



Chemical vapor treatment to improve surface finish of 3D printed polylactic acid (PLA) parts realized by fused filament fabrication

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Abstract

Fused filament fabrication (FFF) is one of the most extensively used 3D printing process for its several advantages and the possibility to obtain complex geometries. Different materials can be processed and polylactic acid (PLA), a thermoplastic biodegradable cost-effective material, is widely used for consumer FFF. Typically, PLA printed parts have high surface roughness, due to the staircase effect, the slice-to-slice construction texture and the filament deposition. In this work, authors propose a quantitative analysis of the effects of a chemical treatment based on ethyl acetate vapors, to improve the surface finish of PLA printed parts. The solvent was selected for its low toxicity, easy availability, and low cost. To validate the treatment, a 2³ full factorial plan was designed and a roughness analysis before and after the chemical treatment was performed to highlight the influence of each parameter involved.

Keywords Additive manufacturing · Fused deposition model · Roughness · Surface finish · PLA · Chemical vapor treatment

1 Introduction

Additive manufacturing (AM) technologies, also known as 3D printing techniques with particular reference to the fabrication of objects through the deposition of material using a print head or a nozzle [1], are becoming ever more adopted in many industrial fields and they are well integrated in the concept of advanced manufacturing, a key principle of Industry 4.0 [2]. The leading companies, from US to China and Europe reserved great investments in AM technologies due to their great potential and their applicability in several manufacturing fields [3], even considering the integration with subtractive techniques [4, 5]. The advantages in using these technologies are many and, among them, the possibility to fabricate very complex parts, as well as customized parts with the integration of reverse engineering techniques, and the sustainability, demonstrated for certain applications [6, 7], are prevalent. Regarding the cost analysis, it was found to be strongly dependent on the batch size, as reported in [8], where a cost evaluation model based on

computational algorithm was developed in order to assess the overall cost due to design and production of aerospace parts made by Wire + Arc AM and compare them to the costs coming from traditional machining technologies.

Regarding the use of polymers, since the early 2000s, fused deposition modeling (FDM) has been the most popular additive manufacturing and 3D printing process worldwide. FDM consumer technologies have registered a huge increase: cheaper machines make the filament-based technologies more accessible today than ever before, partly due to the expiry of the FDM patent in 2009. Afterwards, the term fused filament fabrication (FFF) was also used to denote the same technology. There are many thermo-plastics used in the FFF processes, such as ABS plastics, polycarbonate (PC), etc., and many studies have been carried out to evaluate its properties before and after solidification [9, 10]. Among them, one of the most interesting materials is the PLA poly(lactic acid) along with combinations in the form of composites [11, 12]. The great interest towards this polymer is attributable to its derivation from sustainable sources with the fulfilling of the new environmental requirements. In particular, the diffusion of high-molecular weight polymers enabled the implementation of this material and its diffusion among the FFF technologies, broadening its use [13]. Nowadays, the most appreciated characteristics of this material are

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the cheapness, the easy availability, printability, low toxicity and biodegradability [14].

The main criticalities of the FFF technologies are attributable to the mechanical properties, the surface finish due to the typical staircase effect, and the dimensional accuracy, which make this technology still not suitable for some engineering purposes.

In this context, authors propose a quantitative analysis of the surface finish improvements on FFF parts made of PLA using a chemical vapor treatment based on ethyl acetate. The main advantages in using this method are related to the availability of this solvent, its affordability, the rapidity of the process and the very low solvent concentration needed.

2 Research background

Countless studies about FDM have been conducted to analyze and optimize the process parameters and to predict the mechanical and topological characteristics of parts made by this technology [15–18].

Based on their results, several parameters are considered significant for the improvement of the mechanical characteristics as well as for the surface roughness, such as layer height, nozzle diameter, printing speed, raster angle, shell thickness, infill density and so on. Moreover, the anisotropic behavior of FDM parts make the surface finish, as well as the mechanical properties, specifically dependent on the building direction [19–21].

The surface integrity of FDM/FFF parts is one of the main criticalities affecting the widespread industrial diffusion of these techniques. The poor surface texture is mainly a result of the layer-by-layer deposition of material, which produces the typical staircase effect.

Several works were conducted trying to improve the surface finish characteristics through different methodologies and, according to the literature review, the basic method/approaches for improving the surface finish are operated by parametric optimization, empirical and analytical modelling, surface roughness prediction [15], mechanical post-processing methods and chemical treatments.

The mechanical post-processing methods usually involve machining, abrasive treatment [22], heat cutting, barrel finishing (BF) [23]. In [24], the improvement in surface finish of FDM parts was achieved using computer numerical control (CNC) milling machines; however, these treatments are well suited for simple geometries and not for free-form surfaces with undercuts. Chemical treatments are widely adopted, due to their several advantages, such as the absence of geometrical limitations and the rapidity of the process. Chemical treatments comprise the use of solvent in its liquid form or as vapors.

In [25], a dimethyl ketone–water solution was used to improve the surface finish of ABS parts made by FDM, considering the influence of the treatment on the mechanical properties. In [26], the same solution was used, considering both the lateral sides and top surfaces of parallelepiped samples. More recently, chemical vapors treatments were used. In [27], a chemical vapor treatment based on acetone was used to improve the surface finish of ABS parts with a marginal reduction in mechanical strength observed after post-built treatment. In [28], the Vapor Smoothing Station (VSS) was used for improving the surface finish of FDM printed parts through chemical exposure of a cost-effective volatile fluid (acetone). In [29, 30], cold vapors of dimethyl ketone applied to ABS material proved to be a good way to improve surface quality without sacrificing the dimensional accuracy or the feature geometries. In [31], cold vapor smoothing with acetone and methyl ethyl ketone (MEK) was used and the surface roughness analyzed with respect to the treatment time. For both solvents a consistent roughness reduction was achieved after at least 30 min. Chemical vapor smoothing (CSV) has been also successfully tested in [32] for the improvement of the surface finish of ABS replicas.

