by using a microscope after breaking the test piece in a fragile manner, as could be seen in Figure 1.

A deep knowledge of the influence of FFF printing settings is needed to obtain components with improved mechanical performance (Percoco et al. 2021). It was underlined that the fused filament deposition generates an anisotropic behavior in the produced part due to the presence of voids that could reduce its tensile strength, and Young Modulus thus generating failures, as reported by (Dawoud et al. 2016), (Fayazbakhsh et al. 2019), (Sood et al. 2010), (Pawar and Dolas 2020), (Vega et al. 2011), and (Ahn et al. 2002).

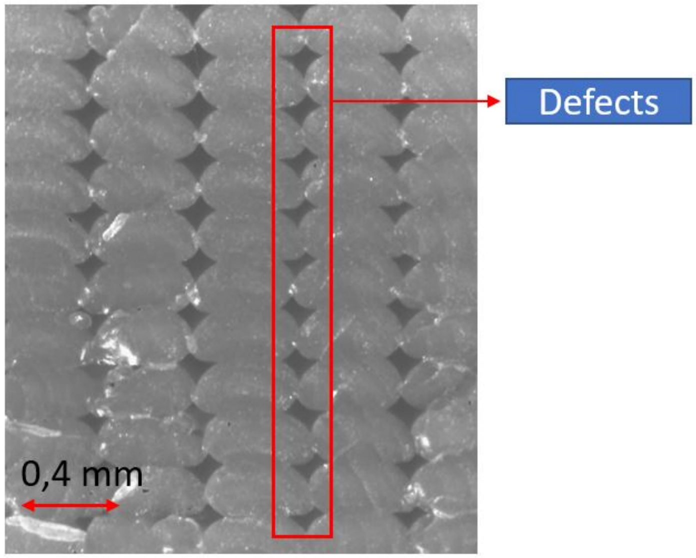


Figure 1. Defects appearance on a PLA sample, the voids have a rhomboidal shape due to the FFF printing process

1.2 Objectives

The model arises from the need to understand the influence of slicing parameters and in particular the line width on the number and volume-percentage of defects present in the workpiece. The geometry of a printed lines is parametrized as seen in Figure 2, the same parametrization is used by two well-known slicing programs like Slic3r (Hodgson et al., 2021) and (Prusa Research a.s. 2021) for the generation of the extrusion toolpath. Subsequently, a mathematical model based on the gcode used by the 3d printed is built up. In this way a test of the effects of various set of slicing parameters on a specific specimen could be assessed. The dimension of the specimens is shown in Figure 3. The choice of a square-base specimen is related to computational simplification, but results can be easily generalized to complex geometries too. The model aims to clarify the influence of line width on overall defects reduction in 3D printed objects.

