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Effects of milling parameters on roughness and burr formation in 3D- printed PLA components

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Abstract

This study investigated the 3D-printed PLA (Polylactic Acid) workability during the operation of milling. It is difficult to obtain as a result of a Fused Deposition Modeling (FDM) 3D printing a very strict tolerance, and a good roughness surface. A possible solution can be the usage of the last milling operation that can complete the workpiece in terms of desired roughness and dimension tolerances. A design of experiments (DOE) analysis has been applied to observe the optimizing result. Three factors have been analyzed: feed rate, depth of cut, and rotational speed. Two responses were investigated: roughness (Ra) and burr height. The results show that these two parameters present optimum results in two different values of the process parameters: the Ra is better at a higher feed rate and low depth cut, but the situation reverses for the burr height, for which lower heights are obtained when using higher feed rate and depth cut.

Keywords: PLA; roughness; milling; DOE; burr formation; additive Manufacturing.

1. Introduction

Additive manufacturing is a technology that allows the creation of single three-dimensional objects starting directly from digital data processed by CAD / CAM software and has evolved and differentiated with the introduction of new printing techniques and countless materials with different mechanical characteristics, printable alone and in

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combination, allowing the diffusion of this production technique in many fields, such as industry, medical and domestic fields.

Every 3D printing system leaves more or less evident signs of its progress by layer. Each technology is characterized by a certain basic surface finish, which can be improved within certain limits with the optimization of variables during printing.

In Fused deposition technology (FDM), a particularly serious problem is making a layer adhere to the previous one. Habitually, the maximum normal stress that can be tolerated in the direction perpendicular to the layers will be less than that along the X and Y directions as demonstrated by Ahn et al. [1].

Several authors studied in their works [2-7] how to optimize the FDM parameters to obtain optimal mechanical properties. The parameters that influence the printed materials are numerous. Apart from the build orientation, the nozzle diameter and the layer thickness also have a great influence on the intra-layer cohesion and can increase the Ultimate Tensile Strength by 3.5 times [3]. Printing temperature, bed temperature [21], and feed rate influence the mechanical properties [5] and the percentage of the ideal specimen mass [6]. Pandzic et al. studied the influence of the color of the PLA on its mechanical properties [20].

The surface roughness depends mostly on two process parameters: the thickness of the layers and the print orientation [10-12]. A great deal of research has been done to try to optimize these 2 parameters to obtain an excellent surface finish and the tightest possible print dimensional tolerances. Kovan et al. [11] demonstrated that the roughness is deeply influenced by the layer thickness, and in particular decreases with the reduction of it. Furthermore, the printing temperature influences the quality of the surface, and in a certain range, the lower the printing temperature the smaller Ra value is obtained. Moreover, the printing direction of the sample influences the surface quality, and the best result is obtained for a printing angle of 70° [10].

Additional solutions for the optimization of process parameters have been proposed by various authors through the addition of chemical or mechanical processes after printing. Lalehpour et al. [13] proposed in their work the use of an Acetone Vapor bath. Pandey et al. [14] proposed instead the usage of a hot cutter to improve the surface finish.

Pămărac et al. [15] instead carried out a study on the milling of some FDM printed materials as a final process. Lalegani et al. [16] have studied the effect of milling in different printing orientations on surface roughness. In this work, the tensile test has been performed on the specimens printed in 3 different directions to evaluate the mechanical properties with the printing condition used. The aim of the present study is to find the optimum milling parameters to obtain a good surface roughness as well as a minimum burr height, the elimination of which would require a further process of removal. The experiment was carried out by applying the Design of Experiment (DOE) with 3 different factors and levels. This might be the first study and proposition of an evaluation method of the burr formation on 3D printed PLA samples, as well as potentially one of the few papers to study the Ra of the surface with the application of a DOE.

2. Experimental procedure

The additive manufacturing technique used for this paper is fused deposition modeling (FDM), and the chosen material is PLA. The material used is a commercial product from NatureWorks LLC, named PLA LITE (4043D): the mechanical properties provided by the manufacturer have been reported in Table 1.