Another methodology to improve surface quality for wax injection tool fabricated by FDM was developed by filling the gaps with other materials, such as aluminum epoxy-based composites [33].

As it is possible to observe, most of the literature review is focused on parts made of ABS. However, recently, great interest arose for the PLA material, as already discussed in the introduction, considering both mechanical properties and surface finishing treatments [11, 21, 34–36]. In particular, chemical surface finishing treatment was applied in [37] through a NaOH solution and dichloromethane vapors, obtaining a decrease of the surface roughness. Dichloromethane vapors were also used in [38], where the evolution of the surface topography during the chemical treatment was also represented by a geometrical model. Moreover, in [39], different chemical post-processing methods were applied to polylactic acid pieces obtained by FFF, by immersing the samples in four inorganic solvents with an improvement in the roughness of the pieces of up to 97% when using chloroform and of about 35% when using Ethyl acetate. Similar results were found in [40], where different solvents were used during the post-processing of FFF parts made of PLA by dipping and spraying the solvent (100% of concentration) on the parts surface. A qualitative case study of surface finishing treatment effects based on ethyl acetate vapor is shown in [41]. In this latter research, authors applied the treatment on bevel gears improving the surface finish, but it is not reported any numerical evaluation of the effects on the roughness values obtained after the treatment.

In all reported papers dealing with chemical vapor treatment on PLA 3D printed parts, there are no structured experiments analyzing the treatment process parameters and how they affect the roughness reduction.

In the present work, authors tried to fill this gap, by conducting a quantitative analysis of the roughness reduction achievable by using a chemical vapor treatment based on ethyl acetate. The solvent was selected for its low toxicity, easy availability, and low cost. The aim was to demonstrate the effectiveness of the proposed treatment on parts made by PLA, without neglecting the issues related to the toxicity and the sustainability of the process. The first part of the paper is focused on evaluation of the effects of 3D printing process parameters on the roughness. The second part is dedicated to the analysis of the effect on the roughness reduction produced by the chemical treatment by varying two main parameters: the treatment time and the amount of solvent. Results are greatly supported by statistical analysis.

3 Materials and methods

With the aim of improving the surface finish of components made by FFF of PLA, a method exploiting the ethyl acetate (C₄H₈O₂) vapors was developed. The dimethyl ketone is usually used to improve the surface finish of ABS parts, while ethyl acetate is a good solvent for PLA, both in its liquid form and when it is brought to boiling temperature, except when it is in crystalline form [42].

In this paper, PLA made by Fabbrix® was used (density equal to 1.24 g/cc, without any colorant (natural color), melting point 145–160 °C and a glass temperature 60 °C). For the experimentation, two full factorial plans 2³ were designed (Table 1). The first for analyzing the influence of the machine process parameters on the surface finish (roughness) before the chemical treatment, the second to analyze

the improvement of the surface finish due to the proposed treatment.

In total, 24 × 2 cubic samples with overall dimensions of 20 × 20 × 20 mm³ were made. The test samples were manufactured using a FFF Delta Wasp consumer machine with 0.4 mm nozzle diameter, 1.75 mm filament diameter and using the following fixed process parameters: 100% infill for all tests, 0.8 mm perimeter thickness, and an extrusion temperature of 210 °C. Ultimaker Cura software 3.6.0 was used to generate the part program for the FFF machine. The top and bottom slices have the same structure of the inner slices.

The variable process parameters selected as input factors for the first (pre-treatment) experimental plan were: the layer height, the infill line distance (the same value for the internal, top and bottom slices), and the deposition speed (Table 1, group1). The infill line distance is defined as the distance between the axis of two adjacent roads (see Fig. 1) and, typically, it affects the roughness of the horizontal/top surface, while the layer height normally affects the roughness on the lateral surfaces.

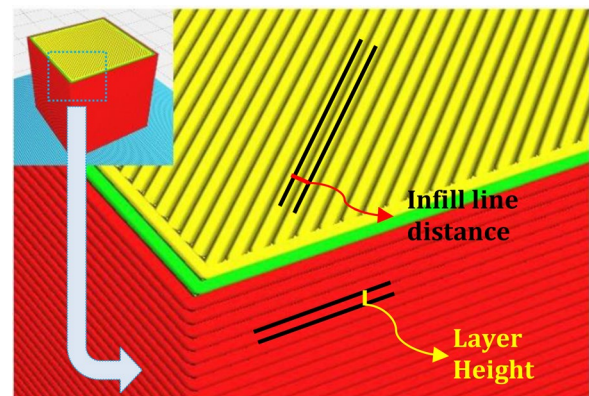


Fig. 1 Process parameters description on the fabricated cube

Table 1 Input factors of two 2³ factorial plan (without and with chemical vapor treatment)

Group 1 first factorial plan Specimen type	Without chemical vapor treatment			Group 2 s factorial plan specimen type	With chemical vapor treatment only on types 6 and 8 specimen layer height 0.35 mm, deposition speed 100 mm/s		
	Layer height [mm]	Infill line distance [mm]	Deposition speed [mm/s]		Infill line distance [mm]	Solvent [ml]	Treatment time [s]
1	0.25	0.2	50	9	0.2	3	180
2	0.35	0.2	50	10	0.4	3	180
3	0.25	0.4	50	11	0.2	5	180
4	0.35	0.4	50	12	0.4	5	180
5	0.25	0.2	100	13	0.2	3	360
6	0.35	0.2	100	14	0.4	3	360
7	0.25	0.4	100	15	0.2	5	360
8	0.35	0.4	100	16	0.4	5	360

Considering this first experimental plan, two output parameters were examined: the surface finish in terms of roughness (Ra) and the production time.

