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*Research Article*

# Computer Numerical Controlled Grinding and Physical Vapor Deposition for Fused Deposition Modelled Workpieces

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The use of additive manufacturing (AM) enables companies to directly produce complex end-use parts. Fused deposition modelling (FDM) is an AM technology based on an extrusion process of fabricating parts. This layer-by-layer method results in a poor surface finish, and as a result, manual finishing is often required, which consequentially reduces the definition of the geometrical features. This research proposes a novel way of achieving high surface finishing by using additive and finishing processes, followed by a physical vapor deposition (PVD) coating. Two test pieces were produced, the first one was subjected to computer numerical controlled (CNC) mechanical grinding with appropriate grades of grindstones; the second one was subjected to microsandblasting to remove excess material and the stair-stepping effect. Both test pieces were then subjected to a PVD coating process to provide a metal thin film. To benchmark the test pieces, the authors used a coordinate measure machine for dimensions and a roughness meter to verify the effectiveness of this postprocessing approach.

## 1. Introduction

Very recently the interest of research about the metallization of additive manufactured (AM) parts has grown. The metallization of ABS (acrylonitrile-butadiene-styrene) parts has been studied on flat part surfaces, fabricated on a fused deposition modelling (FDM) machine [1]. The coating process was electroless copper deposition using two different surface preparation processes, namely, ABS parts prepared using chromic acid for etching and ABS parts prepared using a solution mixture of sulphuric acid and hydrogen peroxide ($H_2SO_4/H_2O_2$) for etching. However, since one of the main advantages of AM is easy manufacturing of freeform surfaces, it is important to consider more complex features [2] where an indirect AM approach of thin-walled alloy structures is proposed. In the cited paper, metallization is exploited to coat an AM polymer template to deposit metal layers by electroplating using chemical vapor deposition. Among the metallization processes, physical vapor deposition (PVD) attracts particular attention since it is one of the methods that can achieve a consistently thin coating [3], resulting very promising applications such as for the biomedical field. The advantages of PVD are low environmental impact and its possible use on almost any type of inorganic material. Disadvantages include high costs since the process requires complex machines operated by skilled people and low coating rates.

The authors focused the aim of the present paper on PVD mainly for its capability to give very low coating thickness and for the possibility to apply the same method to other AM processes. As a consequence, surface finishing of products, being produced from AM is essential. The stair-stepping effect of AM parts creates a high level of roughness which affects functional and aesthetic properties of parts. In the previous literature, many researchers have focused on analysing dimensional performance [4] and on improving the surface finish of parts produced from AM ranging from build orientation to various posttreatment techniques.

Early studies [5] explored the limitations of FDM machines and how well they could cope with different levels of geometric complexity and suggested that machine settings and the built parameters played a key role in the quality of surface finish. Key methods for improving surface finish have been divided into four categories, namely, optimization of build orientation, slicing strategy (layer thickness), fabrication parameters optimization, and posttreatment [6]. They described that the first three methods are used before making the FDM parts, and the fourth method is used after producing the part. More importantly, they noted that chemical treatments are regarded as a successful method to achieve good finishing.

CNC milling to improve surface finish is a potential method that has not been utilised extensively. One of the first papers [7] used this method to resolve the staircase problem by using CNC milling machines, but this method of surface removal was ineffective when complex surfaces or minute details have to be machined. In the work [8], a virtual hybrid FDM system was proposed that combined both layer-by-layer deposition and machining. More recently, the issue has been integrated with Design for X such as Design for Manufacturing (DFM) to combine manufacturability aspects during the design stage [9] and with experimental approaches [10] where a variable cutting depth was considered to avoid inner defects.