For the realization of the projects, the open-source software FREECAD was used, which created the mesh of the project and the g-code file readable from the 3D printer. The 3D printer used is a TRONXY 5SA FDM. The lacquer spray has been used to improve the adhesion on the printer surface.

Table 1. Mechanical properties according to the information provided by the manufacturer.

Material	Color	Density [g/cm^3]	Tensile Strength [MPa]	Tensile Modulus [MPa]	Elongation at Break [%]	Melting point [°C]
PLA LITE (4043D) (Commercial name)	red	1.24	110	3310	160	145-160

The specimens have been printed for the tensile tests and the milling machines, with the geometry reported in figure 1. There is no international standard on the evaluation of mechanical properties of FDM printed materials. Thus, the tensile test pieces, following the UNE 116005:2012, were printed in three directions X, Y, and Z (Figure 1). This Spanish standard has been chosen because it is more appropriate for FDM printed samples, and mechanical tests have better repeatability than other standards [17].

For each printing direction, the same parameters were used; Table 2 shows the parameters used for printing all the samples, both tensile and milling specimens. As already extensively discussed, the choice of each parameter during the printing must be done carefully because each one deeply influences the mechanical properties of the samples [2]. The printing condition had been chosen following the indication provided by the manufacturer and reported by numerous authors [2-9].

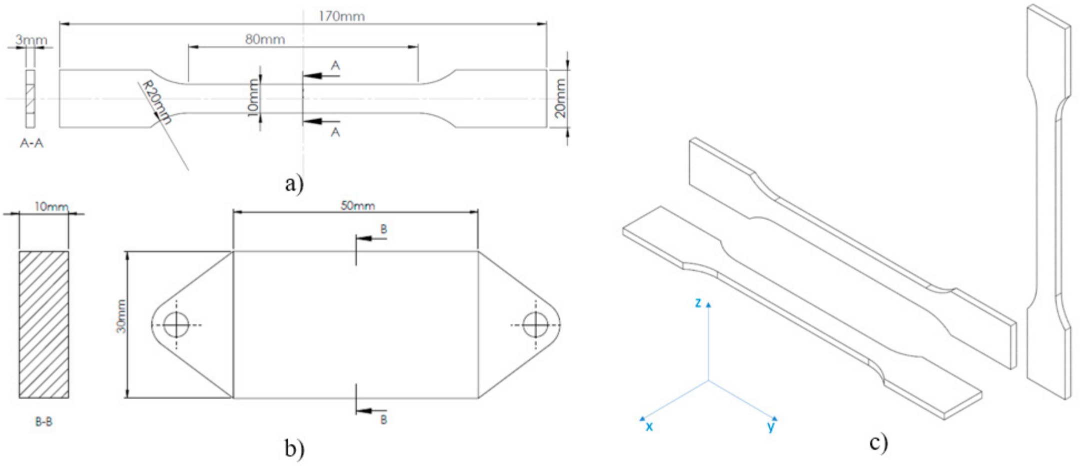

Fig. 1. Sample’s dimension for tensile tests following the UNE 116005:2012 (a) and CNC machining (b) and printing orientation for tensile samples (c).

Table 2. Printing parameters for every type of sample.

	Nozzle Diameter	Retraction Speed	Layer Height	Extruder Temperature	Bed Temperature	Printing Speed	Layer Cooling Fan	Infill
Tensile Samples	0.4 mm	45 mm/s	0.2 mm	210°C	48°C	44 mm/s	100%	100%
CNC samples	0.4 mm	45 mm/s	0.2 mm	210°C	48°C	44 mm/s	100%	15 % and 100% for last 5 mm layers

2.1. Tensile Test

The tensile tests were performed to evaluate the mechanical properties of the printed samples of PLA. The tests were conducted at room temperature on a Galdabini SUN500 servo-electric machine with a load cell of 5 kN. An HBM DD1 Displacement Transducer was used for measuring the strain over a gauge length of 50 mm. During the test, the applied load and displacement were recorded to evaluate the Young modulus (E), the 0.2 percent yield strength ($\sigma_{0.2}$), the Ultimate Tensile Strength (σ_{UTS}), and the Ultimate percentage Elongation (A%). The Tensile tests were performed on 3 PLA samples for every direction of printing.