The only purpose of the first factorial plan was to determine a set of 3D printing starting parameters considering both roughness and production time, since they can vary from machine to machine, especially for consumer ones. For FFF consumer machines, such as Delta WASP, it often occurs that the data declared by the manufacturer, in terms of optimized parameters for achieving certain values of accuracy and surface finish, are different from the ones measured. The second factorial plan (which is also the core of the paper) was designed to study the effect of the chemical treatment on the maximum roughness reduction obtainable, whatever the starting values of roughness. Furthermore, 3D printing process parameters are not influent with respect to the amount of roughness reduction achieved with the chemical treatment, as demonstrated by some preliminary tests conducted by the same authors before planning the post-treatment factorial plan. Thus, for the post-treatment factorial plan (Table 1, group2), the amount of ethyl acetate, the treatment time and the infill line distance were considered as the input parameters. As output, only the surface finish (Ra) was considered. As process parameters selected for the post-treatment factorial plan, the layer height and the deposition speed were kept constant (0.35 mm and 100 mm/s, respectively), thus the surface finishing treatment was applied only to the samples produced in the shortest time (groups 6 and 8, Table 2). Before choosing the input parameters for the post-treatment plan, some preliminary experiments were carried out to verify the non-significance of the layer height on the effect of the vapor treatment. Given the results of these experiments and considering the influencing factors coming from the first factorial plan, the infill line distance was considered, since in pre-treatment factorial plan, it was found to be the most influencing factor on the roughness values (see Sect. 4). Moreover, the amount of solvent and the treatment duration were considered in the experiments.

The surface finishing treatment was carried out using a watertight cylindrical container of 1 L (having the diameter equal to 50 mm and height 127 mm) with the exact amount of ethyl acetate (Fig. 2). Each sample was placed and suspended in the middle of the container, by a wire passing through a small half ring, printed on the top of the cube, to avoid any contact between the sample and the liquid solvent. The container was then put in boiling water (100 °C) to evaporate the solvent throughout the treatment duration. The effects due to two different treatment times, 180 s and 360 s, were then analyzed. After treatment, the part was dried using a low-pressure air flow.

The surface texture analysis was carried out using a Taylor Hobson CCI-MP-HS optical profiler with a 20× lens mounted and an optical resolution of 1 μm; this instrument allows to acquire a 2.5D surface contactless, without leaving traces and preserving the original state of the surface. The acquired surfaces were analyzed with the Talymap

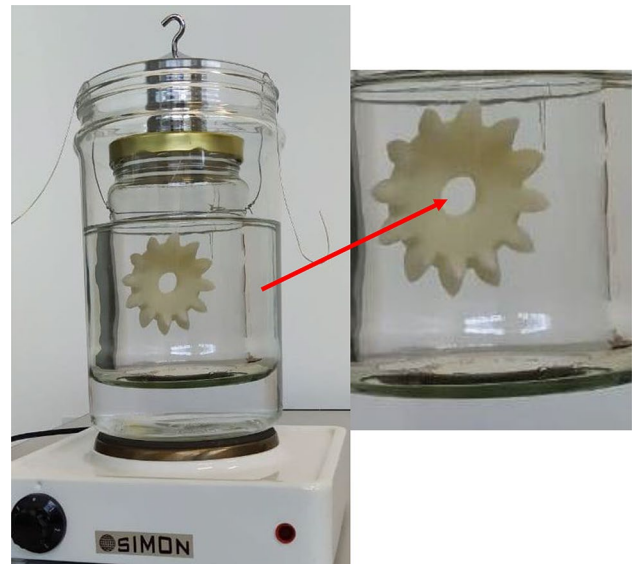


Fig. 2 Equipment used for the treatment with ethyl acetate

Table 2 Top surface roughness (Ra) and production time before chemical vapor treatment

Group # first fact. plan	Layer height [mm]	Infill line dist. [mm]	Dep. speed [mm/s]	Average roughness Ra [μm]	Average Ra standard deviation	Prod. time [min]
1	0.25	0.2	50	2.25	0.91	77
2	0.35	0.2	50	4.23	1.41	64
3	0.25	0.4	50	7.06	2.14	33
4	0.35	0.4	50	10.85	3.98	25
5	0.25	0.2	100	3.65	0.42	43
6	0.35	0.2	100	5.25	0.87	36
7	0.25	0.4	100	7.05	0.94	19
8	0.35	0.4	100	8.04	2.55	14

Platinum version 7.2.7481 software. Thus, the roughness was evaluated from the average profile of a series of 1536 profiles extracted in the orthogonal direction with respect to the deposition direction, using a Gauss cut-off filter, equal to 0.8 mm ($\lambda_c = 0.8$ mm) according to the ISO 4287. The surface analysis was first conducted on the top surface of the sample (on the central area of 15×15 mm², excluding the peripheral parts). Moreover, to verify the efficiency of the treatment, the Ra was also measured on the lateral surfaces of the samples, using the Taylor Hobson Surtronic 3P roughness tester, with the same cut-off equal to 0.8 mm.

