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# Improving dimensional and surface quality of additive manufactured parts

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**Abstract.** In modern manufacturing of polymer components the injection moulding represents the conventional way to get the desired shape respecting dimensional and surface requirements. But, such process plan requires the design of the tools and that of whole manufacturing process. A different choice could be done when the production consists of small batches or a single unit. In this case it is useful to realize the workpiece without tools taking into consideration the additive manufacturing technique. The limit of such flexible manufacturing technology is represented sometimes, in particular in working polymers such as ABS, by the difficulty to respect dimensional and surface requirements. The research activity to be presented involved the realization of cubic geometries in ABS by FDM (Fused Deposition Modeling). The staircase, the waviness and roughness of the surfaces were evaluated and quantified. The slight machining phase performed by front milling considered in the process plan allowed to reduce the staircase effect up to about zero and to reduce the waviness of about some decimals of millimeter to some hundredth of millimeter. The surface roughness was also improved. The methodology and the details are reported.

## 1. Introduction

The manufacturing of polymer components is usually performed by injection molding in order to get the desired shape in terms of dimensional and surface quality. But, such process plan requires the design of the tools and that of whole manufacturing process. When a small batch or a single unit has to be made the design and the realization of a product with customized tools could become very expensive and time consuming.

The advantage of additive manufacturing techniques consists in realizing parts without the use of conventional tools in a completely flexible way. In most of the cases the flexibility can be managed by the simply use of the input data. The limit of such flexible manufacturing technology is represented sometimes, in particular in working polymers, by the difficulty in respecting dimensional and surface requirements [1].

In particular, the dimensional quality depends on waviness [2] and staircase effect [3] which in turn depend on different phenomena taking place during the process itself also related to thermal expansion and shrinkage. The method to solve the shrinkage taking place in the injection molding of ABS is reported in [4]. The reprocessing of the ABS particles obtained after testing of previously made



components allows to reduce the shrinkage of about 0.1 % with an amount of reprocessed material up to 50%. By [5-9] it is possible to make a comparison between some characteristics obtained for ABS components made by injection molding and FDM concluding that some properties, such as density, produced with those technologies are similar to each other, confirming the flexibility and the sustainability of the FDM in realizing different geometries without any conventional tool.

In [10] some parameters used in realizing samples in Polypropylene by Fused Deposition Modeling with different deposition strategies, nozzle temperatures, linear plotting speeds with a layer thickness varying in the interval of 0.20- 0.36 mm are reported. It can be observed that for given values of other parameters the layer thickness dimension affects the tensile strength of the specimens. When operating under very strictly requirements such parameter can affect the geometry and the in service properties of the components. In [11] the management of the error was previously performed in the CAD – STL format conversion, while in [12] the correction was made by the slicing approach. In [13] some simulative tools are reviewed and proposed. In particular in [14] some skills in assisted additive manufacturing taking into consideration adaptive slicing and a tool path assigned by G-code were proposed, but such approach is mainly directed to the increase of the flexibility of the process. In [15] the researchers compared to each other the textures of a given hybrid additive manufacturing technology produced under different conditions. Some authors in understanding the difficulty in evaluating geometrical quality of additive manufactured parts tried to give some rules in evaluating them [16]. In the same way the surface roughness [2] represents an output to be considered in the evaluating of surface quality. In particular, in [17] some authors compared the surface roughness values, varying from 6.5 to 12.5  $\mu\text{m}$ , of additive manufactured areas obtained at different layer thicknesses of 0.178 and 0.254 mm. In [18] the researchers found a surface roughness of the additive manufactured area considered varying up to about 10  $\mu\text{m}$  and a waviness of about 50  $\mu\text{m}$ . In [19] after additive manufacturing treatment by polishing of an ABS part the surface roughness was reduced from about 3 to about 1  $\mu\text{m}$ . Other authors presented methods based on reverse engineering [20] in order to evaluate the dimensional quality of FDM parts. But in literature only few works can be found related the both dimensional and surface quality of additive manufactured parts.