Other researchers [11] focused their attention on abrasive flow machining (AFM) which has the potential to deal with holes, small surfaces, and complex shapes. However, the key limitation was due to the inaccuracy, poor pressure control, and distribution of the viscous fluid. In the paper [12], the authors used a hot-cutter machining method which exploited the use of a heated tool to allow material to be effectively removed with a very low cutting effort (15 mm/min). Although they were able to achieve roughness values of lower than 1.6 $\mu$m, this method would be unfeasible for highly complex geometries. Cheah et al. [13] suggested an investment casting technique using a fine-grained abrasive paper which was able to improve the surface finish by 96%, from an Ra value of 17.895 $\mu$m to an Ra value of 0.550 $\mu$m. However, this method was time-consuming and impractical for large pieces. Leong et al. [14] proposed the use of abrasive jet deburring to improve the surface finish of AM parts. They studied abrasive machine parameters such as the flow pressure and analysed dimensional errors before measuring the reduction of the surface roughness. Using 5 bar pressure over 15 seconds, the quality of roughness was reduced to a value of 71% (from 16.26 $\mu$m to 4.59 $\mu$m). However, stray cutting had to be avoided using this method. In [15], the main causes that produce poor surface finishing were analysed. Considering the staircase effect, they evaluated the distance between the theoretical CAD object curves and those obtained after slicing and proposed a more accurate slicing procedure for layered manufacturing. The work [16] examined production processes to find optimal machine setting parameters and part orientation to improve the finishing. Examining data obtained by adaptive slicing with different thicknesses, they concluded that although having finer slices made an improvement in surface finish, it consequentially increased the production time. Ahn [17] proposed an algorithm to identify the optimum part orientation. Unlike previous studies, their aim was to minimize the postmachining process. The roughness was monitored, and the nominal distribution before and after postprocessing was analysed. Their study investigated the relationship between the roughness and the staircase effect, as well as the relationships between the roughness, the surface angle, and the slice height. The study [18] shows the influence of FDM machining parameters that affected the surface finish of acrylonitrile-butadiene-styrene (ABS) parts. The authors used a chemical treatment (dimethyl-ketone and water based) to decrease the overall surface roughness. They also concluded that slice height and the raster width are important input machining parameters. Using this method, the Ra value was effectively reduced by 90% from a Ra value of 20,695 $\mu$m to a value of 2.16 $\mu$m.

## 2. Materials and Methods

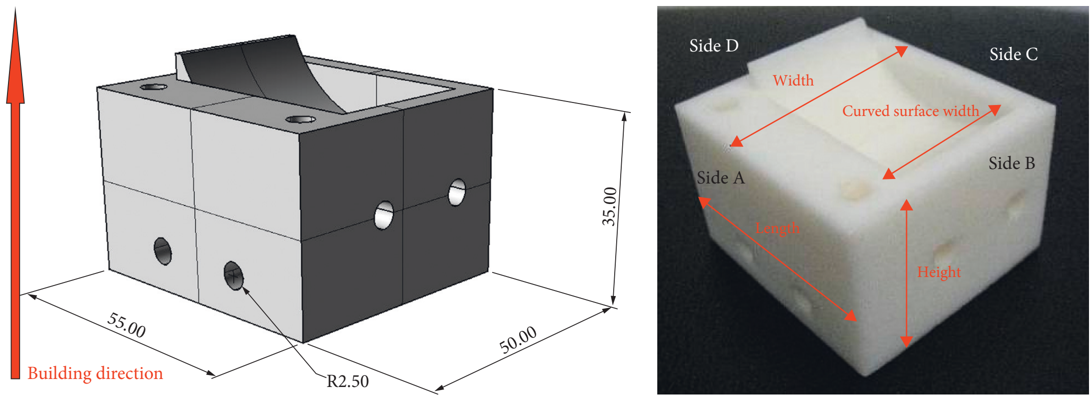
The aim of this preliminary research is to propose a novel postprocessing approach by subjecting an ABS part produced using FDM technology, to PVD treatment. Two test pieces were produced, the first was subjected to CNC grinding and PVD coating and the second to micro-sandblasting and PVD coating. A test piece was designed including geometrical features that could potentially encounter roughness problems during slicing and in the build phase such as holes, complex surfaces, peaks, and valleys. A standard test piece, measuring 55.0 × 50.0 × 35.0 mm was modelled in CAD (SolidWorks) with hole features on each side of the block and with a curved recessed profile on the top that represented a complex feature for finishing. The design of the test piece is shown in Figure 1.

In the FDM process, the test pieces were produced using the Stratasys FDM3000 machine using ABS P400 as the model material and soluble P400SR for the support material. FDM is one of the most widespread use of AM processes [8], and the ABS material has excellent mechanical properties. For the Stratasys FDM3000 machine, the construction parameters were as follows:

(i) Nozzle diameter: 0.3 mm
(ii) Contour width: 0.305 mm
(iii) Depth of contour: 0.610 mm
(iv) Part raster width: 0.305 mm
(v) In-fill density: 100% (solid)

The overall process of the experiments is represented in Figure 2.