For both measurements, top and lateral surfaces, several profiles were considered. As mentioned, for the top surface, since it was measured by an optical instrument, a series of 1536 profiles were considered in the computation.

Regarding the lateral surfaces, evaluated by a contact roughness profilometer, 5 profiles/side were considered, with a total of 20 profiles/sample. Measurements were taken by the same operator, with the same environmental conditions and considering different trace positions on the sample.

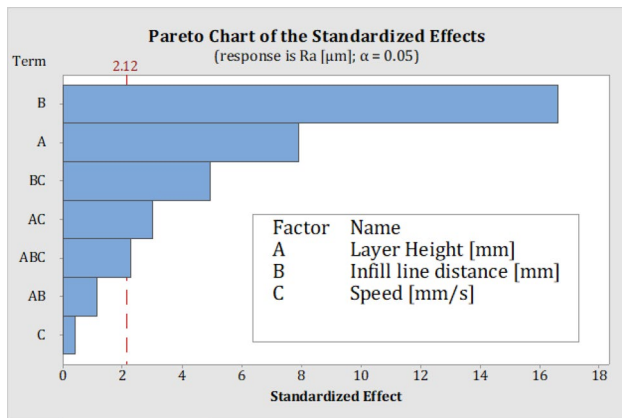


Fig. 3 Pareto chart (significance level, $\alpha = 0.05$) of the standardized effects of layer height, infill line distance, deposition speed on Ra

4 Results and discussion

4.1 Effects of process parameters on the roughness (Ra) before the chemical treatment

The roughness evaluated on the top surface of the samples is one of the two output parameters of the first factorial plan: the average values computed over three samples for each group, are reported in Table 2. The data analysis of the first factorial plan showed that the worst surface finish was achieved with the highest value of the infill line distance.

The deposition speed was found to be mostly irrelevant process parameter, while the layer height was influential on roughness of top surface (Fig. 3), but less than the infill line distance. The deposition speed became influential only in interaction with the layer height and the infill line distance. Indeed, the influence of these two factors on the roughness decreased when increasing the deposition speed.

This concept is visible by analyzing the Surface plot of Ra (Fig. 4), where, with a hold value of deposition speed equal to 100 mm/s, the surface is less inclined than the one with the speed hold at 50 mm/s. Figure 4 shows that increasing the infill distance had a worsening effect on the top surface finish. The same, but to a lesser extent, was registered when increasing the layer height. The speed resulted to have a mitigating effect on the increase of the roughness when a higher value of the infill line distance and of the layer height are considered.

More in details: the maximum roughness value was obtained in correspondence of the layer height value of 0.35 mm, the infill line distance set to 0.4 mm and the deposition speed equal to 50 m/s. One possible explanation of this result could be that, increasing the infill line distance, or the distance between two adjacent roads, the roughness increases because of the higher distance between peaks and valleys. The lowest production time was assured by the

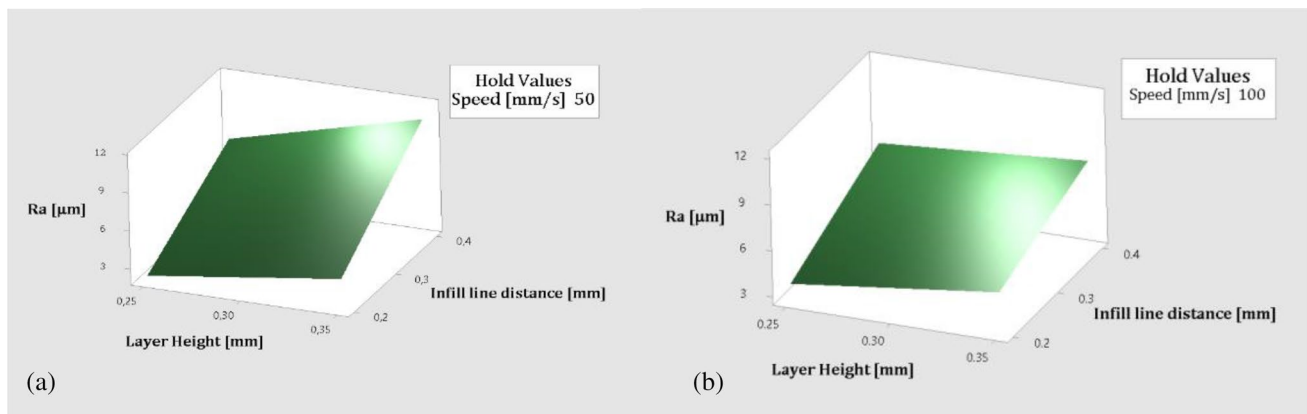


Fig. 4 Surface plot of Ra [μ m] vs gap [mm]; layer height [mm], (a) deposition speed 50 [mm/s], (b) deposition speed 100 [mm/s]

combination of the maximum layer height (0.35 mm), the maximum infill line distance (0.4 mm) and the maximum speed (100 m/s). By increasing the layer height, the filaments tend to be less crushed and this creates, albeit in a milder way, the same phenomenon described above, i.e., the increase of the distance between peaks and valleys.