2.2. Processing of milling machines

A DOE has been elaborated for the execution of the experiment, described here, and reported in Table 3. A full factorial design has been chosen with 3 factors: rotational speed (n), feed rate (Vf), and depth of cut (ap). The milling operations were conducted on a CNC3018 with a commercial 6 mm diameter milling head with two cutting edges: the Master 660C. The VECTRIC ASPIRE software was used for the milling project and the GRBL CONTROL opensource controller was used for the CNC control. A coolant has been used during the milling process.

Table 3. Full Factorial Design Summary Table.

Factors			Levels			
Type	Units	Symbols	1	2	3	4
Rotational speed (n)	[rpm]	A	3000	5500	8000	-
Feed rate (Vf)	[mm/min]	B	400	600	800	-
Depth of cut (ap)	[mm]	C	0.2	0.4	0.6	0.8

2.3. Roughness and burr measurement

As already mentioned, the quality of the milling process has been evaluated with two parameters, the calculation of the burr height at both sides of the milling passes and the measurements of the roughness on the milled surface. The roughness meter used is Taylor Hobson 50 mm Intra 2.

The profile measurements were carried out for every sample and in every milling condition, along the milled surface and in the direction of the feed rate. The starting point of the measure is at the center of the milled surface and 5 mm from the border for 20 mm. Just one measure was done for all the lengths of the milled surface to have a good mean on the profile. Figure 2 shows a comparison of the roughness profile of the as-printed and the milled surfaces. Afterwards, the profile has been elaborated for the evaluation of the Ra parameter. Ra is one of the most used parameters to evaluate the quality surface, and it is defined as the arithmetic mean of the departures of the profile from the mean line and it is calculated on a sampling length l:

$$Ra = \frac{1}{l}\int_0^l |Z(x)|dx \tag{1}$$

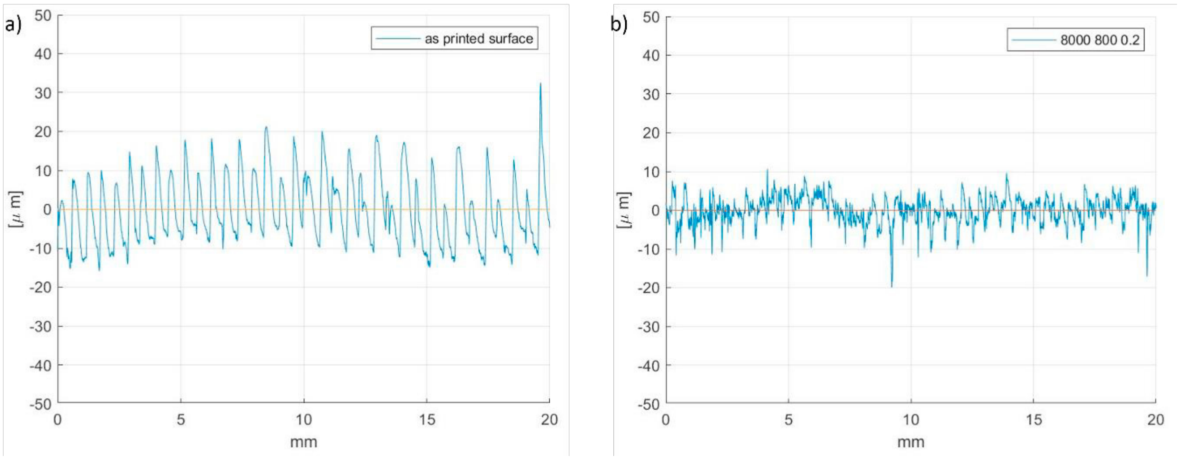

Fig. 2. Comparison between the profile on the as-printed surface (a) and the profile with the little roughness obtain after the milling process (b).