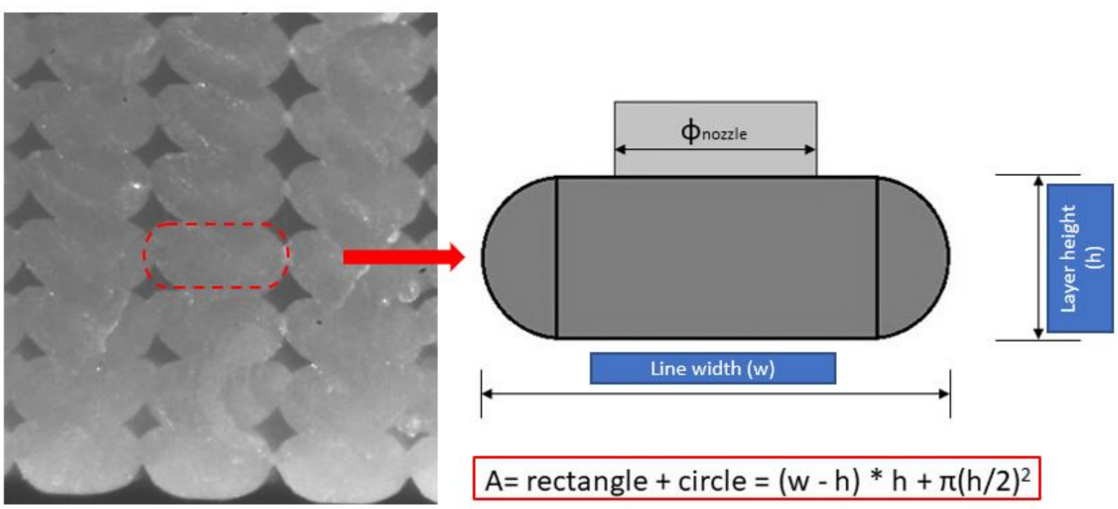


Figure 2. Parametrization of the section of a printed line

3. Materials and Methods

3.1 Model Construction

3.1.1 Geometry

The geometry used is a solid cube (material infill set at 100%), the dimensions are set at 30x30x30 mm, unless otherwise specified. The dimension of the cube remains fixed during all the numerical test performed. Only to evaluate the combination of line width and geometry the dimension is scaled.

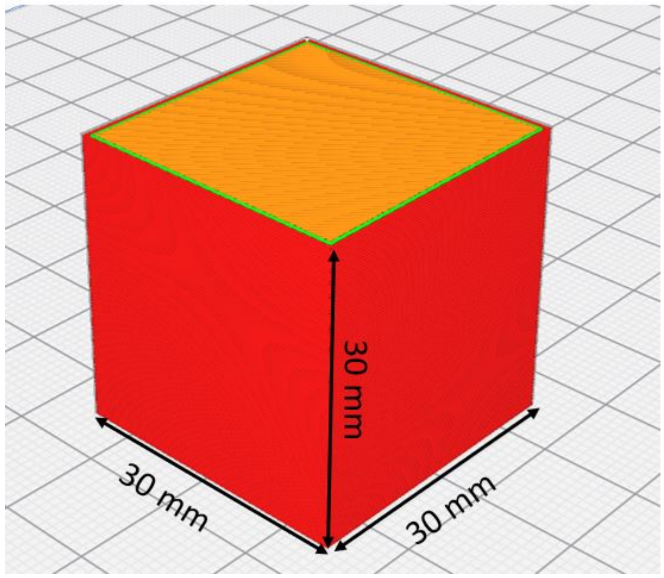
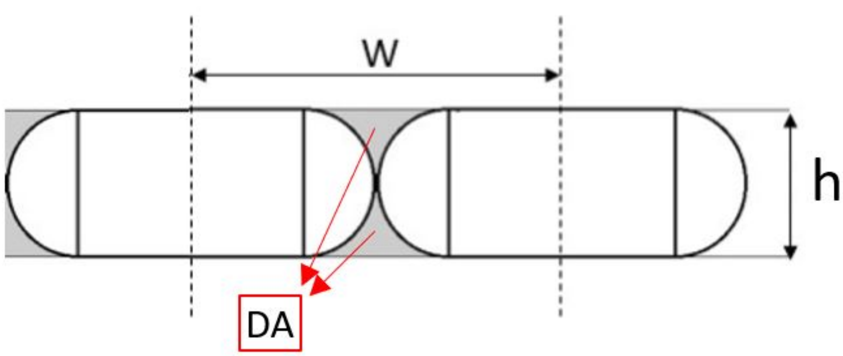


Figure 3. Test piece dimension

3.2 Defect Instances

The first hypothesis of the mathematical model is that each line touches the adjacent one only at a point. This allows to get into a "standard" test condition, and it is also the way the slicer creates the toolpath. The possibility for the lines to have a non-point contact path is in fact an "improvement", in a mechanical properties point of view, over the point contact condition. In general, the effective contact area strongly depends on slicing settings like temperature, extrusion flow, speed, etc, so the contact on a single point can be a good ideal test condition that simplified the overall model and make it general, and material type independent. The geometry of the voids is parametrized using the same method adopted in Figure 2 for the printed lines and it's reported in Figure 4. Thanks to this parametrization it was possible to use the mathematical gcode-based model to evaluate the overall volume of defects and how they increase or decrease in percentage changing the slicing parameters.



$$DA = \text{square} - \text{circle} = h^2 - \pi(h/2)^2$$

Figure 4. Voids parametrization

3.3 Mathematical model Parameters

The mathematical model is a gcode-based algorithm that allow to evaluate the effects of the variation of specific input slicing parameters values on the final volume of defects present in the cubic sample. Details for parameters for input and output are reported in table 1

Table 1. Mathematical Model Parameters.

