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STUDY REGARDING THE OPTIMAL MILLING PARAMETERS FOR FINISHING 3D PRINTED PARTS FROM ABS AND PLA MATERIALS

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Abstract: *In this paper we proposed to identify the optimum milling parameter required for finishing processes performed on 3Dprinted parts from ABS and PLA materials. We have identified the optimum milling parameters for a constant spindle speed of 3500 rot/min for face milling and profile contouring operations with different tools diameters. The study was performed on 3D printed specimens from ABS and PLA materials.*

Key words: Additive Manufacturing, Roughness, CNC milling

1. Introduction

Additive manufacturing (AM) can be defined as a fabrication process where lot size one, end-user parts with a high geometrical complexity can be rapidly obtained with low energy consumption. From its earliest stages, AM has been identified as a method for rapid prototyping of parts that display a high level of complexity and in some cases, impossible to be manufactured with conventional methods (e.g. CNC machining). Despite the advantages that AM offer, it has yet to be included into industrial mass production lines, as an alternative to conventional manufacturing techniques, due to high manufacturing times and the lack in repeatability and process stability. In some cases, this might not be a significant issue, but in some industrial purposes, where high precision parts are required, there are restrictions with the outer layer's rough surfaces and lack in precision. In order to meet these limitations, additional finishing process are required.
While there are some process that can address this issues with different results, as identified in [1] where the finishing process involves bathing the finished product in acetone based solution, where the surfaces are smoothen to an acceptable roughness degree as depicted by the ISO 4287:1997 [2] standard, but with considerable changes in dimensional properties of the finished part, proportional with the time the material is exposed. While this method is accepted for correcting roughness, it can lack precision thus more effective methods are needed.
An alternative to the chemical bathing can be considered the hot cutter machining (HCM), which is a method of removing material from the surfaces of the part. The main disadvantage of this method is that it cannot be used with complex geometry parts. As depicted in [3] this technology can produce parts with 0.3 μm with 87% confidence level.
This article will focus mainly on the third alternative for finishing the surfaces of the materials, the material subtraction technique thus studying the effects on the usage of milling cutter CNC machines with limited RMP on the finishing process of the surface of additive manufacturing pars.

2. Methodology

For this research, we chose fused deposition modelling (FDM) as the AM technology. From previous studies that we have conducted [4] [5], we chose the optimum parameters for dimensional precision and tensile strength for the 3D printed samples used in this study.
The finishing processes studied, are to be conducted on a 3-axis CNC milling machine: DMC 635V eco (fig. 1). The main characteristics include: a machining area of 635 [mm] on the X axis; 510 [mm] on the Y axis; 460 [mm] on the Z axis. The maximum spindle rotation is 9000 [rpm]. Main application is for medium and high precision manufacturing, up to 0.01 [mm].
In general, coolants are not required for most machining thermoplastic materials. However, petroleum-based fluids can be used for many semi-crystalline plastics such as nylon, acetal, polyesters, PTFE and most

thermosets. Avoidance of this type of coolant is generally a good practice if any amorphous materials are being machined as it can be difficult to determine the compatibility. [6]
During the experiments we chose to use pressurised air. In addition, to the cooling effect that the pressurized air has, it is also used to remove the residual material resulted from the milling process and it's useful in avoiding the chip wrap.

Figure 1 DMC 635 V eco

Figure 2 Ultimaker Pro 3D printer

As for the 3D printer we used the "Ultimaker Pro 3D" printer which has a semi closed printing chamber. We chose this printer due to the high possibilities of varying the fabrication parameters that its software permits. The 3D printer is driven by G-Code generated with the "CURA" software. The same printing technique was used throughout the printing of all the specimens, with the particularities for each type of plastic, in order to obtain a consistency for the roughness parameters of the specimens.
The materials used to fabricate the specimens are:

- ABS (Acrylonitrile butadiene styrene) with the optimum printing temperature between 240 and 255°C with the solidification temperature ranging between 60 to 100 °C
- PLA (Polylactic acid) – for PLA the printing temperature is ranging between 220 and 230°C with a lower solidification temperature than ABS, between 60 and 20°C

From each type of material mentioned above 6 specimens are fabricated, with 2 mm added on each exterior surface that will be removed during the finishing process.
The specimen's walls are 4 mm thick and the infill has a gyroid structure. The reason for choosing the gyroid infiill structure is that it exercises the least amount of presure on the walls of the specimen and during the milling process it dissipates the milling forces through the entire specimen.