From this pre-treatment factorial plan, a set of 3D printing process parameters was selected: maximum speed (100 mm/s) and maximum layer height (0.35 mm) as a trade-off between low roughness and low production time. Moreover, considering the aim of the paper, values of the roughness registered before the chemical treatment are not crucial for the analysis of the maximum roughness reduction achievable after the treatment. In this context, from preliminary tests, it was found that the roughness reduction achievable with the chemical vapor treatment implemented is not affected by the 3D printing process parameters analyzed in the first factorial plan. However, after the vapor treatment, the reduction of roughness was also measured on the lateral surfaces.

4.2 Effects of vapor chemical treatment on Roughness

The second full factorial plan 2^3 with three repetitions was designed to analyze the performance of the finishing treatment. Two post-treatment factors and one 3D printing factor were selected. The only variation among the machine parameters in this plan was the infill line distance, considered from the pre-treatment factorial plan, because it resulted to be, from Pareto chart in Fig. 3, the most influential one among the 3D printing process parameters. Moreover, during the vapor treatment, it is conceivable that a part of the PLA dissolved by Ethyl Acetate is redeposited in the space between two filaments. For this reason, it is expected that lower surface finish improvements can be obtained for greater infill distance values, using this treatment.

In Table 3, the average value of roughness, evaluated on the top surface of the three samples for each combination of

the parameters (groups 9–16), is reported. The treatment was able to reduce the roughness in all the analyzed conditions. The combination of highest solvent quantity and the highest treatment time led to the greatest improvement, leading to a surface finish with a Ra reduction greater than 85%, while the combination of lowest solvent quantity and highest treatment time led to the lowest improvement (43%).

Figure 5 shows two samples (Fig. 5a group 8 and Fig. 5b group 16). The sample in Fig. 5a is untreated, while the one in Fig. 5b is treated with vapor process. Their sections are illustrated in Fig. 5a' and b' and each section is orthogonal to the toolpaths. In particular, the groups 8 and 16 were characterized by the maximum values of layer height, deposition speed and infill line distance. The treatment made the surface more smoothed and uniform.

Figure 6 shows two primary profiles extracted from two samples belonging to group 8 (pre-treatment) and group 16 (post-treatment), which were fabricated with the same process parameters (layer height, deposition speed and infill line distance, see Table 1).

With reference to the influence of the selected parameters on the surface finish improvement (Fig. 7), analyzed through the second factorial plan, it was found that the infill line distance had not significant effects on the finishing treatment, while the treatment time strongly affected the process. Solvent quantity was also influencing but only in combination with the treatment time. Indeed, increasing the duration and keeping the solvent at a low quantity, the surface finish improvement was lower. With higher durations, higher solvent quantities improved the surface quality, probably due to a chemical effect of the solvent. In Fig. 7, the standardized effects (significance level, $\alpha=0.05$) on percent of Ra reduction are reported, with reference to treated samples.

More in details, by analyzing the response surfaces for each combination of parameters, it is possible to observe how the roughness reduction behaved in each case.

Four surface plots are reported: the first two (Fig. 8a and b) consider the solvent quantity and the treatment time as predictors variables, the roughness reduction as response

Table 3 Roughness (Ra) before chemical vapor treatment (Groups No. 6 and 8) and after chemical vapor treatment

Group 2nd fact. plan	Infill line dist. [mm]	Solvent [ml]	Treat. time [s]	Avg Ra pre treat. [μm]	Avg Ra post treat. [μm]	Avg std dev	% Ra reduction
9	0.2	3	180	5.25	1.62	0.42	69
10	0.4	3	180	8.04	3.93	2.45	51
11	0.2	5	180	5.25	1.21	0.18	77
12	0.4	5	180	8.04	2.97	0.58	63
13	0.2	3	360	5.25	2.23	0.58	57
14	0.4	3	360	8.04	4.58	2.26	43
15	0.2	5	360	5.25	0.70	0.13	87
16	0.4	5	360	8.04	1.57	0.46	81

Fig. 5 Untreated (a) and treated (b) specimens. Microscope analysis of untreated surface (a'), treated surface (b')