	INPUT
Parameter	Unit
Line Width	mm
Nozzle Diameter	mm
Number of Contour Lines	/
Layer Height	mm
	OUTPUT
Overall Volume of Defects	%

3.3.1 Mathematical model Parameters Description

Line width: is the middle distance between a line and the adjacent one. The line width must not be confused with the "actual line width", as it's possible to see in Figure 5. In the case of the proposed model, due to the imposed pointy contact, the "actual line width" and the line width share the same value. This parameter can be set in the slicer but depends on hardware configuration and on nozzle and flat area diameter. The nozzle dimension gives the base value to the line width; for example, with a 0,4 mm nozzle, a starting value for the line width is 0.4. Small reductions of this value are still feasible in the range of -10% to accomplish walls thicknesses not multiple of the base value. The diameter of the flat area gives instead the maximum value of extrusion width since al the material extruded must be kept under it, to avoid defects generation. On the market many different producers of nozzle are available, one of the most diffused nozzle types are that developed by E3d. in Figure 6 are reported nozzle diameters and related flat area values.

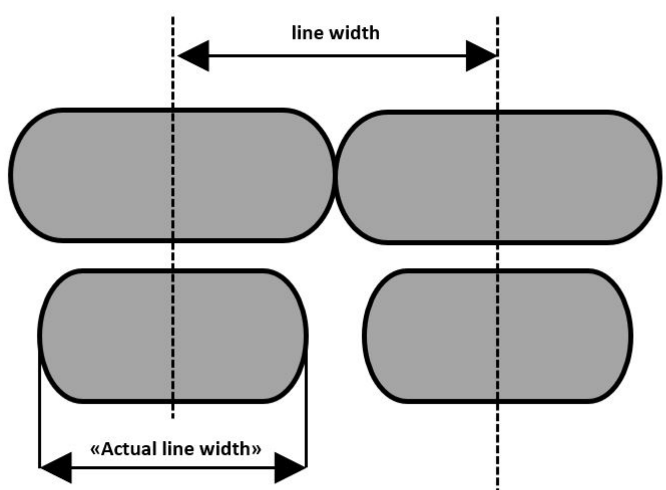
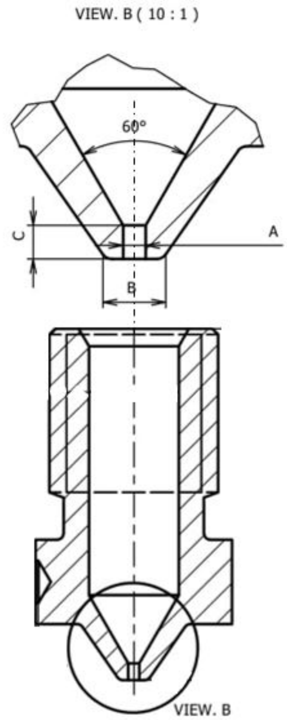


Figure 5. Line width and "actual line width". The first parameter is mathematical and related to the toolpath, the second one depends on extrusion temperature, extrusion flow, speed etc.



A	B
0.15	0.30
0.25	0.63
0.30	0.75
0.35	0.88
0.40	1.00
0.50	1.25
0.60	1.50
0.80	2.00
UNDRILLED	1.00

Figure 6. Nozzle dimensions as given by E3D

Layer height: is the thicknesses of each extruded layer. Also, this parameter is related to the nozzle diameter, usually ranging from 15- 20% up to 75-80% of the nozzle dimension. Lower values lead to a much higher counterpressure inside the fusing chamber that generates possible stripping effects on the filament, higher values of this could lead to a poor adhesion between layers and reduced mechanical performance. *Number of contours lines:* this is the number of lines that follows the external path of the component. This parameter is crucial especially when small areas are concerned, in relation to the nozzle dimension, as clarified in the results section. *Nozzle diameter:* corresponding to the nominal diameter of the nozzle, as said before this has a direct influence on line width and layer height. *Overall volume of defects:* this is a value that gives the percentual number of defects with respect to a defects-free solid cube.