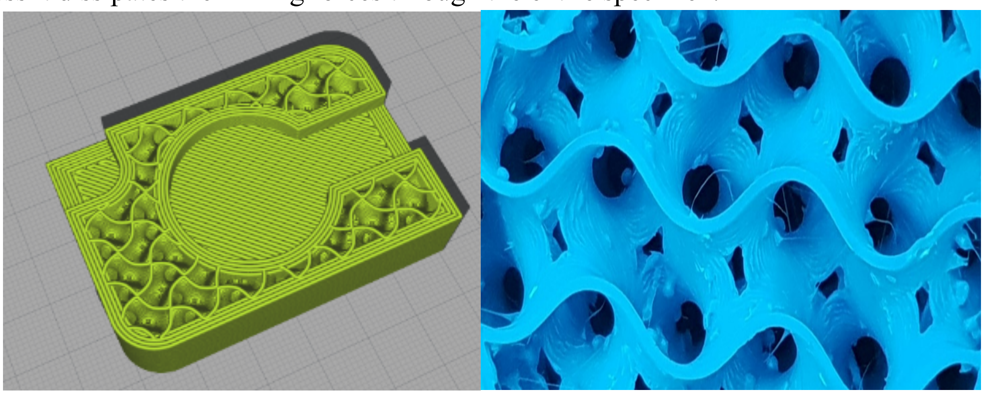


Figure 3 Gyroid structure

The 3D model of the specimens was designed using Catia V5 CAD [7] software and because no specimen standard that is used for roughness determination for thermoplastic materials, we designed a model that includes the most common geometrical features. We also kept in mind that our specimen must have the geometry designed in such a way that several milling operations commonly used in industry can be performed: face milling, profile contouring and pocketing.