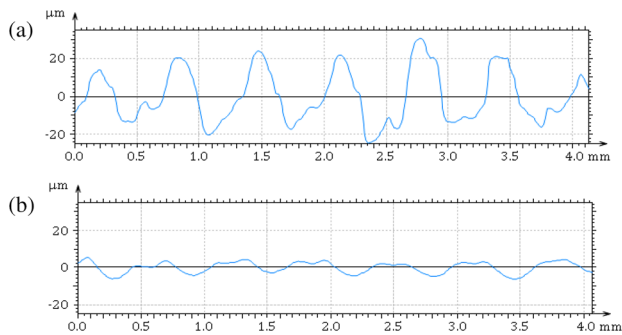
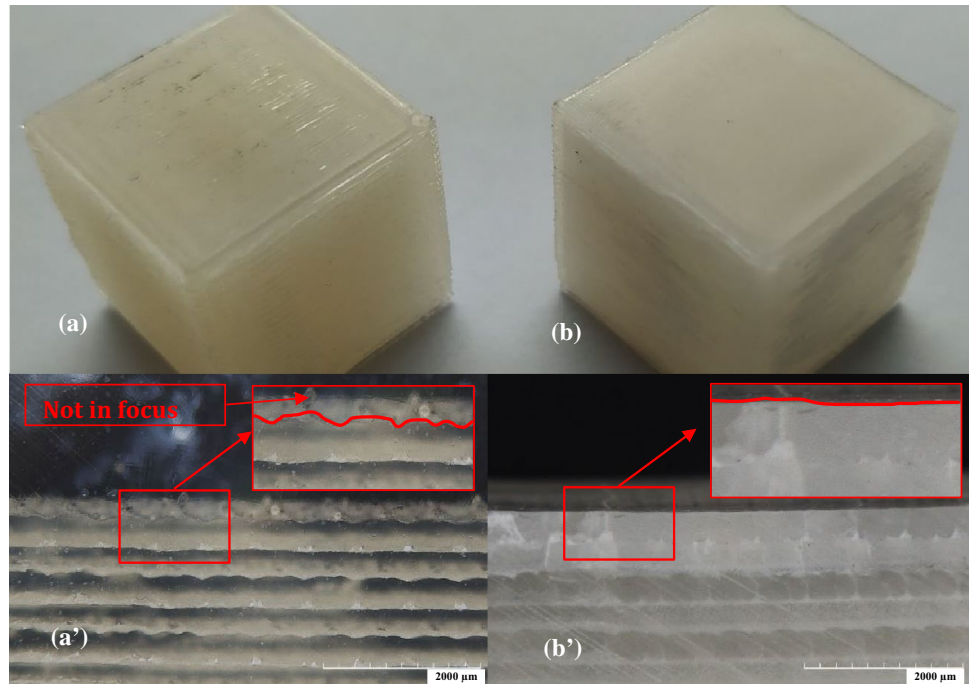


Fig. 6 Primary profiles: (a) group 8 pre-treatment, (b) group 16 post-treatment

variable, while the infill line distance was kept constant to 0.4 mm (Fig. 8a) and to 0.2 mm (Fig. 8b); the two others surface plots (Fig. 9a and b) consider the solvent quantity and the infill line distance as predictors values, the roughness reduction as response value, while the treatment time was kept constant to 180 s (Fig. 9a) and to 360 s (Fig. 9b).

4.2.1 Solvent quantity and treatment time (hold value: infill line distance)

In Fig. 8a, keeping fixed the infill line distance to its maximum value (0.4 mm), the maximum roughness reduction (about 80%) was achieved with the maximum treatment time (360 s) and the maximum solvent quantity (5 ml). Considering the case of infill line distance fixed to its

minimum value, again the maximum roughness reduction was achieved with the maximum treatment time and the maximum solvent quantity, and it was greater (90%) (Fig. 8b). Moreover, when the infill line distance was set to its minimum, even in the worst case (low solvent quantity, high treatment time), the roughness reduction was higher (about 60%) that the one with infill line distance set to 0.4 mm (50%). It is highlighted that the treatment time had a strong influence on the reduction of the roughness only when the quantities of solvent were greater. In the case of the amount of solvent equal to 3 ml, it is useless to increase the treatment time, as the results are similar, and even worse, to those obtained with a duration equal to 180 s.

4.2.2 Solvent quantity and infill line distance (hold value: treatment time)

Analyzing the surfaces plot in Fig. 9a and 9b, keeping fixed the treatment time, the maximum roughness reduction was achieved considering the maximum solvent quantity (5 ml) and the minimum infill line distance (0.2 mm); the reduction of the infill line distance for every solvent quantity (3–5 ml) increased the surface finish improvement. When the treatment time was kept to its maximum value (Fig. 9b), the roughness reduction was more marked and strongly dependent on the solvent quantity: the higher the solvent quantity, the higher the roughness reduction.

Fig. 7 Normal plot of the standardized effects (significance level, $\alpha=0.05$) on percentage reduction of Ra

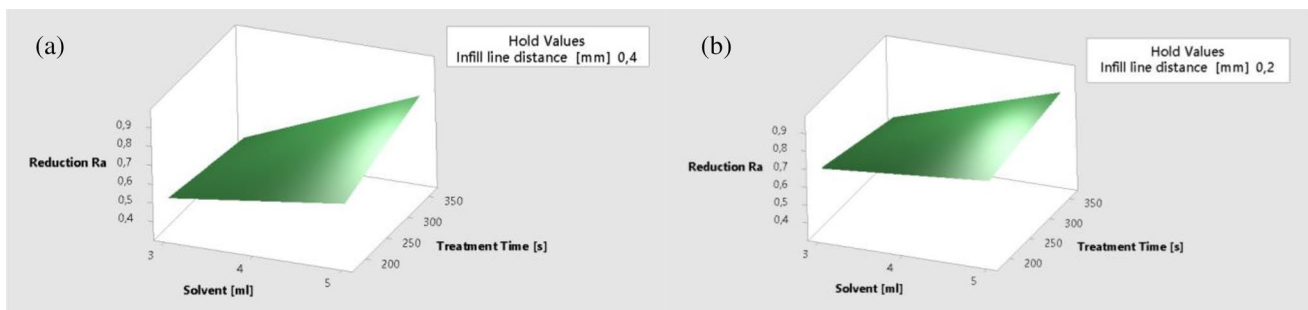
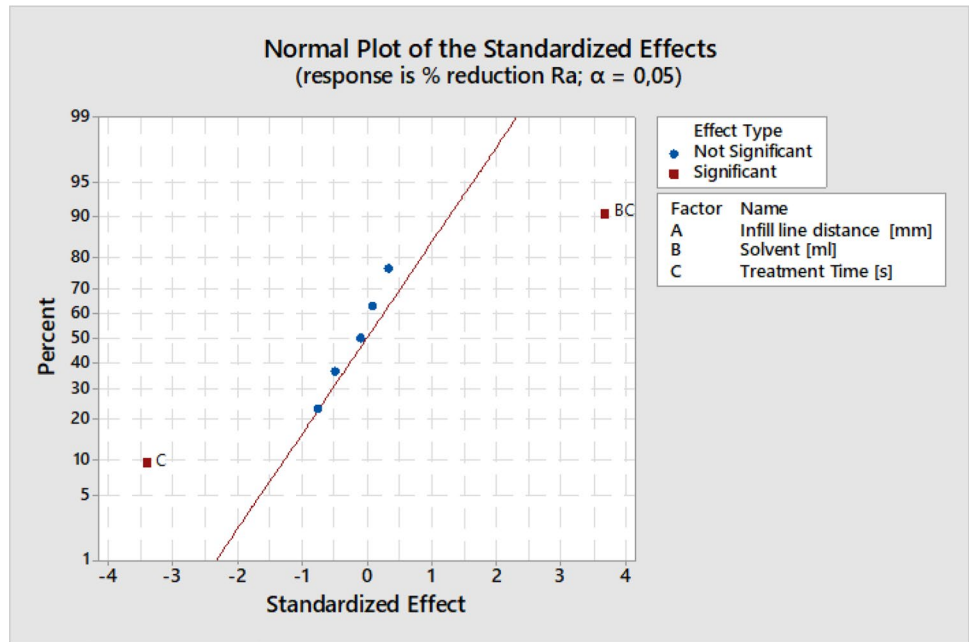