4 Results

4.1 Influence of the Width in Defects-Number Reduction

The line width is the central distance between a line and the following one. Taking in consideration a given section with a length L, the effect of increasing the value of line width is clearly visible as a reduction in the number of defects sites as seen in Figure 7. For the same reason there is also an increased contact area between a layer and the subsequent one. In this case the positive contribution of increased adhesion surface can be better evaluated with tensile tests. In Figure 8 is reported the theoretical percentage defects reduction in a printed cube of 30x30x30 mm by varying the line width. The other parameters are fixed at 0.4 mm for the nozzle dimension,2 contour lines, raster angle of 45° and layer height 0.15.

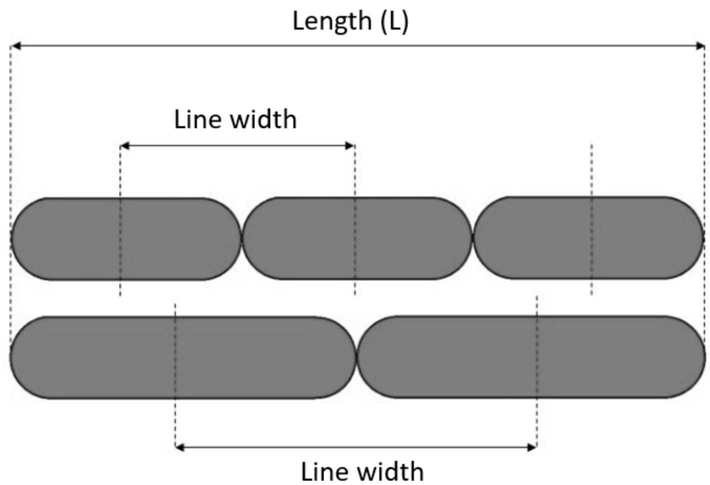


Figure 7. Effect of an increase in the "line width" parameter

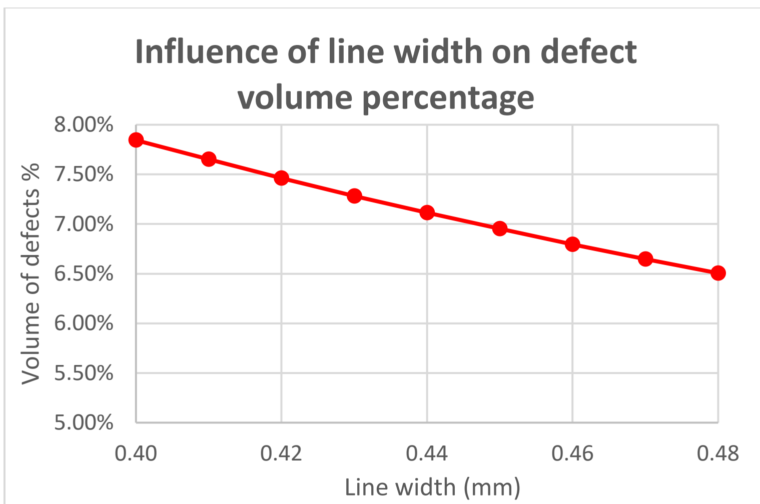


Figure 8. Influence of line width on defect volume percentage

4.2 Influence of nozzle diameter

To understand the effect of changing the nozzle diameter it was chosen to use the 30x30x30 mm cube also for this test since also the biggest nozzle dimension used in the test is far smaller than the test pieces dimension, so the exclusion of the local geometric-extrusion problem could be done that will be analyzed in the next section. In the previous chapters it is clarified that the nozzle dimension has effects on the choice of minimum layer height and base line width. For each nozzle the starting layer height is fixed at 20% of nozzle diameter and the line width equal to nozzle orifice dimension. As seen in Figure 9 it is possible to keep the same volume of defects but increase the layer height by using a bigger nozzle, this can also be a way to speed up the printing process if an increased surface roughness and decreased dimensional accuracy is not an issue. Decreasing the layer height for a given nozzle size is an effective way to reduce the defects percentage. Considering a fixed layer height and selecting a bigger nozzle can give an improvement in defect reduction as well. The possibility of also varying the line width can offer multiple opportunities and the final choice is related to the dimensions of the smallest vertical section of the component. This aspect will be clarified in the next section.