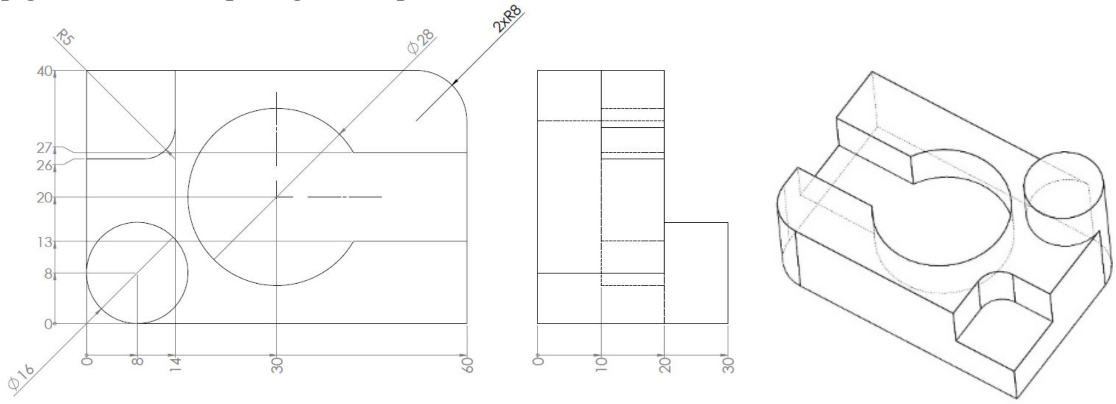


Figure 4 Specimen design and milling dimmensions

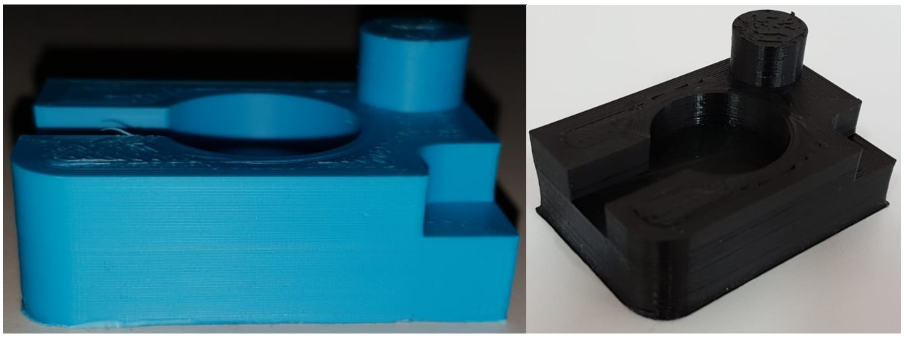


Figure 5 Specimens prior to finishing processes

The G-Code for the milling process has been generated using “SprutCAM 11.5” CAM software, as showed bellow the tool followed a climbing path on the selected contour both for the Ø6 mm and the Ø12 mm mill.

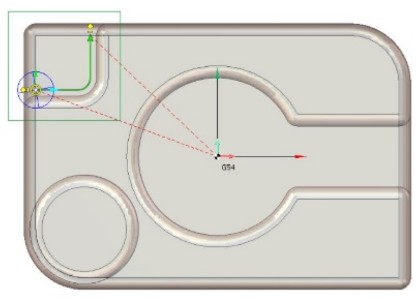


Figure 6. Ø6 mm end mill climb trajectory

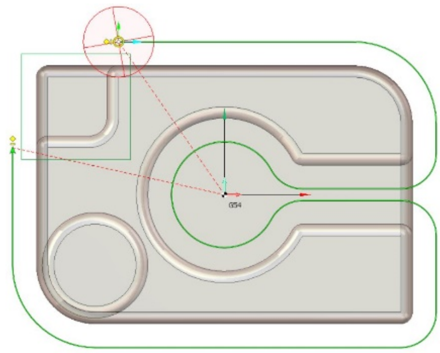


Figure 7. Ø12 mm end mill climb trajectory

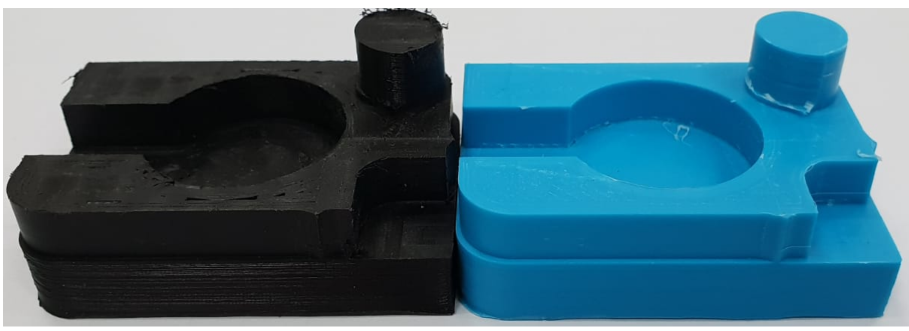
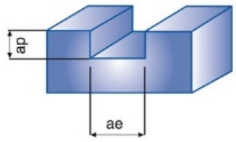


Figure 8 Specimens after the finishing operations

2.1. Milling parameters:



$V_c = \frac{\pi * D * n}{1000}$ (m/min) $\quad ae = 1 * D$

$n = \frac{1000 * vc}{\pi * D}$ (rev/min) $\quad ap = 0.5 * D$

$Vf = fz * z * n * k = f * n$(mm/min)