To ensure dimensional accuracy, benchmark measurements before and after each operation were systematically taken. The measurements were made using a reliable DeMeet-400 touch probe. The accuracy of measurement ranged from 4 + L/150 $\mu$m to 5 + L/150 $\mu$m with L = maximum part dimension in mm measured along one of the $X$-, $Y$- and $Z$-axes, and the Renishaw probe diameter was equal to 2 mm. The expected error, due to filament fabrication, was $R_z/2$, and for specimen A, it was equal to 20.5 $\mu$m while for specimen B was 21.5 $\mu$m.




(a) (b)

Figure 1: Geometrical design of the test piece (a) and measurements taken for the test pieces (b).

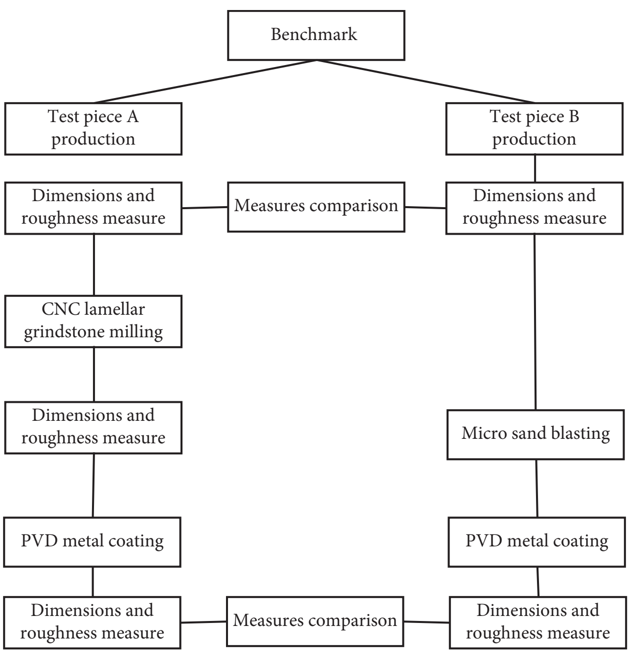



Figure 2: Flowchart of experiments.

Each test piece was measured using 3 placements, and for accuracy, ten repetitions of each measurement were made. For the first piece (Test piece A), finishing was done using a bulk sanding roller mounted onto a spindle of a Roland Modela CNC milling machine, followed by metallization that was achieved by physical vapor deposition (PVD) treatment. The results of each treatment were monitored by measuring both dimensional deviations and achieved surface finish results. The toolpaths for the CNC milling machine were designed using Delcam FeatureCAM using a z-level strategy. A second test piece (Test piece B) was treated with a microsandblasting treatment followed by metallization using PVD. The microsandblasting treatment was carried out by a third-party service provider who did not share these data.

## 3. Results

Each side of the two test pieces was measured, and the dimensional shrinkage was recorded under "Raw part dimensions" in Table 1. It was found that that the height of Test piece B (35.081 mm) was higher than that of Test piece A (34.89 mm), and it was less than 1% from the measurements of the CAD file. Measurements and comparisons between the curved surfaces of Test pieces A and B were also made. Figure 1 shows where the measurements were made on the test piece. Test piece A had a higher shrinkage ranging from a minimum of 0.074% to a maximum of 0.1.426%. For Test piece B, the values of shrinkage range from a minimum of 0.011% to a maximum of 1.26%. The results of part accuracy due to the resolution of the printer as well as the effect of material shrinkage were within acceptable limits as indicated by the manufacturer's guidance sheet.

Measurements were taken to verify the geometrical deviations between the digital CAD model and the physical artefacts that were printed using the FDM process (Test pieces A and B). To measure the roughness of the surface, a profilometer, Surtronic 3P, was used with a cutoff equal to 2.5 mm. This instrument had an accuracy of 2%, and four surfaces and four points over each surface were analysed. For greater accuracy, each point was measured at least ten times over. The Ra, $R_z$, and $R_y$ Max were the values obtained with the profilometer, and the areas examined were named as side A, B, C, and D (Figure 1). The mean roughness values of the four sides of both test pieces were obtained, and the results were compared as shown in Table 2.