Three measures (named A, B, and C) were also performed perpendicularly to the milling direction and equidistant to 10 mm each other in order to evaluate the height of the burr at both sides of every milling surface (figure 3). The measurements of the burr height have been elaborated in MATLAB® by calculating a zero line with the methods of the least-squares to have a level reference to correctly evaluate it, with the same method used in [16]. Specifically, each measure had been divided into five zones, the surface zones not milled, the regression line which had been evaluated in each zone using the points without burr, and the burr's height that had been calculated just by doing the difference between the coordinate of the burr higher point and the correspondent coordinate in the regression line.

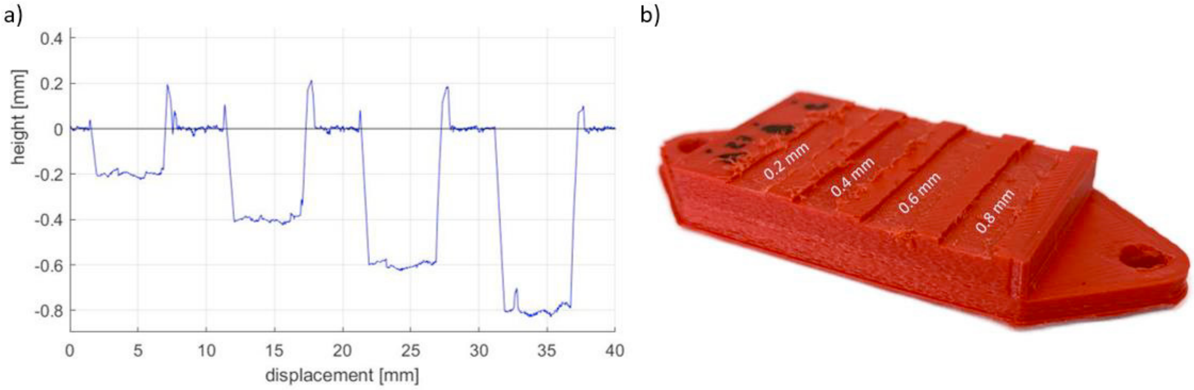

Fig. 3. Profile of a sample on perpendicular milling direction, with the reference regression line (a) and sample surface after milling process (b).

4. Results

The results of the Tensile Tests have been portrayed in figure 4. The figure shows the stress-strain curves for every printing orientation. As expected, and in common with the studies of several authors [1-9], the samples show different properties in the 3 directions: the X and Y printed samples curves are quite similar and show the best mechanical properties, and the Z-direction has the worst tensile responses. Figure 4 has reported the mechanical properties obtained for every printing direction.