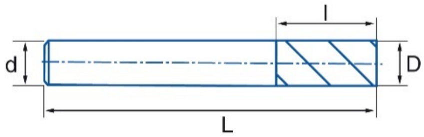
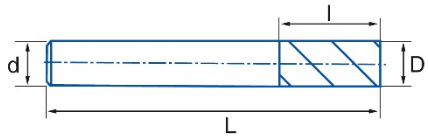
V_c – Cutting speed(m/min); D –Cutter diameter (mm); n – Spindle speed (rev/min); V_f – Feed speed; f_z – Feed per tooth(mm/tooth); f – Feed per rev(mm/rev); z – Number of teeth; ap -depth of cut; ae – width of cut; K – Correction coefficient.
The milling parameters used are presented in table 1:

Table 1: Chosen milling parameters

Parameter	Ø6mm end mill	Ø12mm end mill
n (constant)	3500 (rot/min)	3500 (rev/min)
$supplier's\ catalogue\ V_c$	180 (m/min) with K 0.7	180 (m/min) with K 0.7
supplier's catalogue f_z	0.04 (mm/tooth)	0.06 (mm/tooth)
Resulted V_f	280 (mm/min)	420 (mm/min)

The tools used for finishing the specimen parts are a Ø6mm and a Ø12mm solid carbide end mill described in table 2.

Table 2: Solid carbide end mills properties

	
$ae = 6$	$ae = 12$
$ap = 3$	$ap = 6$
L = 40mm	L = 60mm
L = 10mm	L = 10mm
D = d = 6	D = d = 6
Helix angle 45 °	Helix angle 45 °
Z = 2	Z = 2

2.2. Roughness measurements

The roughness measured with the "Mitutoyo Surftest sj-301" and "Taylor-Hobson Surtronic 3+".

Figure 9. Roughness measurement with "Taylor Hobson Surtronic 3+" measuring probe

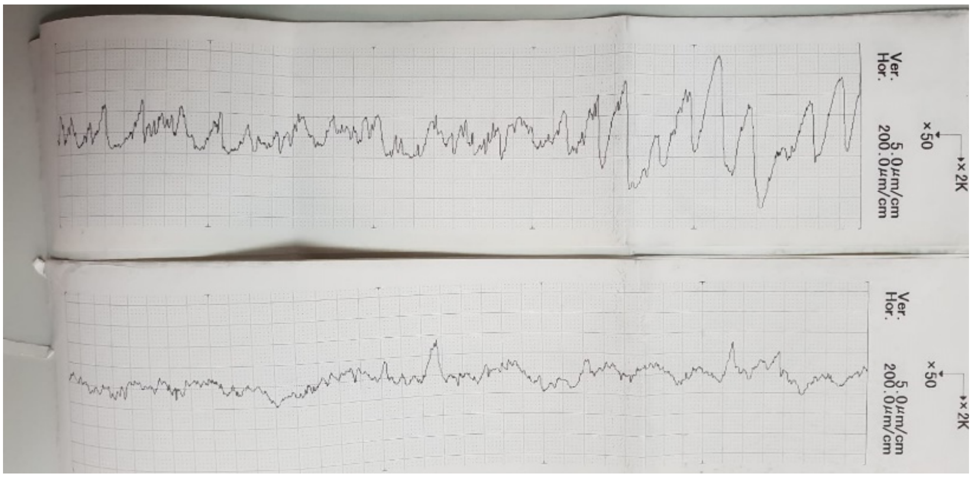


Figure 10. Roughness measurement with "Mitutoyo Surftest sj-301"

We studied the influence that different milling processes and the V_f parameter has on the roughness of the sample's surfaces. The studied values are analysed using the following criteria:

- Rt – average distance between the highest peak and lowest valley in each sampling length.
- Ra – arithmetical mean deviation of the assessed profile
- Rz – five highest peaks and lowest valleys over the entire sampling length.

The studied surfaces are depicted in figure 11.