The roughness value on side B differed by 2.6 $\mu$m between the two test pieces, amounting to a differentiation value of 12%. It was found that this was largely caused by a building defect that occurred in specimen B due to the high humidity inside the support material. In the FDM process, the percentage of humidity in soluble support material is critical which affects the quality of surface finish. The dimensional accuracy of the parts is also influenced by the percentage of humidity in the atmosphere and also the amount of time spent in the ultrasonic bath solution when removing the support structures.

Table 1: Theoretical, real, postfinishing, and postPVD treatment dimensions.

| Test piece | Dimensional features | Theoretical dimensions (mm) | Raw part dimensions (mm) | Standard deviation raw part dimensions (mm) | Postfinishing dimensions (grinding A, sandblasting B) (mm) | Standard deviation postfinishing (mm) | Post-PVD dimensions (mm) | Standard deviation Post-PVD dimensions (mm) | Metal-coated dimensional differences to raw part (mm) | % | Metal-coated dimensional differences to CAD model (mm]) | Metal-coated dimensional differences to CAD model (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | Length | 55.00 | 54.80 | 0.11 | 54.73 | 0.13 | 54.87 | 0.40 | 0.07 | 0.13 | −0.13 | −0.24 |
| | Width | 50.00 | 49.79 | 0.071 | 49.58 | 0.64 | 49.73 | 0.33 | −0.06 | −0.12 | −0.27 | −0.53 |
| | Height | 35.00 | 34.89 | 0.21 | 34.79 | 0.59 | 34.88 | 0.57 | −0.01 | −0.04 | −0.12 | −0.36 |
| | Curve surface width | 30.00 | 29.89 | 0.32 | 29.99 | 0.32 | 29.83 | 0.49 | −0.06 | −0.18 | −0.17 | −0.56 |
| B | Length | 55.00 | 54.72 | 0.24 | x | x | 55.29 | 0.17 | 0.57 | 1.04 | 0.29 | 0.52 |
| | Width | 50.00 | 49.86 | 0.24 | x | x | 50.40 | 0.21 | 0.54 | 1.08 | 0.40 | 0.79 |
| | Height | 35.00 | 35.08 | 0.35 | x | x | 35.74 | 0.22 | 0.66 | 1.88 | 0.74 | 2.08 |
| | Curve surface width | 30.00 | 29.99 | 0.43 | x | x | 29.28 | 0.67 | −0.71 | −2.35 | −0.72 | −2.45 |

x: the results of machinings performed by FORTEX.

Table 2: Roughness values and comparison between row and treated part.

| Test piece | Side | Row part roughness ($\mu$m) | Standard deviation row part roughness ($\mu$m) | Milling machined part roughness ($\mu$m) | Standard deviation milling machined part roughness ($\mu$m) | Metal-coated part roughness ($\mu$m) | Standard deviation metal-coated part roughness ($\mu$m) | Roughness total reduction ($\mu$m) | Roughness total reduction (%) |
|---|---|---|---|---|---|---|---|---|---|
| A | A | 18.80 | 0.8 | 3.66 | 0.07 | 1.37 | 0.52 | 17.42 | 92.71 |
| | B | 18.99 | 0.96 | 3.47 | 1.85 | 1.77 | 1.4 | 17.22 | 90.68 |
| | C | 19.33 | 0.24 | 2.00 | 0.55 | 0.73 | 0.35 | 18.60 | 96.22 |
| | D | 20.28 | 6.75 | 4.63 | 1.48 | 1.80 | 1.1 | 15.64 | 91.12 |
| B | A | 18.93 | 0.38 | x | x | 0.6 | 0.30 | 18.33 | 96.83 |
| | B | 21.59 | 3.66 | x | x | 0.91 | 0.64 | 20.68 | 95.78 |
| | C | 19.75 | 0.89 | x | x | 0.75 | 0.33 | 19.00 | 96.20 |
| | D | 19.85 | 0.85 | x | x | 1.09 | 0.39 | 18.76 | 94.5 |

x: the results of machinings performed by FORTEX.

*3.1. Surface Finishing through CNC Grinding and Microsandblasting.* For Test piece A, a computer numerical controlled (CNC) milling machine grinding was used. It was equipped with a round lamellar sanding roller tool with a 12-inch tip and a diameter of 30 mm in the form of a grindstone with a lamellar abrasive paper with grit quality of P120. The lamellar abrasive paper is radially fixed around the axle of the tool (Figure 3).