In the present investigation, two cubic elements in ABS realized by FDM were analyzed in terms of the dimensional and surface characteristics. In particular, the dimensional characteristics were analyzed in terms of waviness and staircase while the surface ones were quantified in terms of surface roughness. Two different geometries with two different internal cavities were built in order to take into account the effect of the building, of the shrinkage and of the distortion phenomena on the waviness, staircase and surface roughness. A dimensional and the surface quality typical of that got by the machining process was finally obtained by a front milling phase. The methodology and the results are reported in detail.

## 2. Experiment procedures and requirements

The experiment work consisted initially in realizing two specimens by Fused Deposition Modeling using a FORTUS250 and then in realizing a light machining phase. The methodology is reported in Figure 1 and described as follows.

The two specimens, reported in figure 2, in ABS-PLUS with the external nominal dimensions of 50x50x50  $\text{mm}^3$  got two different internal cavities. The specimen A characterized by a cavity of 15x15x15  $\text{mm}^3$  and the specimen B with a cavity of 45x45x45  $\text{mm}^3$ . In order to check the possibility to realize lightweight components, the effect of the internal cavity dimensions on the dimensional and surface characteristics was evaluated.

During the building process the temperature of the table was 100-120°C while the temperature at extrusion head was about 220-230°C. The slice of the thickness used was 0.28 mm, while the fused

deposition speed was about 17000 mm<sup>3</sup>/h. A layer of about 1 mm at the basis of each specimen was considered as supporting material. The two specimens, after building, were subjected to the conventional cleaning procedure.

The dimensional and surface characteristics of both the specimens were detected by a 2D scanning and by a surface roughness measurement.

The scanning method was applied for specimens A and B on the top and on the lateral surfaces. In the present investigation, the building axis was Z, while plane perpendicular to the building one was X-Y. It was possible to reveal the main profile shape amounts:

- the low frequency information measured as waviness;
- the staircase phenomenon;
- the high frequency information measured as surface roughness.

The surface roughness Ra was evaluated by:

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

Where l is sample length and y the height of the profile point on the mean line. The maximum peak to valley roughness value was evaluated by R<sub>z</sub>.

In order to obtain given specifications that are the waviness < 0.05 mm, Ra < 2 μm and a staircase value less than Ra requirement, a conventional machining phase was performed on a turning milling centre. The machining parameters used were 0.025 mm/(rev tooth) with a cutting speed of 1500 m/min. In both the A and B specimens a total of 0.3 mm was machined getting a smooth profile shape and an improved surface roughness. After machining the 2D scanning and the surfaces measurements were repeated. The details of the measurement values were reported in the next paragraph.

