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Improvement of Surface Finish for Additive Manufactured Parts - A Comparison Study of Six Post Processing Techniques

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***Abstract*— The surface finish of additively manufactured parts is often poor mainly due to the "stair-stepping" effect of the manufacturing process which is mostly influenced by the layer thickness, build orientation and the inclination angle of the surface on the part. For form, fit or functional purposes, the surface finish of additive manufactured parts must often be enhanced. The aim of this research is to compare the surface finish of additively manufactured polymeric parts when post-processing techniques are applied. The test pieces were additively manufactured in nylon polyamide 12 (PA12), Alumide® and Acrylonitrile Butadiene Styrene (ABS) materials. The Laser Sintering (LS) process was used to manufacture the nylon and Alumide® test pieces while Material Extrusion (MEX) was used for the ABS test pieces. Six post processing techniques, namely tumbling, shot peening, Computer Numerical Control (CNC) machining, spray-painting, undercoat and hand finishing and chemical dissolving of surface of the test pieces were applied to the test pieces. Despite being the most time-consuming technique and producing poor consistency in dimensional accuracy, the hand finishing method resulted in the lowest surface roughness with improvements of up to 97.6%, 96% and 98.3% for nylon, Alumide® and ABS test pieces, respectively compared to the originally manufactured parts. Although CNC machining has the potential to improve the surface finish of a single face, the technique was found to be not efficient for improvement of surface roughness of a complex part with various inclination angles.**

Keywords*— Nylon; Alumide®; ABS; post processing techniques; surface finish

I. INTRODUCTION

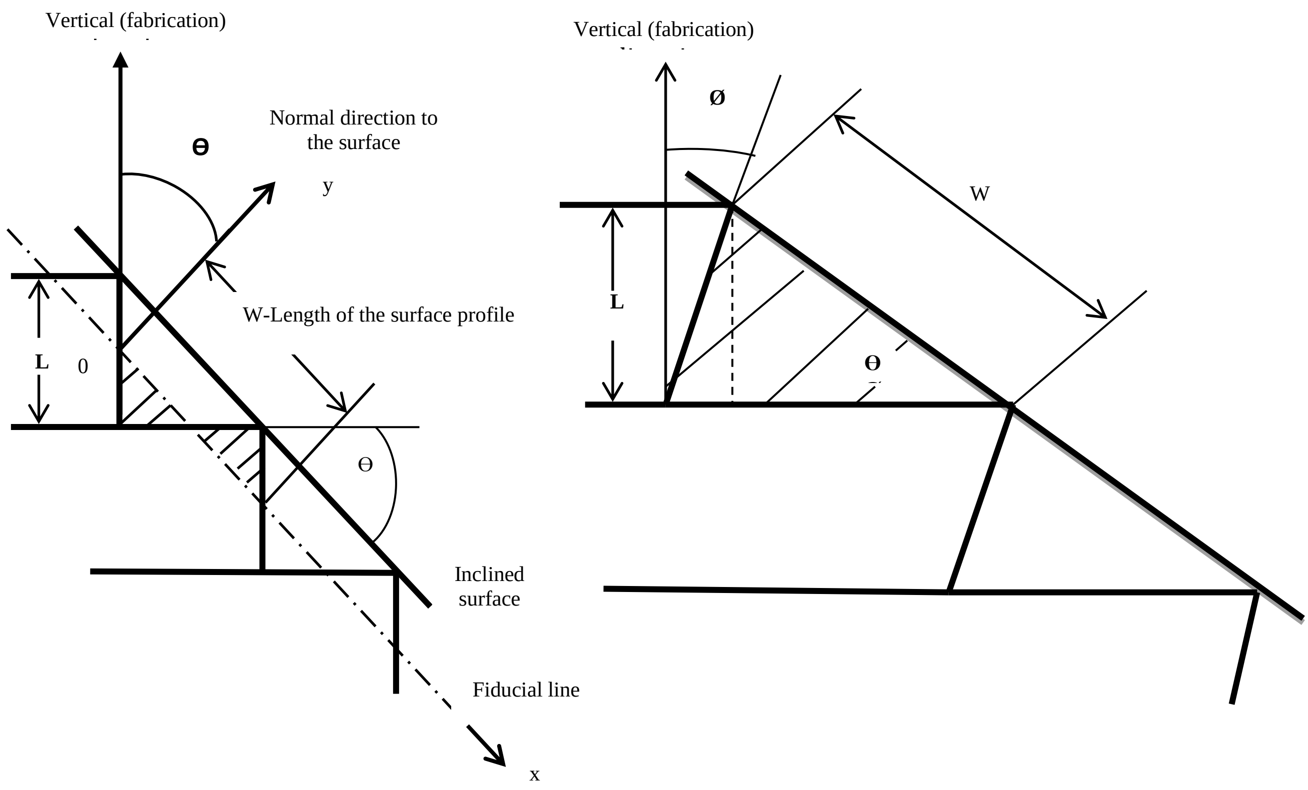
Based on the nature of all Additive Manufacturing (AM) processes whereby a Three-Dimensional (3D) object is built layer upon layer, it has been established that the surface finish of additively manufactured parts is dependent on the layer thickness L, the surface angle θ and the surface profile angle φ (Figure 1). According to Giovanni *et al*. [1], the average surface roughness, denoted by R_a can be analytically predicted by the following relationship:

$$R_a = \frac{L\cos\theta}{4},\ 0 \le \theta \le 180^\circ \qquad [1]$$

Taking into consideration the effect of the surface profile (built orientation) angle φ, Daekeon, Hochan and Seokhee [2] showed that the surface roughness Ra of AM parts can be calculated as follows:

$$R_a = \frac{L}{2}\left|\frac{\cos(\theta-\varphi)}{\cos\varphi}\right|, 0 \le \theta \le 180^\circ \qquad [2]$$

Equations (1) and (2) are only based on the geometry of the AM process and do not consider unpredictable roughness characteristics, such as the raster width, contour width, raster angle, air gap, solid or sparse support fill, support removal burrs, and other process parameters such as processing and removal temperatures, laser power, beam speed and hatch spacing. For a better planning of AM processes, extensive research aimed at the analytical prediction and optimization of process parameters to reduce the surface finish has been carried out by several scholars [3, 4, 5, 6, 7, 8, 9, 10, & 11]. The building of theoretical models and optimizing the fabrication parameters has still not been able to fully eliminate the stair-step effect [12]. Hassan et al. [13] found that even though more material would be required, a higher infill density is better than a sparse infill for generating smoother surfaces for Material Extrusion (MEX) of Acrylonitrile Butadiene Styrene (ABS).



a. Surface profile angle $\varphi = 0$

b. Surface profile angle $\varphi \neq 0$

Fig. 1: Layer thickness and the inclination angle of the surface profile of AM parts

Chohan and Sing [14] reiterated the shortcomings associated with the optimization of the process parameters during the printing stage as the geometry of the part may significantly vary from simple to more complex and convoluted shapes, thus raising the necessity of combining both optimization of the process parameters and post processing techniques to significantly improve the surface finish of AM parts.

II. POST PROCESSING TECHNIQUES FOR IMPROVEMENT OF SURFACE FINISH OF ADDITIVELY MANUFACTURED PARTS

Since the discretisation in modern AM processes is rarely isotropic, the surface roughness and resulting mechanical properties are also usually anisotropic [15]. The Standard Triangulation Language (STL) that approximates the part surface into a web of triangles by tessellating the Computer-Aided Design (CAD) geometry, causes the part to lose its resolution as only triangles and not curves represent its outline. For making aesthetically pleasing parts, acceptable surface roughness for investment castings for rapid tooling applications and for enhancing mechanical properties of prototypes and functional end use parts obtained from AM technologies, the surface finish must be improved through post processing techniques.

A. Improvement of surface finish of LS of nylon and Alumide® parts

Schmid, Simon and Levy [16] used a Rosler vibratory grinding machine with different ceramic beads in an investigation carried for 4 h, 8 h and 12 h to improve the surface finish of Duraform PA12 (polyamide 12) and Duraform HST (fibre-reinforced plastic) parts manufactured through the LS process. It was found that the surface roughness of all tested parts was around Ra=2 µm with equal standard deviation and a processing period of 8 h delivered the best surface finish. Furthermore, they subjected the PA12 samples with dip coating in silicon, polyurethane and vinyl-acrylpolymers solutions to increase the water tightness. The dip coating in silicon and vinyl-acrylpolymers showed desirable results for enhancement of water tightness. Precision grinding and Magnetic Field Assisted Finishing are techniques that can improve the surface finish of parts with complex geometry, yet preserving the profile of their microstructure. Guo *et al*. [17] improved the surface finish of LS PA12 from 15 µm to 2.81 and 0.89 µm Ra using precision grinding and Magnetic Field Assisted-Finishing (MFAF) respectively. For wear testing, Bai *et al.* [18] improved the surface finish of laser sintered polyamide 12 from 16.72 to 0.73 µm Ra through grinding followed by polishing. De Beer et al. [19] used tumbling in an abrasive media to polish Alumide® jewellery manufactured through the LS process. They obtained aesthetically pleasing smooth surfaces with a