The height of the removed material was 0.637 mm when compared to the geometrical dimensions of the CAD file. For the milling process, we subjected the cutting tool path according to 3 different ways: parallel to the build direction, perpendicular to the build direction, and combining both parallel and perpendicular paths to the build direction of the FDM process. The cutting speed was 612.6 m/min (spindle speed of 6500 RPM) and feed speed was equal to 1778 mm/min. At the end of the milling process, we observed an absence of surface flaking and plastic burns. The treated surfaces were found to be polished and smooth to touch and uniformly machined. From this process, the staircase effect was almost completely absent. After the milling process, Test piece A was measured again. The dimensions taken before and after the processing were length, width, part height, and width of the curved surface as reported in Table 1.

After processing, when comparing the curved surface with the CAD model, a deviation of −0.483 mm was noted. Taking the part shrinkage into consideration (where there was a slight reduction of −0.637 mm), it was found that the grinding process removed an average of 0.15 mm of material.

In terms of surface roughness, the effect on finishing was influenced by the different orientations of the grinding process. Both sides A and B (Figure 1) of the test pieces were worked in a normal and parallel direction to the building direction (Figure 4).

Side C (Figure 1) was worked in parallel and side D (Figure 1) normally to building direction (Figure 4). The roughness level was measured in parallel to build direction. Normally was not very significant indeed the profilometer head is forced to run between two tracks represented by two adjacent slices. After CNC grinding, it was found that side C produced the best finishing value with a value of roughness

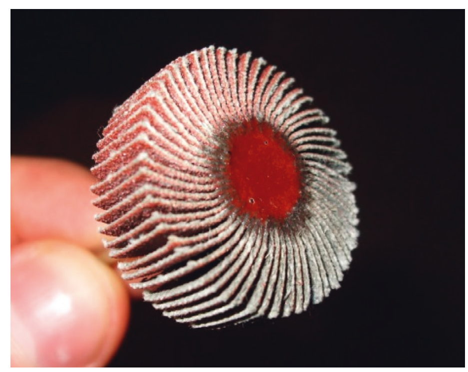


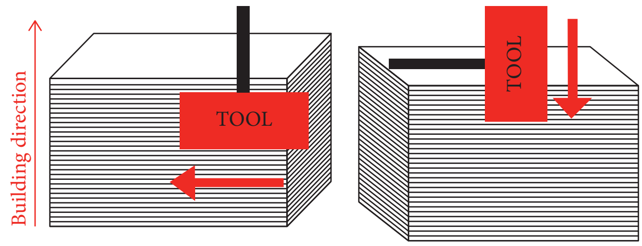
Figure 3: Bulk sanding roller.

equal to 2 $\mu$m. The use of the lamellar abrasive paper left some very fine streaked marks parallel to the machining direction on the surface. Using this abrasive treatment, a percentage reduction of 83% was obtained.

For Test piece B, instead of a milling machine, the sandblasting process was used. For this method, a commercial sandblasting machine using abrasive media is accelerated through a blasting nozzle by means of compressed air. Corundum sand (size 70/110 $\mu$m) was used with 4 and 5 bar of pressure. The treatment time was 1 minute.

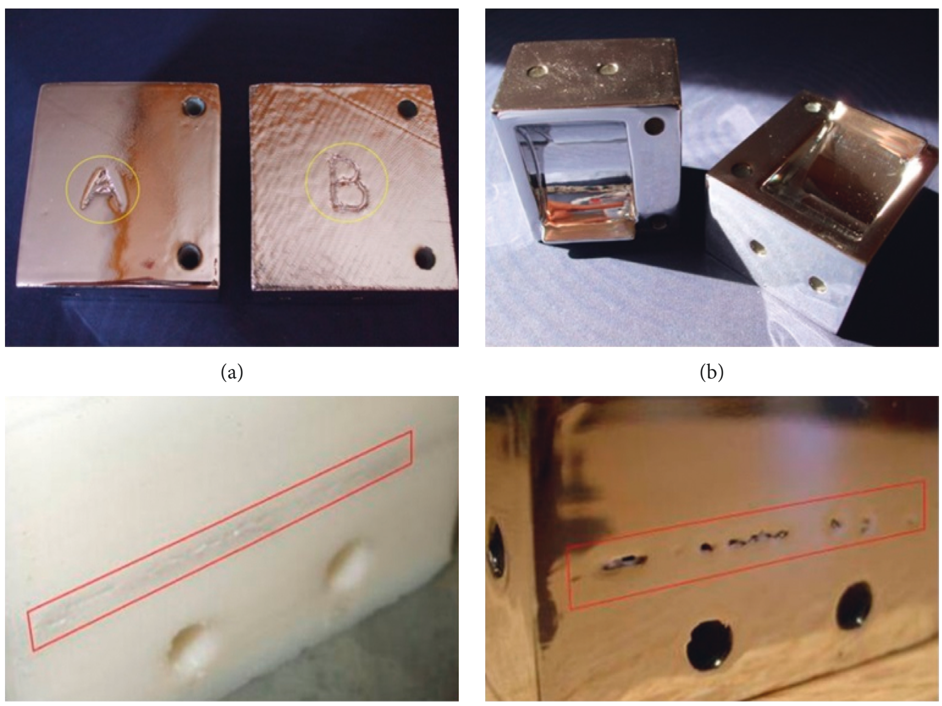
The microsandblasting was carried out by a third-party service provider who did not share dimensional measurements and roughness data after making this treatment.