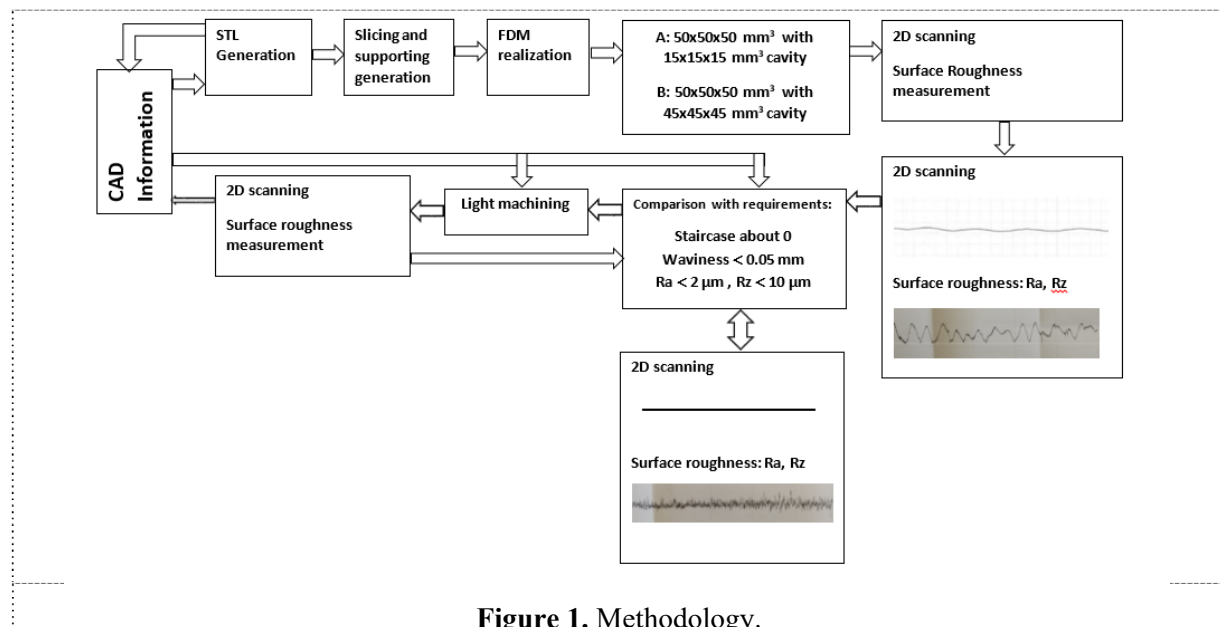


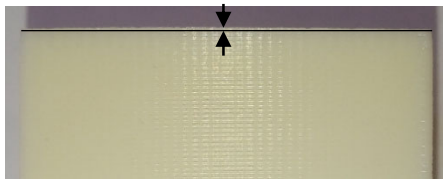
Figure 1. Methodology.



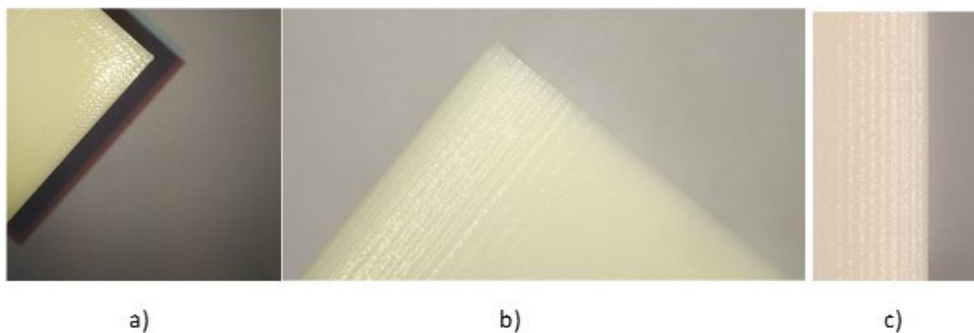
**Figure 2.** Specimens realized with Fused Deposition Modeling.

### 3. Results and discussion

The real dimensions of the two specimens produced by FDM can differ from the nominal ones of a quantity equal to 0.3 mm depending on the directions. In particular, it was observed that the dimensional and surface quality can have different contributions. Among them, it is possible to distinguish: the low frequency information detected as waviness, the staircase phenomenon and the high frequency information detectable as surface roughness. From the general point of view, the waviness can be responsible for the configuration shown in Figure 3, while the staircase effect and the surface roughness can be seen in Figure 4.



**Figure 3.** Dimension lack of quality of the specimens.

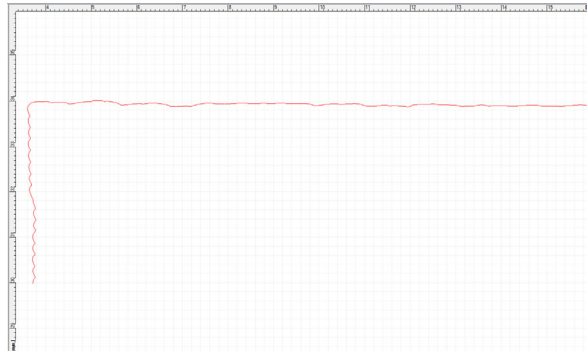


**Figure 4.** Surface appearance and staircase effects on specimens realized by FDM: top surface (a), lateral surface (b), staircase effect (c).

The staircase effect and the waviness were detected by a 2D scanner performed along the building direction (the Z axis), on the top surface and on the surfaces of the X-Y plane .