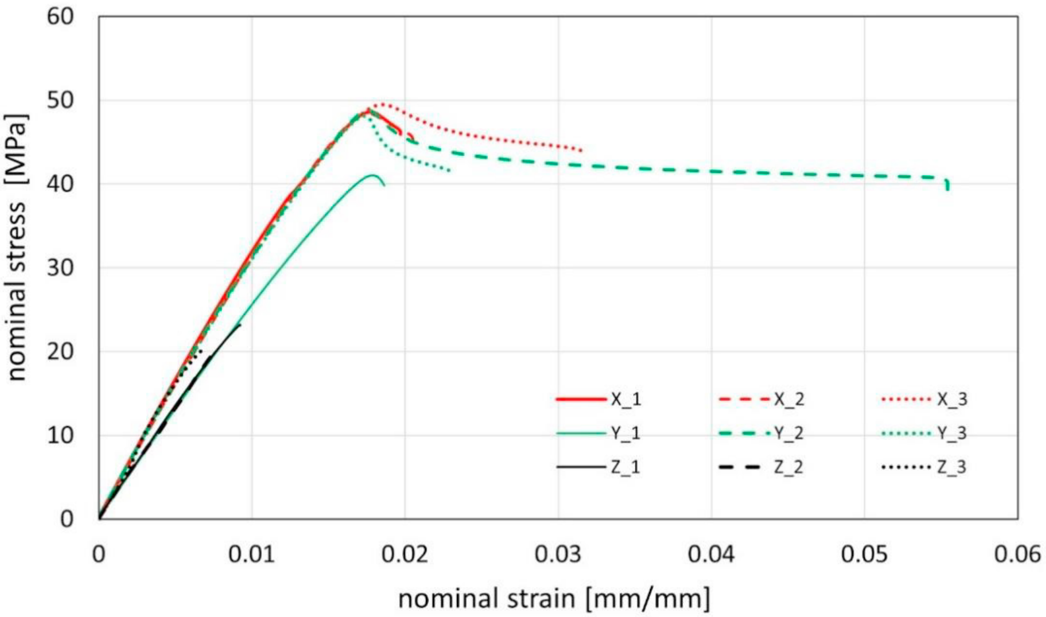

Fig. 4. Results of the Tensile test for the three printing directions X, Y and Z.

As discussed before, the mechanical properties of the printed samples largely depend on the printing parameters. Table 4 reported the results obtained by several authors in similar printing conditions to our study. The variability of the results obtained could be explained by some small differences in the printing parameters, but also by the usage of different PLA filament manufacturers.

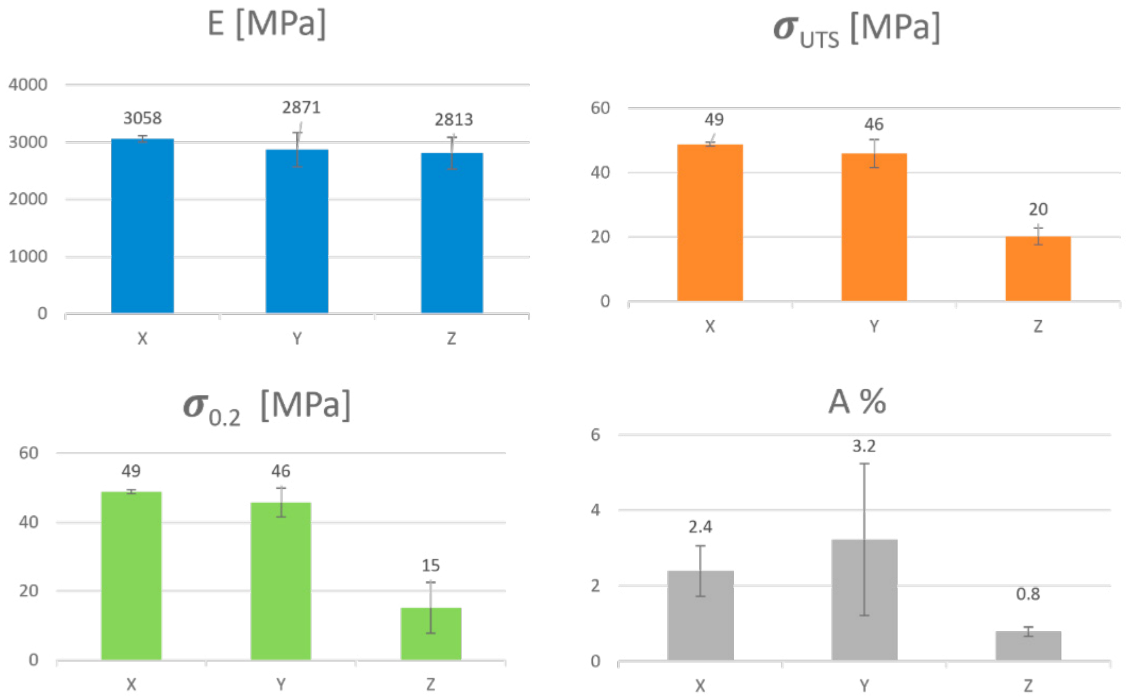

Fig. 5. Mechanical properties in the 3 printing directions (X, Y, Z), the error bars show the standard deviation.