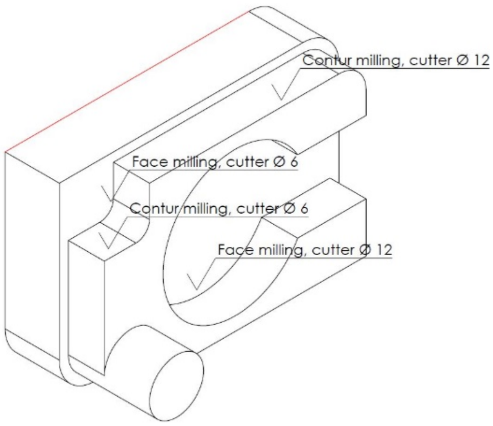


Figure 11. Part surfaces used for determining the roughness value

Prior to the machining finishing process the average roughness couldn't be measured on the PLA parts due to the high values that were out of the roughness tester's range. However, on ABS parts the surfaces roughness could be measured but the resulted values were very high: Rt = 10.4µm, Rz 4.91µm and Ra 0.894µm.

3. Results and discussion

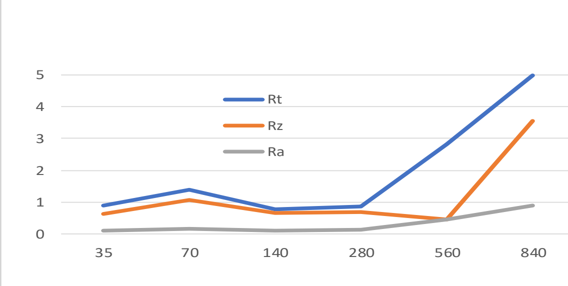
For the tests performed on ABS and PLA fabricated parts we obtained the optimum values for V_f for different milling processes and different end mills. The results can be visualized on figures 12,13,14 and 15.
The optimum V_f values can be analysed in table 2.

Table 2: Optimum resulted V_f

Specimen's material	Milling process	Milling tool	Optimum resulted V_f
ABS	Face milling	Ø6mm end mill	Between 140 and 280 (mm/min)
ABS	Contour milling	Ø6mm end mill	Between 35 and 140 (mm/min)
ABS	Face milling	Ø12mm end mill	Until 210 and after 900 (mm/min)
ABS	Contour milling	Ø12mm end mill	Around 105 and after 1200 (mm/min)
PLA	Face milling	Ø6mm end mill	Around 800 (mm/min)
PLA	Contour milling	Ø6mm end mill	After 1000 (mm/min)
PLA	Face milling	Ø12mm end mill	Around 200 and 850 (mm/min)
PLA	Contour milling	Ø12mm end mill	Around 1300 (mm/min)

Face milling

Specimen n	Material	D	n	Vf	Rt	Rz	Ra
1	ABS	6	3500	35	0.9	0.63	0.119
2	ABS	6	3500	70	1.39	1.06	0.177
3	ABS	6	3500	140	0.77	0.657	0.118
4	ABS	6	3500	280	0.88	0.687	0.137
5	ABS	6	3500	560	2.81	0.47	0.47
6	ABS	6	3500	840	4.99	3.55	0.887



Contour milling

Specimen n	Material	D	n	Vf	Rt	Rz	Ra
1	ABS	6	3500	35	2.75	2.36	0.505
2	ABS	6	3500	70	3.03	2.39	0.505
3	ABS	6	3500	140	3.21	2.48	0.543
4	ABS	6	3500	280	19.4	12.2	1.85
5	ABS	6	3500	560	3.67	2.86	0.575
6	ABS	6	3500	840	3.28	3.13	0.696