The staircase effect detected can be attributed to the mechanisms taking place during the process that consist in generating the filament of fused polymer and in depositing it over the previous one. During that phase the previous layer tends to melt a bit while the actual layer tends to solidify. In that mechanism the local expansion-shrinkage cycle produces an increase of uncertainty. That uncertainty is then distributed along the building direction and on the direction perpendicular to that. When the last layer is deposited the surficial tension and the drop effect can produce an increase in the waviness. The waviness is reported in Figures 5, 6, 7 and 8.

The weavy behaviour is shown by the two specimens giving a peak to peak difference in the case of specimen A of  $0.1 \div 0.2$  mm and of  $0.2 \div 0.3$  mm in the case of specimen B. That different behaviour of two specimens could be probably attributed to the different response to the thermal expansion and shrinkage taking place during and after the fused deposition process of the material under investigation. The specimen A is in fact characterized by an external thickness of about 17.5 mm while the specimen B got a thickness of 2.5 mm.



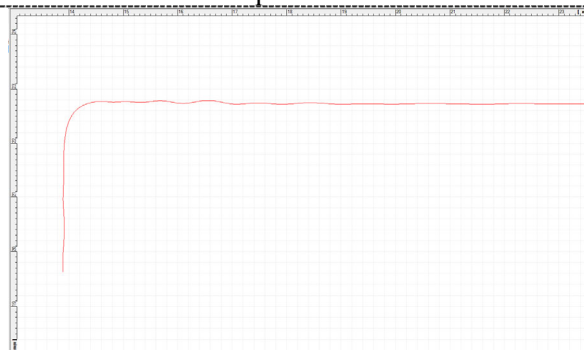
**Figure 5.** Profile shape of specimen A in the Z direction and on the top surface.



**Figure 6.** Profile shape of specimen A in the lateral surfaces of the X-Y planes



**Figure 7.** Profile shape of specimen B in the Z direction and on the top surface.



**Figure 8.** Profile shape of specimen B in the lateral surfaces of the X-Y planes.

Such phenomena are also responsible for the detected surface roughness  $R_a$  and  $R_z$  reported in Table 1 for both the specimen A and B.

In particular, the  $R_a$  detected on the top surface for A and B were 15.09 and 13.45  $\mu\text{m}$ , while those measured on the lateral surfaces were 1.679 and 1.803  $\mu\text{m}$ , respectively. The  $R_z$  values were 84.45 and 77.28  $\mu\text{m}$  for the top surfaces of specimens A and B. The  $R_z$  of the lateral surfaces were 7.73 and 9.984  $\mu\text{m}$ . Such values are in agreement with those found in [3].

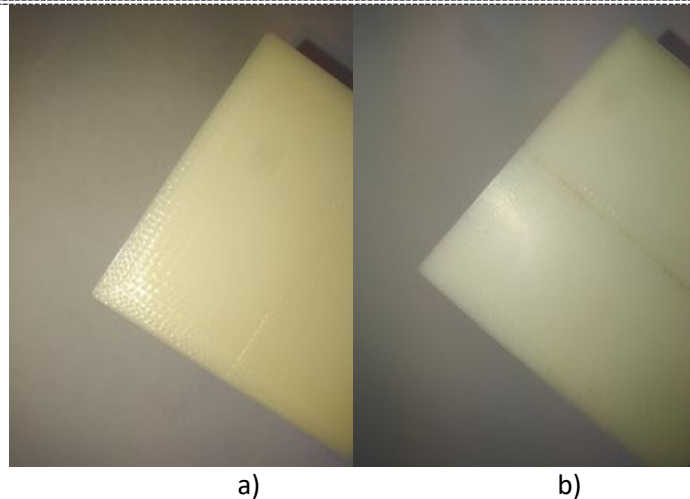
**Table 1.** Surface roughness  $R_a$  and  $R_z$  detected on the specimens A and B after FDM.

Specimen		$R_a$ ( $\mu\text{m}$ )	$R_z$ ( $\mu\text{m}$ )
A	Top surface	15.09	84.45
	Lateral surface	1.679	7.730
B	Top surface	13.45	77.28
	Lateral surface	1.803	9.984

All of the contributions to the dimensional and surface quality determined the assembly problems at macro-contact level reported in Figure 9 in which the discontinuity line between the two surface specimens is evidenced.