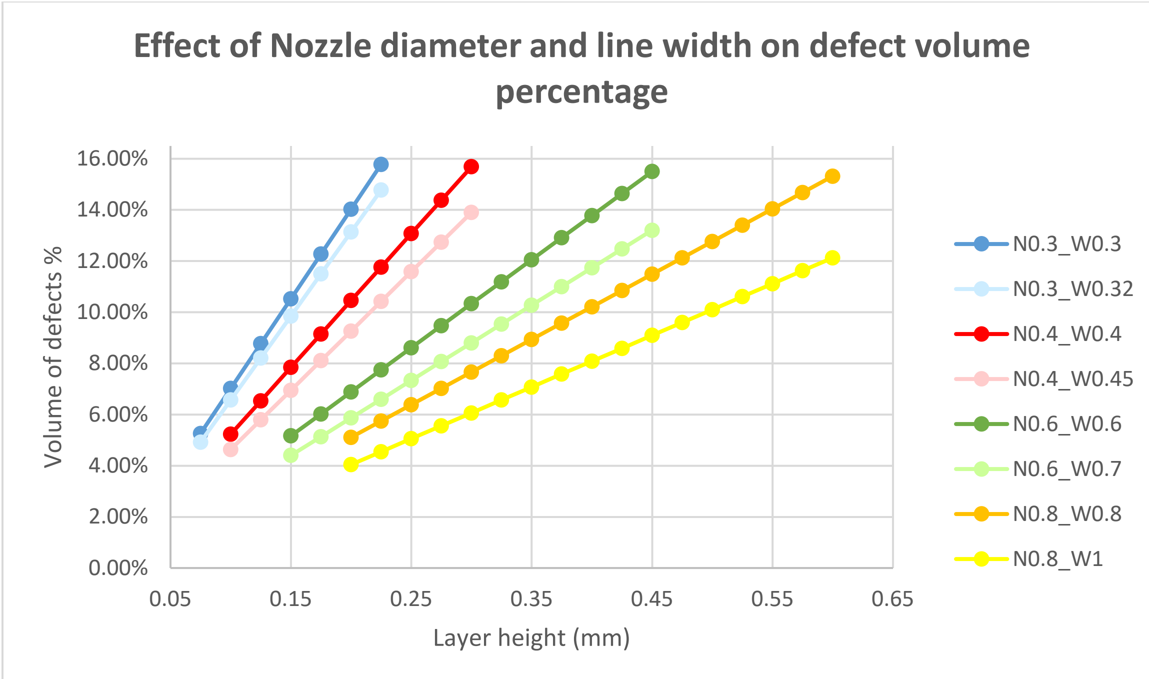


Figure 9. Effect of nozzle diameter and line width on defect volume percentage. N =nozzle diameter, w=line width

4.2 Influence of the Geometry

In this chapter the influence of line width is taken into consideration when the dimension of the printed section is in the range 3-10 times the nozzle orifice diameter. This is critical since it could undergo into a concentration of defects due to the impossibility to completely fill with lines this section area. The case studied was a single layer with the height of 0.15mm and a square section of 3x3 mm. The nozzle used is 0.4 mm, layer height 0.15, raster angle 45°, 2 contour lines and the parameter that was modified is the line width. In the previous section a reduction in percentage of volume of defects could be seen increasing the line width, but when the printed section geometry is small, an increase of voids volume for certain values of line width is obtained as seen in Figure 10. In Figure 11 the preview generated by Ultimaker Cura for three interesting cases is shown.