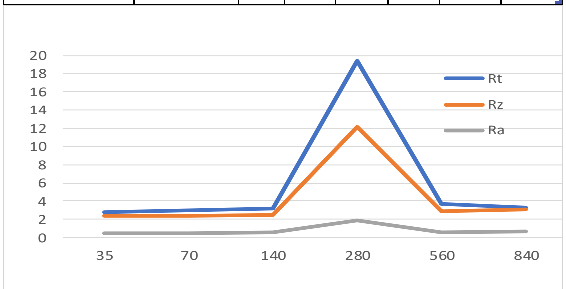
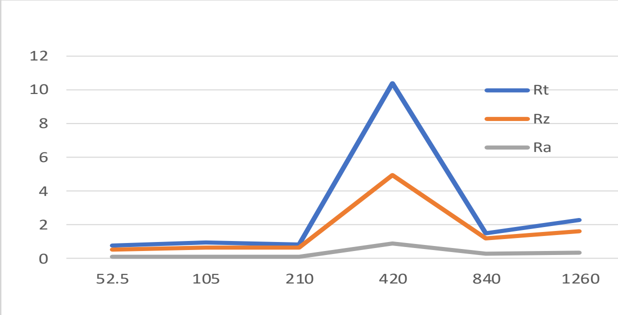


Figure 12. Roughness values for ABS parts after the machining with the Ø6mm end mill

Face milling

Specimen n	Material	D	n	Vf	Rt	Rz	Ra
1	ABS	12	3500	52.5	0.76	0.53	0.105
2	ABS	12	3500	105	0.96	0.652	0.125
3	ABS	12	3500	210	0.83	0.665	0.126
4	ABS	12	3500	420	10.4	4.91	0.894
5	ABS	12	3500	840	1.52	1.18	0.28
6	ABS	12	3500	1260	2.26	1.6	0.314



Contour milling

Specimen no.	Material	D	n	Vf	Rt	Rz	Ra
1	ABS	12	3500	52.5	4.43	2.86	0.624
2	ABS	12	3500	105	3.47	2.73	0.643
3	ABS	12	3500	210	6.33	4.33	0.843
4	ABS	12	3500	420	5.37	3.64	0.724
5	ABS	12	3500	840	4.66	3.85	0.754
6	ABS	12	3500	1260	3.71	2.85	0.639

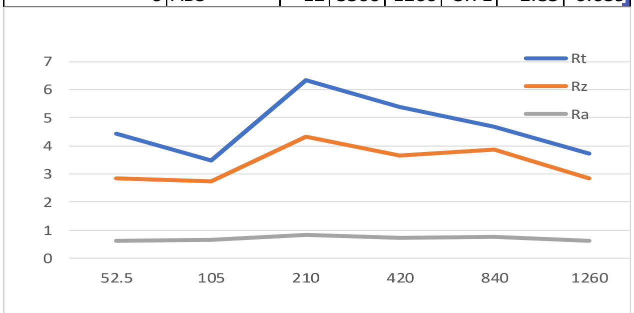
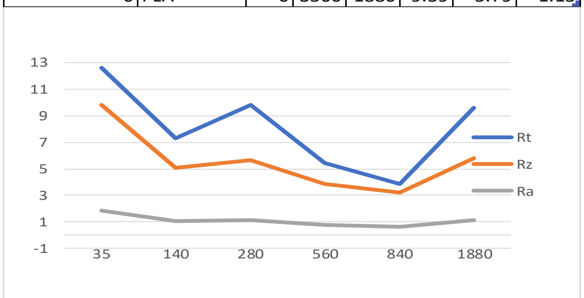


Figure 13. Roughness values for ABS parts after the machining with the Ø12mm end mill

Face milling

Specimen n	Material	D	n	Vf	Rt	Rz	Ra
1	PLA	6	3500	35	12.6	9.77	1.86
2	PLA	6	3500	140	7.27	5.1	1.02
3	PLA	6	3500	280	9.78	5.68	1.16
4	PLA	6	3500	560	5.41	3.85	0.76
5	PLA	6	3500	840	3.88	3.19	0.625
6	PLA	6	3500	1880	9.59	5.79	1.15