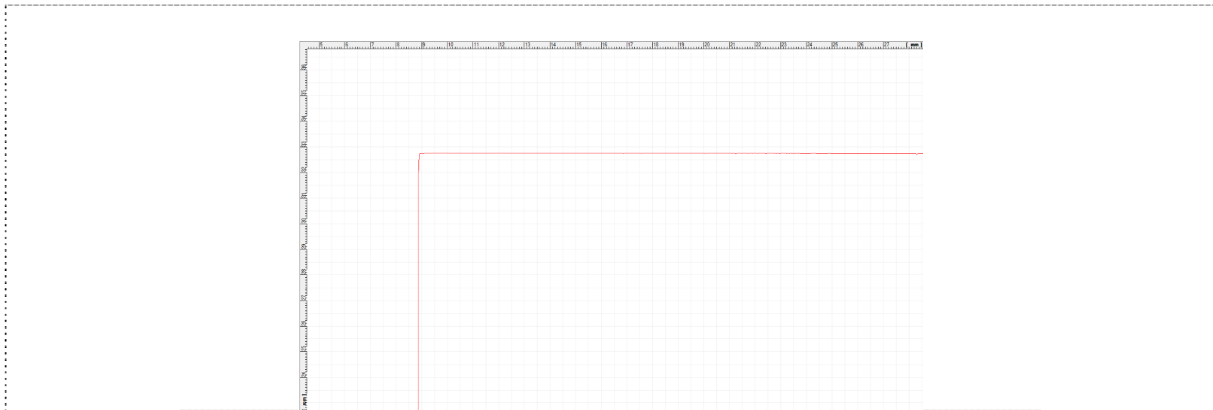
**Figure 9.** Assembly problems at macro-contact level of the built specimens.



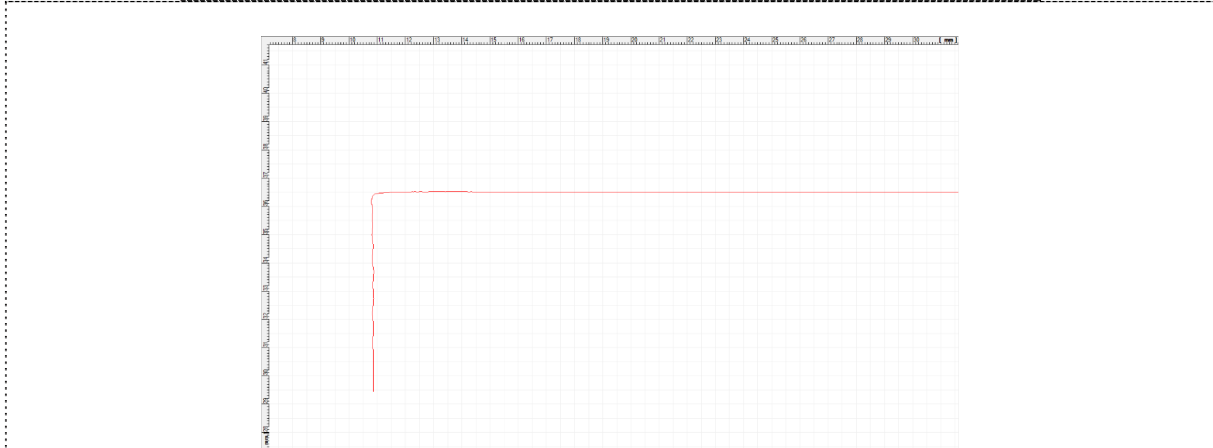
**Figure 10.** Comparison between the top surfaces after additive manufacturing a) and after machining b).