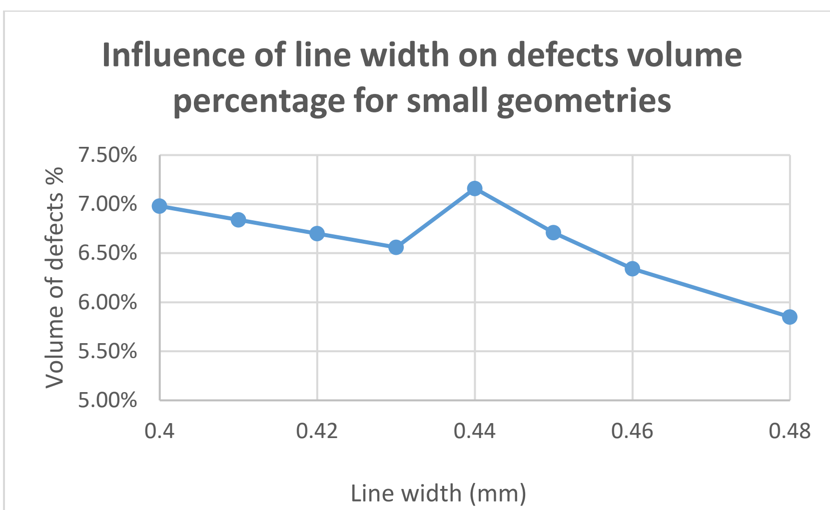


Figure 10. Influence of line width on defects volume percentage for small geometries

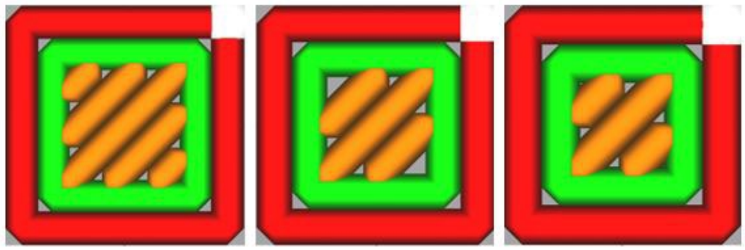


Figure 11. From left to right, Line width 0.40; line width 0.44; line width 0.48. The grey areas are voids.

5. Conclusions

The mathematical Gcode-based model demonstrated the importance of the line width as a crucial slicing parameter in the FFF process. This parameter has a direct effect on the number and final volume of defects obtained in the printed component. A reduction on the volume of defects proven to be feasible by means of a modification of input printing parameters and correct hardware selection. Furthermore, changing the percentage of volume of defects implies that mechanical characteristics of the material would change accordingly and can be compromised because of poor choice of printing settings for a given 3D printed part. This approach and the use of a mathematical model with "standard" predefined condition made possible to make a valuable comparison between different slicing settings and therefore appreciate the theoretical gain in defects reduction with the given setting. This work consequently represents a step forward in order to turn FDM technology processes into the mainstream production of components with higher mechanical properties and that would turn this process feasible for creating structural-applicable parts.

6. Future Developments

To extend this study and consider further parameters like positioning defects of the machine and filament tolerances. To extend this algorithm for the evaluation of defects also on complex geometries. To identify a correlation between defects volume and mechanical properties of the specimen by means of tensile test.

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Leonardo Frizziero is a Senior Assistant Professor of the Department of Industrial Engineering, at Alma Mater Studiorum University of Bologna. He promotes the scientific issues related to the Mechanical Design and Industrial Design Methods (CAD 2D, 3D, Advanced Design, QFD, TRIZ, DFSS, DFD, DFA, ecc.). In 2005, he was recruited by Ferrari Spa, as project manager of new Ferrari cars projects. In 2009 he came back to University, obtained the Ph.D. degree and started collaborating with the Design and Methods Research Group of Industrial Engineering becoming Junior Assistant Professor in February 2013 at DIN of AMS University of Bologna. He teaches and follows researches in the design fields, participating at various competitive regional, national and international research projects. Since 2018 he has been a Senior Assistant Professor. Since 2017 he is qualified Associate Professor of Design and Methods of Industrial Engineering (ING-IND/15). Prior to the role of university professor, he held relevant positions for some industrial companies.