Contour milling

Specimen no.	Material	D	n	Vf	Rt	Rz	Ra
1	PLA	6	3500	35	N/A	N/A	N/A
2	PLA	6	3500	140	N/A	N/A	N/A
3	PLA	6	3500	280	8.28	4.55	0.923
4	PLA	6	3500	560	7.77	5.14	1.08
5	PLA	6	3500	840	5.25	4.29	0.803
6	PLA	6	3500	1088	3.72	3.07	0.601

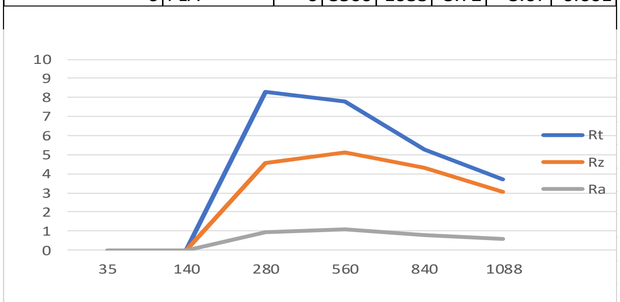
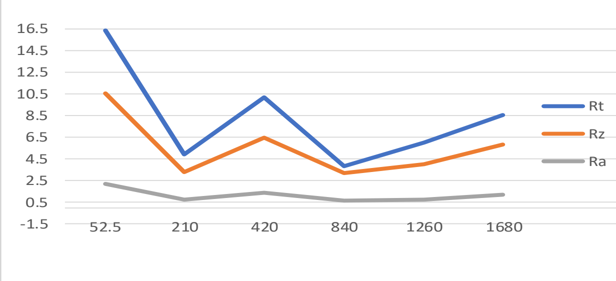


Figure 14. Roughness values for PLA parts after the machining with the Ø6mm end mill

Face milling

Contour milling

Specimen no.	Material	D	n	Vf	Rt	Rz	Ra
1	PLA	12	3500	52.5	16.3	10.5	2.17
2	PLA	12	3500	210	4.95	3.3	0.695
3	PLA	12	3500	420	10.2	6.47	1.39
4	PLA	12	3500	840	3.85	3.19	0.63
5	PLA	12	3500	1260	6.03	3.97	0.705
6	PLA	12	3500	1680	8.54	5.78	1.16



Specimen no.	Material	D	n	Vf	Rt	Rz	Ra
1	PLA	12	3500	52.5	17.1	10.4	2.01
2	PLA	12	3500	210	20.1	15.5	3.46
3	PLA	12	3500	420	7.69	5.23	1.07
4	PLA	12	3500	840	8.71	5.01	0.971
5	PLA	12	3500	1260	4.03	3.09	0.593
6	PLA	12	3500	1680	5.54	4.14	0.924

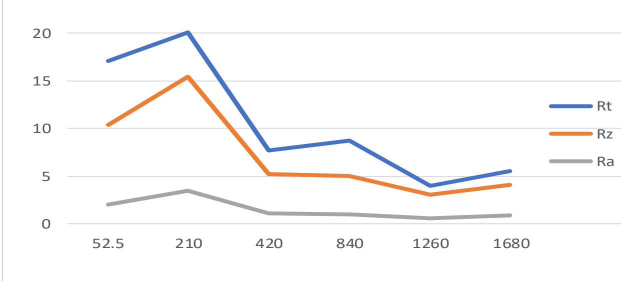


Figure 15. Roughness values for PLA parts after the machining with the Ø12mm end mill

4. Conclusions

From the study we can determined the best parameters for milling 3D printed parts at a constant spindle speed of 3500 (rev/min). Some important observations are: for ABS, slow cutting speeds are producing a better roughness quality. For PLA, the situation reverses, a better surface quality is obtained when using higher cutting speeds. This is due to lower melting temperatures of PLA which implies that the more the cutting tools stays in contact with the part the more heat it will generate and will deteriorate the part's surface.

5. Acknowledgement

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