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metallic lustre look. Wörz *et al*. [20] used nitric, hydrochloric and trifluoroacetic (TFA) acids for chemical treatment that extended to 120 s as the maximum duration, to improve the surface finish of LS PA12 parts. Depending on the duration of the treatments, TFA and nitric acids showed significant progressive decrease of the surface roughness from 80 µm Rz to 10 µm and 30 µm Rz respectively. Contrary to TFA and nitric acids, independently of the duration of treatments, the effect of hydrochloric acid was very little for improvement of surface finish of the parts. Compared to trifluoroacetic and nitric acids, parts treated with hydrochloric acid showed an increase in dimensions that resulted from the absorption of the liquid, thus detrimentally affecting the dimensional accuracy and mechanical properties of the parts. While the treatment with hydrochloric or TFA maintained the original white colour of the parts, nitric acid changed the white to yellow discoloration.

B. *Improvement of surface finish of MEX of ABS parts*

Electromechanical techniques can be used to reduce the surface irregularities resulting from the Material Extrusion (MEX) process. In the review on chemical processes for plastic substrates used in engineering industries, Raja [21] highlighted that electroplating with nickel, copper or chrome, electroless plating, vacuum metallization, metal spraying and cathode sputtering, electrochemical polishing are techniques used to improve the surface finish of AM polymers for enhancement of electromagnetic shielding, electroconductivity, mechanical properties, water and weather proofing. Laser micro machining is another surface finish technique for polymeric, metallic and ceramic substrates mentioned by Kumbhar and Muray [22] in their review on post processing methods to improve surface finish of AM parts. Pandey et al. [23] designed and used Hot Cutter Machining (HCM) to improve the surface quality of MEX produced ABS pieces that had intricate details. The surface finish was improved from 100 to 0.5 µm Ra. To improve the aerodynamic coefficient of an ABS-M30 wind tunnel model manufactured through MEX, Daneshmand and Aghanajafi [24] applied a chromium coating through electroplating to the model. The surface finish of the model was improved from 16 to 0.832 µm Ra. Kuo and Su [25] used a mixture of a hardener and a composite of aluminium powder (70%) and epoxy liquid resin (30%) as filling material to reduce the parabolic surface profile of FDM of ABS fabricated parts. The surface roughness of the wax pattern was reduced from 1710 to 276 µm Ra, thus achieving an 83.85% improvement. Boschetto, Bottini and Veniali [26] used CNC machining to reduce the surface roughness of a MEX produced ABS-P400 square parallelepiped 20 mm x 20 mm x 10 mm geometry where seven inclination angles namely 0°, 3°, 9°, 15°, 30°, 60°, and 90° were considered. The consideration of individual cutting parameters, especially the cutting depth for each inclination angle was a requirement to achieve a small range of surface roughness variation across the entire specimen.

Chemical treatments were used to investigate the effect of various acids on the surface roughness of MEX-produced ABS parts. Immersing the pieces into a mixture of 90% dimethylketone and 10% water for a period of 300 s, Galantuci *et al*. [27] improved the surface finish of ABS rectangular blocks obtained through MEX. For the top surface, the finish was improved from 11.8 to 2.2 µm Ra for a first group of test pieces, and from 17.2 to 4.6 µm Ra for a second group of test pieces. For the side faces, the surface finish was improved from 16.2 to 5.1 µm Ra and from 18.8 to 8.7 µm Ra for the first and the second group respectively.