Fig. 8 Surfaces plot of % Ra reduction vs solvent [ml] and treatment time [s]; hold values: Infill line distance 0.4 ml (a), Infill line distance 0.2 ml (b)

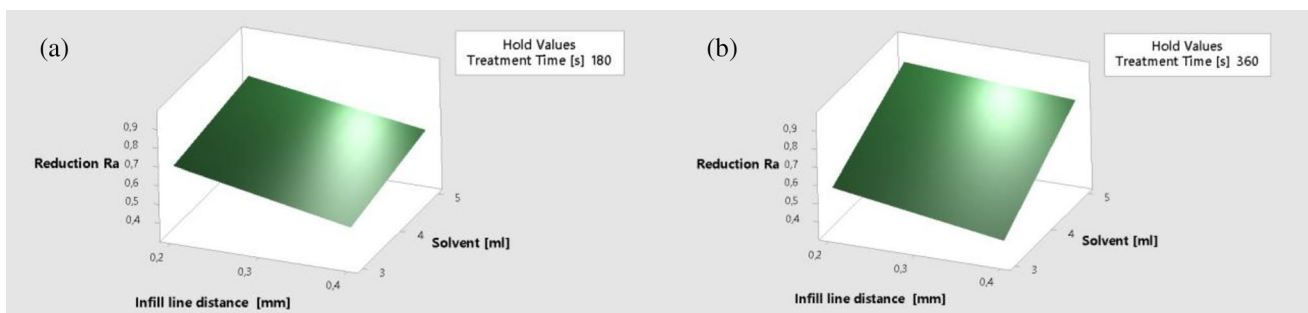


Fig. 9 Surfaces plot of % Ra reduction vs infill line distance [ml] and solvent [ml]; hold values: treatment time 180 [s] (a), treatment time 360 [s] (b)

4.2.3 Treatment time and infill line distance (hold value: solvent quantity)

The solvent quantity minimum value (3 ml) led to a

maximum roughness reduction of 70%, with the minimum treatment time and the minimum infill line distance (Fig. 10a). The worsening trend of the roughness reduction was registered with the amount of solvent equal to

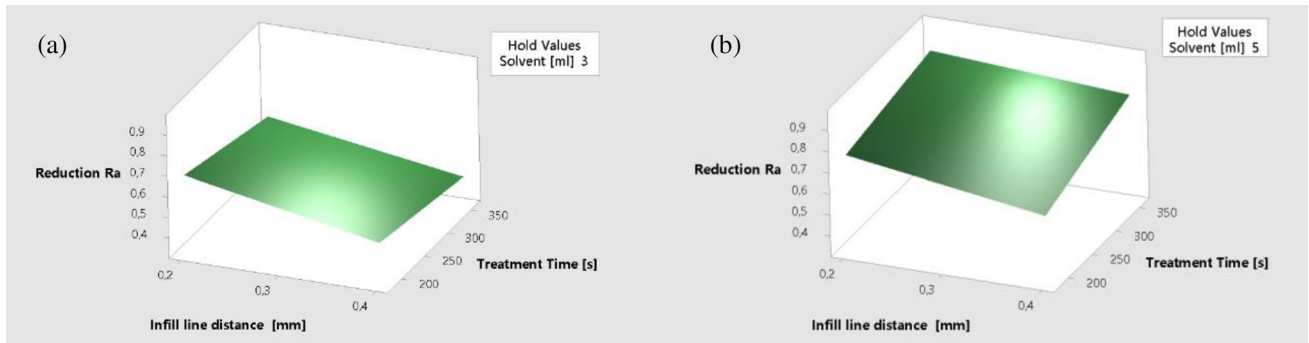


Fig. 10 Surface plot of % Ra reduction vs infill line distance [mm] and treatment time 180 [s]; hold values: solvent 3 [ml] (a), solvent 5 [ml] (b)

3 ml, with the maximum treatment time; this seems to be in contrast with what was found previously. Although, in this case, the standard deviation of the roughness value must be considered. This is the case of the specimen type groups 10 and 14 of Table 3, characterized by a high standard deviation of the roughness (of the same order of magnitude), that increased the uncertainty and made those values less significant. On the other hand, considering the solvent quantity maximum value (5 ml), the maximum roughness reduction was achieved using the maximum treatment time. Moreover, the maximum roughness reduction (about 90%) was achieved with the maximum solvent quantity and the maximum treatment time.