The machining phase introduced an improvement on the surfaces of the specimens. In Figure 10 the comparison between the typical top surfaces before and after machining is reported. This is due to the improved conditions in terms waviness and surface roughness. Concerning the waviness the obtained profiles are reported in Figures 11, 12, 13 and 14. It can be observed in detail that the staircase effect is strongly reduced and the waviness is reduced down to 0.02 mm. The  $R_a$  and  $R_z$  for the specimens A and B detected after machining are reported in Table 2. In particular, the  $R_a$  on the top surface for the specimens A and B became 1.468 and 1.045  $\mu\text{m}$ , while on the lateral surfaces the values were 1.634 and 0.939  $\mu\text{m}$ , respectively. Such values are comparable with those obtained in [21] by other authors even if the attention of them was mainly focused on the staircase component of the dimensional and surface characteristics. The present investigation allows to understand that, from both the dimensional and surface points of view, the external quality after machining seems not depending on the internal cavity dimension. Furthermore, the proposed methodology allows to improve the dimensional and surface characteristics of the additive manufactured samples and their attitude to be assembled together like reported in Figure 15.

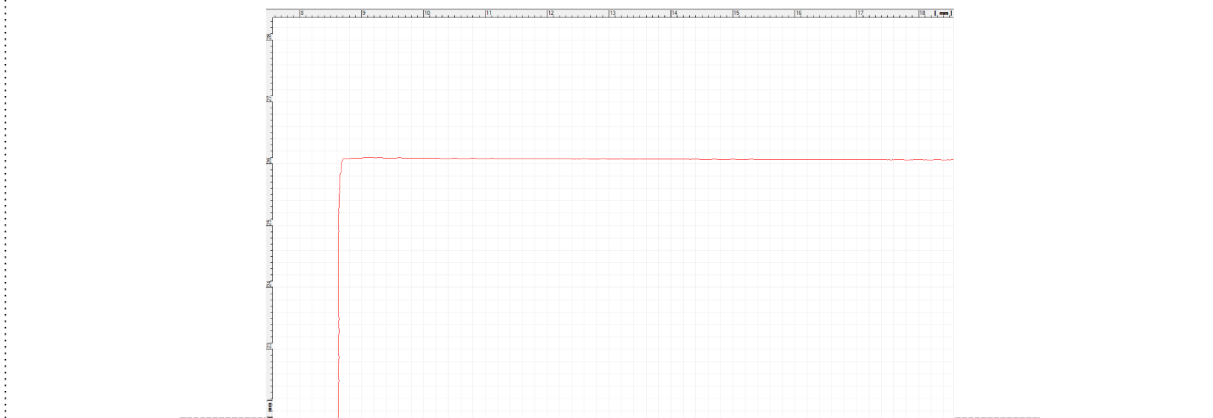




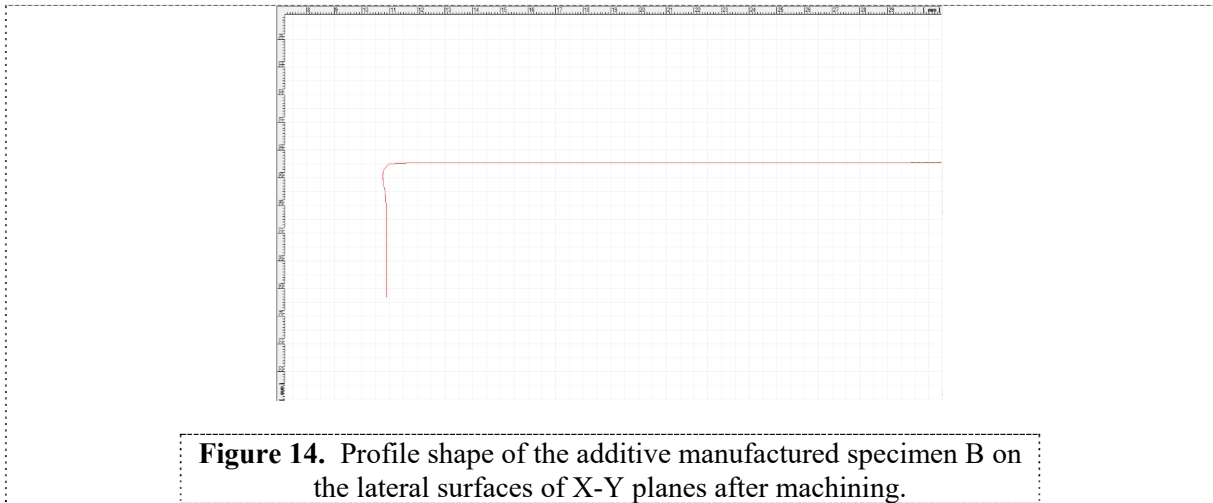
**Figure 11.** Profile shape of the additive manufactured specimen A in the Z direction and on the top surface after machining.