Table 4. Mechanical properties in similar printing condition, obtain by different authors in literature.

	Max stress [MPa]	Young Modulus [MPa]	Elongation to Break [%]
OKsman et al. [19]	53	3400	2.0
Vynias M et al. [8]	47	3470	1.4
Present study – x printed direction	49	3058	2.4

3.1. DOE applied to surface roughness Ra

The Ra values are variable in the range 2÷13 μm, detected for 8000-800 in the 0.2 depth cut, and for 8000-800 0.4 respectively. The mean Ra evaluated in the not-milled surface is 10.4 μm.

A DOE Analysis with a full factorial design has been elaborated on the Ra measures with Minitab 19, and the results obtained can be seen in Figures 6 and 7.

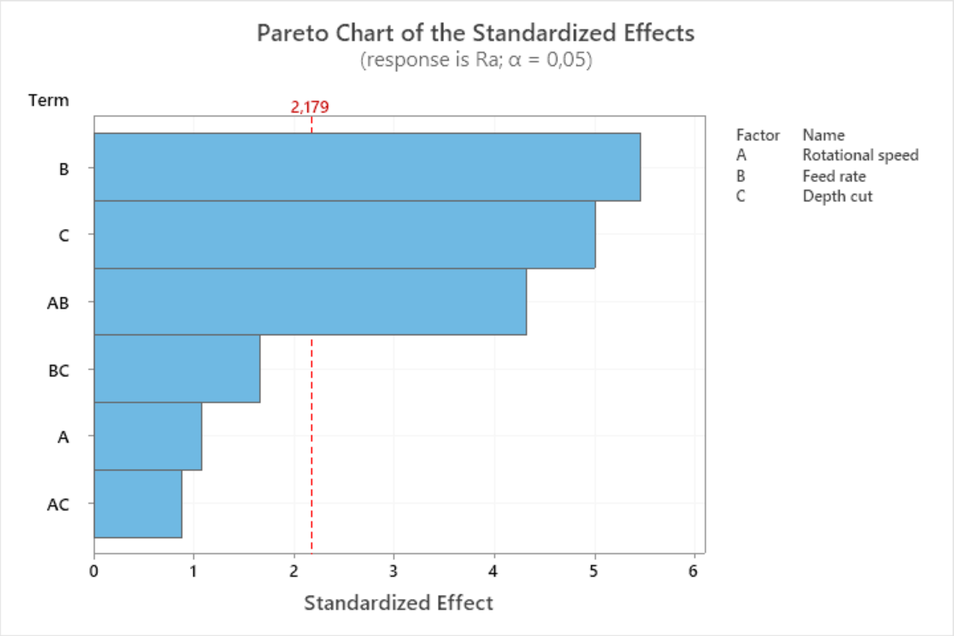

Fig. 6. Pareto Chart for the standardized effects for Ra considered for α=0,05.

By the Pareto chart, it is possible to observe that just three parameters influence the Ra value, in order of impact: the depth cut, the feed rate, and the combination of rotational speed and feed rate. The other factors and combinations have not statistically influenced the quality surface. In figure 7 it is possible to observe the main effects plot for the surface roughness. The value of these parameters shows how the roughness increase with the depth cut and the feed rate but stays mainly constant with the rotation speed, as it is the less impact factor.