Lalehpour and Barari [28] found that 95% improvement of surface finish could be achieved by an acetone vapour bath smoothing applied to the surface of MEX-produced ABS test pieces designed with inclination angles varying from 5° to 90° with 5° increment. The total time that the part was suspended in the vapour bath was found to be the main input factor that influences the surface roughness in the smoothing process. Chohan and Singh [29] used a vapour smoothing apparatus operating with a fluid, composed of Decafluoropentane (30%) and Dichloroethylene (70%) to eliminate the stair step on MEX-produced ABS biomedical hip prosthesis replicas. The uneven surface finish that was more pronounced on the curved regions were significantly reduced to an average improvement of 82.74% for three cycles of 20 s each, and the dimensional accuracy was also enhanced by the process. Singh *et al*. [30] also used the vapour smoothing station to improve the surface roughness of cube, cylinder and hemisphere geometry specimens, each of 16579.2 mm^3 volume, manufactured through MEX-produced ABS-P400. A surface finish of 0.01 µm was achieved in some cases and the overall improvement ranging from 93.38 to 99.20% could be attained without a detrimental effect on the dimensional accuracy of the features.

Hambali, Cheong and Azizan [31] investigated the influence of chemical treatment into acetone bath (10% acetone and 90% water) for 300 seconds, on the strength and the surface roughness of MEX-produced ABS dogbone specimens. Despite of 97.25% of surface finish improvement, 23.7% decrease of the Young modulus was observed. A similar behaviour was observed by Jayanth, Senthil and Prakash [32] when immersion into acetone and dichloroethane baths were subjected to ABS parts produced through MEX. It was found that immersion for 7 minutes produced the least surface roughness for both treatments, and when dichloroethane compared to acetone, it made the samples smoother with 91% of surface finish improvement, but softer with the tensile strength of the samples being reduced up to 48%. Kuo *et al*. [33] developed an apparatus to be used with acetone vapour for improvement of surface finish of MEX-produced ABS parts. The surface finish

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improvement ranging from 83 to 90% could be achieved for parts with different curvatures. Though the apparatus was easy to operate without chemical waste and at low costs, the authors stated that the apparatus could only be used for ABS plastics. Jayanth, Senthil and Prakash [34] used immersion into acetone and dichloroethane solvents to improve the surface roughness of ABS tensile test pieces obtained through the MEX process. With better surface finish for dichloroethane, it was found that for both solvents, the surface roughness reduced with the increase of immersion time that was varied from 3, 5 and to 7 minutes. For a period of 7 minutes, the surface finish of untreated specimen was improved from 9.42 µm to 0.84 and 0.56 µm for acetone and dichloroethane solvents respectively.

Poor surface finish and dimensional accuracy are two defects which are difficult to eliminate together by optimising AM processing parameters [29]. The literature survey shows that very little work has been published in line with improvement of the surface finish of LS of nylon or Alumide® parts. Several methods exist to improve the surface finish and each method has its advantages and limitations. The aim of this research was to compare surface roughness improvement that can be achieved through six post processing techniques performed on parts produced in nylon PA2200, Alumide® and ABS through LS and FDM.

III. EXPERIMENTAL SETUP AND SURFACE ROUGHNESS MEASUREMENT

A. *Geometry of test pieces and post processing techniques*

In a previous study, the authors investigated the effect of post-processing on the dimensional accuracy of small plastic additive manufactured parts [35]. The focus of the current study is to compare the level of improvement of surface finish of additively manufactured plastic parts when post-processing techniques are applied. For consistency, the same test geometry described for the previous study was used and the test pieces were additively manufactured in nylon and Alumide® through the LS process while the ABS test pieces were produced through the MEX process. To investigate the effect of surface finishing techniques on stair-stepping as a result of different AM processes, the test pieces comprised plane surfaces inclined from the horizontal direction at 0 to 90°with an increment of 10° (Figure 2) Other features such as three conical and three prismatic protrusions, and three small holes were incorporated in the geometry of the test pieces to investigate the effects post processing techniques have on dimensional accuracy as described from our previous work [35].