**Figure 12.** Profile shape of the additive manufactured specimen A in the lateral surfaces of X-Y planes after machining.

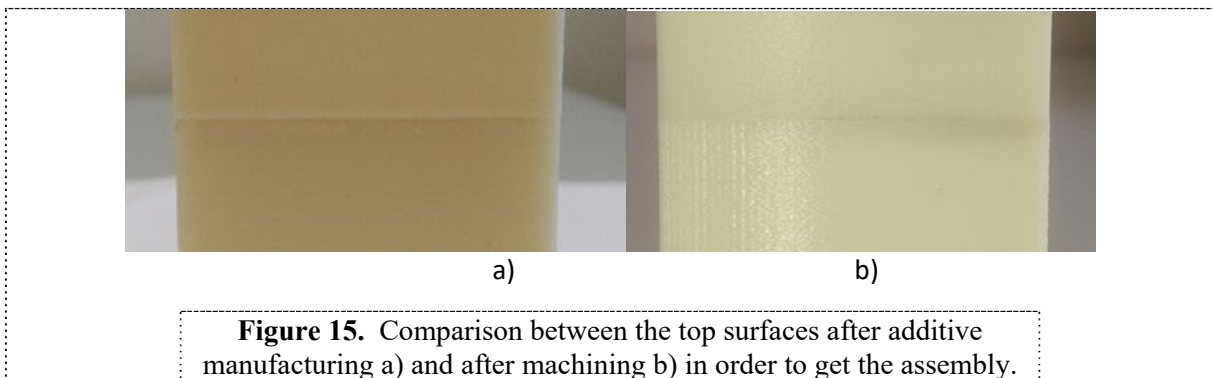


**Figure 13.** Profile shape of the additive manufactured specimen B in the Z direction and on the top surface after machining.



**Table 2.** Surface roughness  $R_a$  and  $R_z$  detected on the specimens A and B after machining.

Specimen		$R_a$ ( $\mu\text{m}$ )	$R_z$ ( $\mu\text{m}$ )
A	Top surface	1.468	12.92
	Lateral surface	1.634	13.84
B	Top surface	1.045	7.136
	Lateral surface	0.939	8.542



#### 4. Conclusions

The dimensional and surface quality was detected in terms of waviness, staircase and surface roughness. Two different conditions are considered that are the simple additive manufacturing and the additive manufacturing plus machining.

After additive manufacturing performed by FDM it was observed that:

- the real dimensions of the specimens can differ from the nominal ones of 0.3 mm depending on the measurement direction;
- the detected waviness was of 0.1 – 0.2 mm for the specimen A and of 0.2 – 0.3 mm for the specimen B;
- the surface roughness  $R_a$  values of the top surface were 15.09 and 13.45  $\mu\text{m}$  for the specimens A and B respectively, while the lateral ones were 1.679 and 1.803  $\mu\text{m}$ .

After machining, an improvement was detected in particular:

- the waviness detected after 2D scanning was 0.02 mm and the staircase completely reduced as can be observed on the profile shapes;
- the surface roughness  $R_a$  was improved down to 1.045  $\mu\text{m}$  for the top and to 0.939  $\mu\text{m}$  for the lateral surfaces of the specimen B.

It can be concluded that in the conditions of the present investigation, the proposed methodology allows an improvement of the assembly attitude after machining for the specimens A and B and the final dimensional and surface quality seems not depending of the dimension of the internal cavity.

In addition the proposed methodology allows to shorten the process plan in order get ABS components respecting given requirements.

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