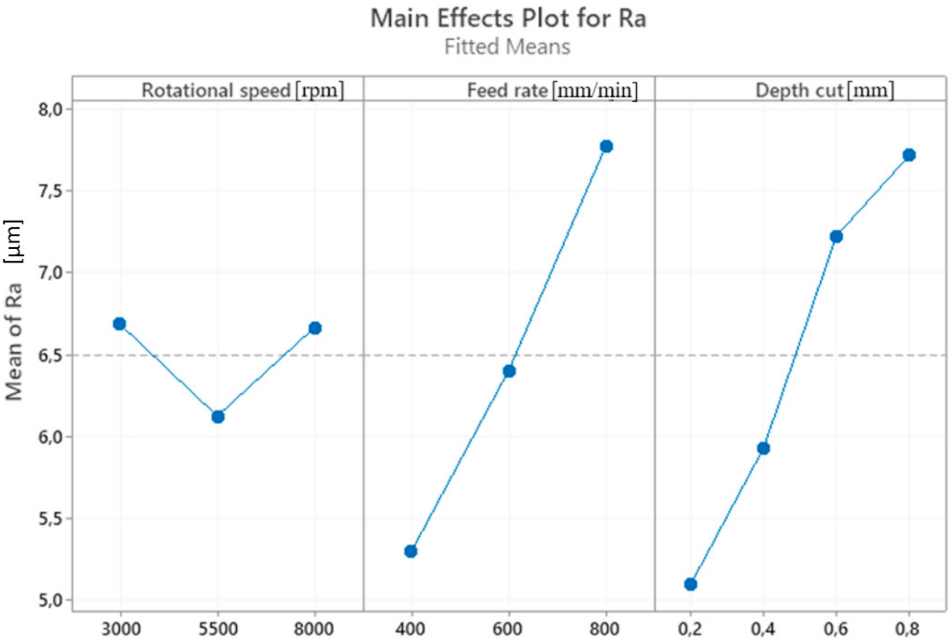

Fig. 7. Main effect plot for Ra related to process parameters.

3.2. DOE applied to burr heights

A DOE analysis has been elaborated on the burr measurements with the same software used before, Minitab 19. The data have been analysed using the mean of the two-side burr height of the milling surface and considering 3 replicants. The results are reported in figures 8 and 9. The Pareto chart (Figure 8) shows how the parameters included in this study have a great influence but also some combination of two factors. The depth of cut (C) is the most impact factor, but also the feed rate (B) has a great impact on the burr formation process. Then in order of impact: the combination BC, AC, and lastly the rotational speed (A). The combination of rotational speed and feed rate AB has no statistical importance in the process of burr formation.

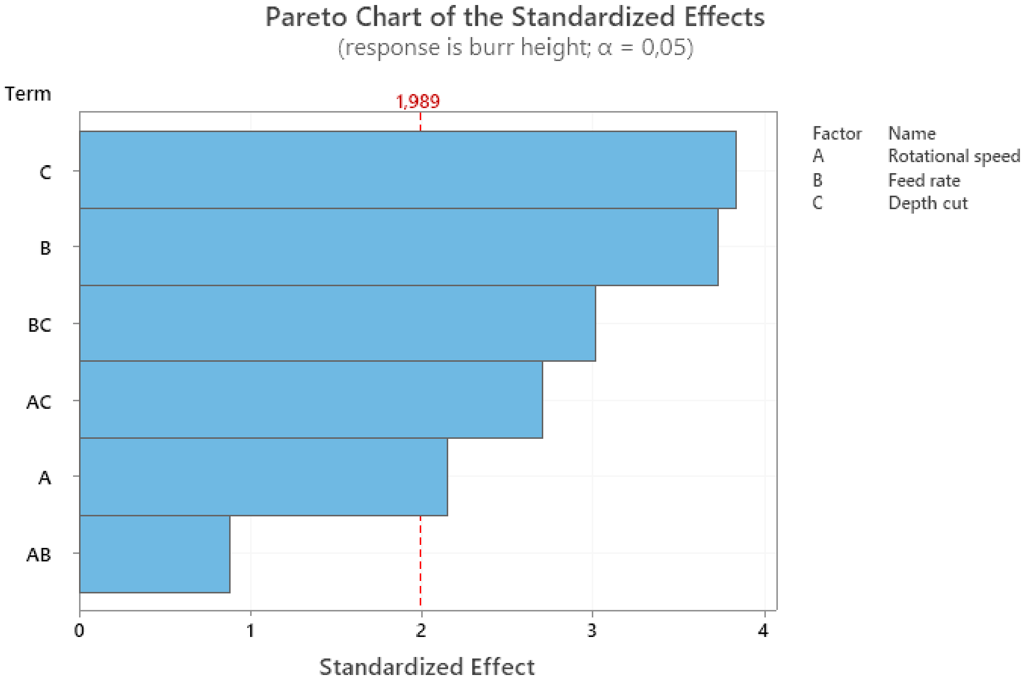

Fig. 8. Pareto Chart of the standardized effects for burr height.