*3.2. Improvement of Surface Finish through PVD Treatment.* In the PVD treatment process, the coated metallic alloy of titanium and aluminium is usually supplied in a vaporized form being transported through a vacuum chamber in a low-pressure gas or plasma (0.00003 bar) to the workpiece. When the vaporized coating condenses, a layer is formed and this process typically occurs at 400°C taking place over 4 hours. Figure 5 is a good visual comparison of the results subjected to both test pieces. Although the PVD process deposits a very thin metallic later, it cannot completely mask all superficial defects. As shown in Figure 5, holes due to excess removal of supporting material are not hidden. It was also observed that




(a) (b)

Figure 4: Grinding directions. (a) Normal working direction. (b) Parallel working direction.



(a) (b) (c) (d)

Figure 5: PVD test pieces and superficial defects on the test pieces.

after the PVD process, the sharp corners and edges become far less pronounced.

Measurements were taken and compared with those before and after the PVD coating process. For Test piece A, a PVD coating comprising of titanium and aluminium alloy (TiAl) of about 60 $\mu$m thickness was deposited and the dimensions obtained after this stage are shown in Table 1. The maximum deviation between the PVD-treated piece and the CAD model was 0.74%, and this is also observed on the height of piece B. The roughness value was very low, and in some areas, the standard deviation values were close to zero. The roughness values were obtained by sliding the probe normally (perpendicularly) to the build direction. The roughness values ranged from a maximum of 0.15 $\mu$m to a minimum of 0.055 $\mu$m, with reductions ranging from a minimum of 0.64 $\mu$m to a maximum of 1.93 $\mu$m, as compared to the values measured after milling. Roughness values measured parallel to the build direction are higher than those measured normally to the build direction but lower than the values measured before the PVD process in the same measurement direction.

In Table 2, the roughness values that are measured parallel to the building direction are shown. The results confirm that setting the processing direction parallel to the building direction, as shown in Table 2 (side C), is the best strategy for treatment.

## 4. Discussion

By comparing the dimensional differences between the final and the designed measurements of both test pieces in Table 1, it can be observed that Test piece A has a lower dimensional variation than B, showing a maximum value equal to 0.266 mm and hence having a much better accuracy. The final roughness values are lower than those of Test piece A, and the quality of finishing in terms of surface roughness on the four sides of Test piece B is more uniform than that of Test piece A, with reduction rates ranging between 95.13%

and 96.45% as shown in Table 2. As a control, to evaluate the surface finish improvement due to the PVD process, the roughness on the bottom of Test piece B which was not been subjected to any finishing operation was also measured. When measured before the combined CNC and PVD coating processes, the roughness value was 16.5 $\mu$m, and after treatment, a roughness reduction of about 14.79 $\mu$m was achieved. This result demonstrates the important role that PVD coating has on improving the surface finish and reducing the roughness value by 89.6%.

## 5. Conclusions

This work has demonstrated the effective use of PVD coating to improve surface finish. It presents a novel approach of combining different postprocessing methods, and future works should include multiple samples being processed in order to determine the repeatability of the experiments. Future work could also investigate the use of PVD for other materials being produced using FDM as well as other AM processes and the improvement in the control of the PVD process to be achieved in order to save the geometrical accuracy of the parts.