Finally, based on the data analysis, it is possible to make some general considerations. When the solvent quantity and/or the treatment time increased, the infill line distance was not significant, and the best result was achieved considering the maximum solvent quantity and the maximum treatment time.

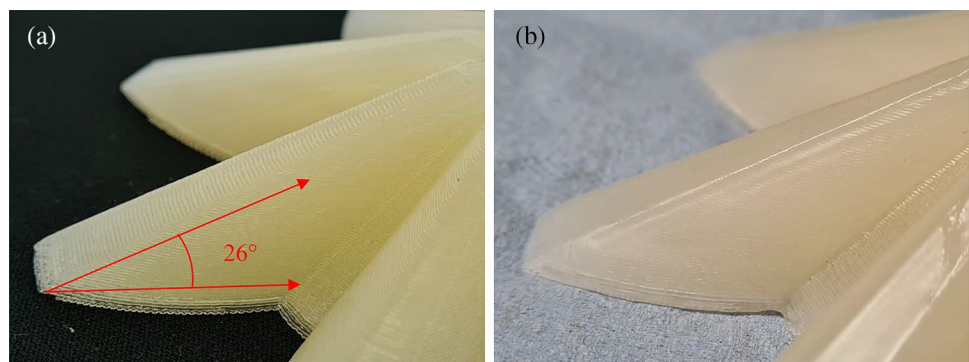
For a more extensive analysis, the roughness on lateral surface of the samples was measured, obtaining a roughness reduction similar to the ones obtained on the top surfaces. The percentage reduction of Ra ranged from 42% (samples with: layer height 0.35 mm, infill distance 0.4 mm, solvent 3 ml, treatment time 360 s) to

81% (samples with: layer height 0.35 mm, infill distance 0.2 mm, solvent 5 ml, treatment time 360 s).

To evaluate the effect of the treatment on a sloped surface (affected by staircase effect), at least in a qualitative way, a gear wheel with a tooth inclination equal to 26° respect to the built plan, was treated using the proposed vapor smoothing process and, in particular, the best combination of parameters (5 ml of Ethyl Acetate for 360 s). Figure 11 shows the gear wheel surface before and after treatment. The treated surface was smoother and without texturing, respect to the one before treatment. The roughness Ra measured before treatment was $20.6 \mu\text{m}$, while the one measured after the treatment was $5.1 \mu\text{m}$.

The results obtained in this paper can be compared with other chemical vapor treatment reported in the literature review for the improvement of the surface finish of PLA 3D printed parts. In particular, it was found that using ethyl acetate as solvent in form of vapor, large values of roughness reductions can be achieved, comparable with the ones achieved using the more dangerous dichloromethane vapor treatment used in [38, 40]. Ethyl acetate vapor chemical treatment is preferable to other vapor methods in terms of less toxicity of the solvent. Moreover, the process proposed in this work is certainly more convenient both for the shorter chemical treatment time and the lower amount of solvent used, compared to the ones reported in literature.

Fig. 11 (a) Untreated and (b) treated gear wheel with a slope angle equal to 26°



It is also possible to compare the vapor chemical treatment used in this paper with the liquid solution immersion methods that use solvents in their liquid form instead of vapors. In general, chemical treatments by immersion lead to high roughness reduction, comparable with the ones achieved in this study [25, 26, 30]. Although, the amount of solvent needed for the chemical process is largely greater. The maximum roughness reduction obtained in this paper (about 90%) involved the use of a low quantity of solvent (5 ml of ethyl acetate) and a reasonable treatment time (360 s).

More generally, minimizing the use of solvents, even if they are characterized by low toxicity, is still the best choice both for treatment cost reduction and from a sustainability point of view. Thus, considering comparable roughness reductions, chemical vapor treatments are preferable with respect to immersion methods.

5 Conclusion

In this research, a quantitative analysis of the effects of a chemical vapor treatment on FFF PLA cubic samples was conducted.

The proposed treatment allowed to achieve almost a 90% of roughness reduction, with several advantages in terms of toxicity, quantity of solvent and treatment time. By considering the solvent quantity and the treatment time, the best results (roughness reduction of about 90%) were obtained by increasing simultaneously the duration of treatment and the solvent quantity, while increasing the duration of treatment with low quantity of solvent, led to a lower surface finish improvement. Infill line distance had no significant effects on the roughness reduction, except for the cases with the minimum solvent quantity or the minimum treatment time, where the effect of the treatment is less pronounced (roughness reduction on the order of 70%).

The proposed ethyl acetate vapor treatment resulted to be effective and it was demonstrated that a proper choice of the treatment parameters can improve surface finish, regardless of the starting values of roughness. This allows also to consider the combination of 3D printing process parameters with higher speed, higher layer height and then, lower production time, while remaining within the limits of dimensional and geometrical accuracy.

Further studies will be conducted for analyzing the effect of the chemical treatment on the dimension stability and mechanical properties of the treated samples.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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