The main effects values reported in Figure 9 show that the burr height decrease with the rise of feed rate and depth cut but with a maximum value of burr heigh at 0.4 mm of the depth of cut. The rotational speed has a minimum value at the medium level (5500 rpm). In order to minimize the burr height, it is suitable to operate at high feed rates and dept cut.

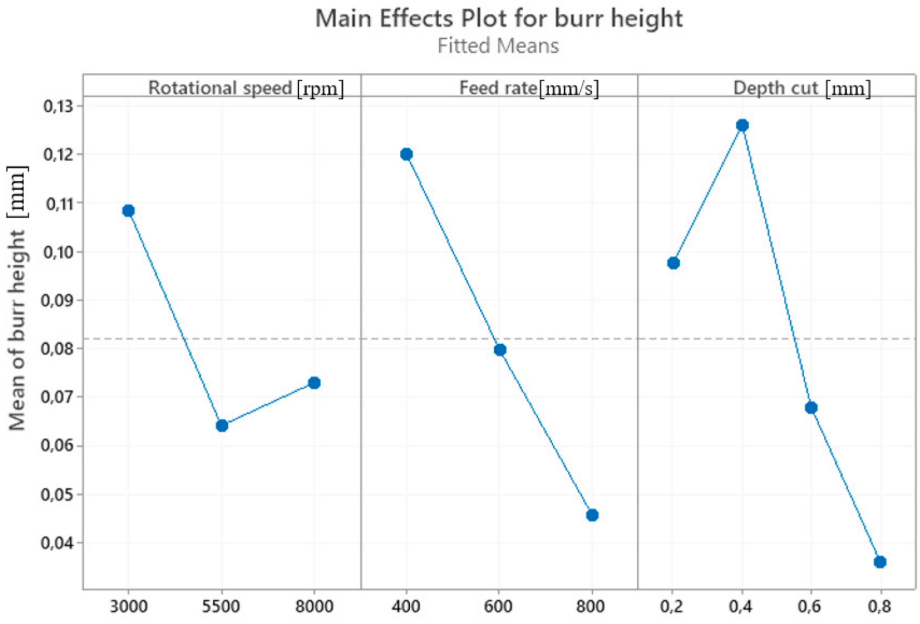

Fig. 9. Main effect plot for burr height.

5. Conclusions

From the bibliographic research, it is possible to observe that it is hard to obtain a low roughness during the 3D printing process, because of an inherent technological limitation. Thus, to obtain a better-quality surface, an additional process must be added and that is the main reason for this study.

From the present paper, the tensile tests and milling process on PLA that we have performed, it is possible to deduce that:

- The results obtained from the tensile test show that the mechanical properties of the printed samples are similar to those reported in the literature, with better results for the samples printed in the X and Y direction than Z samples.
- The Ra parameter, used in his study to indicate the surface quality, is better at the lower level of feed rate (400 mm/min) and low level of depth cut (0.2 mm) at all studied rotational speeds.
- For the burr height, the minimum heights can be obtained when using a higher feed (800 mm/min) rate and a higher level of depth cut (0.8 mm) at a relatively high rotational speed. This is probably due to the heat exchanged during the process: in fact, the longer the tool remains in contact with the surface of the samples, the larger the temperature rise and the burr height and the more the heigh burr.
- Finally, the optimal milling parameters in terms of better milled surface quality are different from the best parameters in terms of low burr formation. Besides, their effects are more or less opposite.

These results influence the machining working time; in fact, the feed rate, and the depth of cut influence the material removal rate. Thus, to obtain a good surface quality, it could be better to perform a final milling pass with a lower depth cut of 0.2 and 600 mm/min of feed rate considering a small formation of burr.

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