## Data Availability

Data supporting this research article are available from the corresponding author on reasonable request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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## References

[1] A. Equbal and A. K. Sood, "Metallization on FDM parts using the chemical deposition technique," *Coatings*, vol. 4, no. 3, pp. 574–586, 2014.

[2] J. H. Martin, D. S. Ashby, and T. A. Schaedler, "Thin-walled high temperature alloy structures fabricated from additively manufactured polymer templates," *Materials and Design*, vol. 120, pp. 291–297, 2017.

[3] B. Moore, E. Asadi, and G. Lewis, "Deposition methods for microstructured and nanostructured coatings on metallic bone implants: a review," *Advances in Materials Science and Engineering*, vol. 2017, Article ID 5812907, 9 pages, 2017.

[4] L. M. Galantucci, I. Bodi, J. Kacani, and F. Lavecchia, "Analysis of dimensional performance for a 3D open-source printer based on fused deposition modeling technique," *Procedia CIRP*, vol. 28, pp. 82–87, 2015.

[5] E. Pei, R. I. Campbell, and D. de Beer, "Entry level RP machines: how well can they cope with geometric complexity?," *Journal of Assembly Automation*, vol. 31, no. 2, pp. 153–160, 2011.

[6] P. Kulkarni and D. Dutta, "On the integration of layered manufacturing and material removal processes," *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, vol. 122, no. 1, pp. 100–108, 2000.

[7] G. Singh Bual and P. Kumar, "Methods to improve surface finish of parts produced by fused deposition modeling," *Manufacturing Science and Technology*, vol. 2, pp. 51–55, 2014.

[8] P. M. Pandey, N. V. Reddy, and S. G. Dhande, "Virtual hybrid-FDM system to enhance surface finish," *Virtual and Physical Prototyping*, vol. 1, no. 2, pp. 101–116, 2006.

[9] O. Kerbrat, P. Mognol, and J. Y. Hascoët, "A new DFM approach to combine machining and additive manufacturing," *Computers in Industry*, vol. 62, no. 7, pp. 684–692, 2011.

[10] A. Boschetto, L. Bottini, and F. Veniali, "Finishing of fused deposition modeling parts by CNC machining," *Robotics and Computer-Integrated Manufacturing*, vol. 41, pp. 92–101, 2016.

[11] R. E. Williams and V. L. Melton, "Abrasive flow finishing of stereolithography prototypes," *Rapid Prototyping Journal*, vol. 4, no. 2, pp. 56–67, 1998.

[12] P. M. Pandey, N. V. Reddy, and S. G. Dhande, "Improvement of surface finish by staircase machining in fused deposition modeling," *Journal of Materials Processing Technology*, vol. 132, no. 1–3, pp. 323–331, 2003.

[13] C. M. Cheah, L. H. Tan, C. Feng, C. W. Lee, and C. K. Chua, "Rapid investment casting: direct and indirect approaches via fused deposition modelling," *International Journal of Advanced Manufacturing Technology*, vol. 23, no. 1-2, pp. 93–101, 2004.

[14] K. F. Leong, C. K. Chua, G. S. Chua, and C. H. Tan, "Abrasive jet deburring of jewellery models built by stereolithography apparatus (SLA)," *Journal of Materials Processing Technology*, vol. 83, no. 1–3, pp. 36–47, 1998.

[15] P. Kulkarni and D. Dutta, "An accurate slicing procedure for layered manufacturing," *CAD Computer Aided Design*, vol. 28, no. 9, pp. 683–697, 1996.

[16] J. G. Zhou, D. Herscovici, and C. C. Chen, "Parametric process optimization to improve the accuracy of rapid prototyped stereolithography parts," *International Journal of Machine Tools and Manufacture*, vol. 40, no. 3, pp. 363–379, 2000.

[17] D. Ahn, H. Kim, and S. Lee, "Fabrication direction optimization to minimize post-machining in layered manufacturing," *International Journal of Machine Tools and Manufacture*, vol. 47, no. 3-4, pp. 593–606, 2007.

[18] L. M. Galantucci, F. Lavecchia, and G. Percoco, "Experimental study aiming to enhance the surface finish of fused deposition modeled parts," *CIRP Annals—Manufacturing Technology*, vol. 58, no. 1, pp. 189–192, 2009.