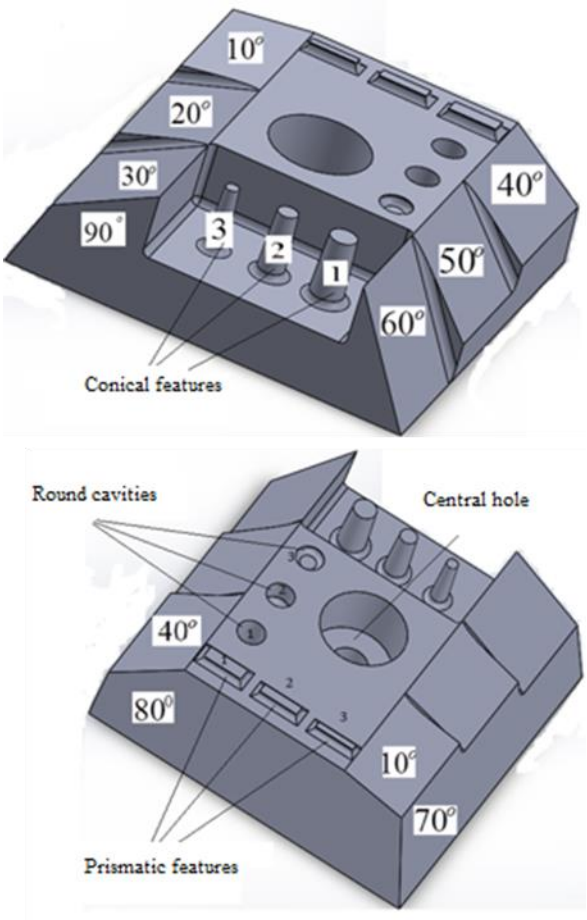

Fig. 2: CAD geometry of the test pieces

Two concentric central holes served for mounting the test piece onto a specially designed jigs while performing hand finishing, spray painting and for surface roughness measurement operations. Table 1 summarizes the post-processing techniques investigated to reduce the surface roughness of the "as built" additive manufactured test pieces.

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TABLE I: INVESTIGATED POST-PROCESSING TECHNIQUES FOR IMPROVEMENT OF SURFACE FINISH

Post-processing technique	**Description of the post processing process**
Tumbling	Vibrating the test pieces together with small abrasive stones in a soapy liquid at a rotation speed of 1500 rpm for a period up to 6 h for Nylon and Alumide® and 4 h for ABS test pieces.
Shot-peening	Blasting the test pieces with small stainless-steel balls of 0.5 mm diameter using compressed air at 5 bar for a duration extending to 4 minutes for Alumide® and 8 minutes for Nylon and ABS test pieces.
Hand finishing	Applying MS epoxy prime with an airbrush on the surfaces of the Nylon, Alumide® and ABS test pieces. Each MS epoxy priming was followed by manual sanding process, starting with the coarsest grid and finishing with the smoothest papers and aided with a sanding block. P60, P180, P320 and P400 sanding paper grades were used and the overall duration of the hand-finishing process could vary from 2h 15 min to 5h 20 min.
Spray painting	Applying one to four coats of primer followed by silver paint using an airbrush.
CNC -machining	Machining the plane surfaces of Nylon, Alumide® and ABS test pieces with a 3 mm diameter ball cutter at a rotational speed of 4000 rpm, cutting dept of 0.3 mm and feed rate of 600 mm/min.
Chemical treatment	Immersion of ABS test pieces into a controlled heated bath of acetone at 50°C for a period of one minute and into acetone vapour at 110°C for a period of 20 minutes.

B. Set up for the surface roughness measurements

Surface roughness measurements were performed using a Mitutoyo SURFTEST SJ-210 Surface Roughness Measuring Tester (SRMT) as shown by Figure 3. The SURFTEST SJ-210 is a portable surface roughness measuring instrument that traces the surfaces of parts, calculates their surface roughness based on roughness standards and displays the results on a Liquid Crystal Display (LCD) screen (Mitutoyo Corporation 2009). A special jig was designed to support the test pieces to enable the necessary translational and rotational motions for the measuring tip of the SRTM to have access to each angled surface of the test piece.

Fig. 3: Surface finish measurement setup with Mitutoyo SURFTEST SJ-210

For each considered angled surface, three surface roughness measurements were taken at different places: left, middle and right sides of the surface (Figure 4). The arithmetic average $R_{a_{av}}$ of the surface finish, as expressed by equation (3), was calculated and considered as the surface finish measure on that surface.

$$R_{a_{av}} = \frac{Ra_{LS} + Ra_{MS} + Ra_{RS}}{3} \quad [3]$$

$R_{a_{LS}}$, $R_{a_{MS}}$ and $R_{a_{RS}}$ respective measured surface finish at the left; middle and right sides as shown by Figure 4.

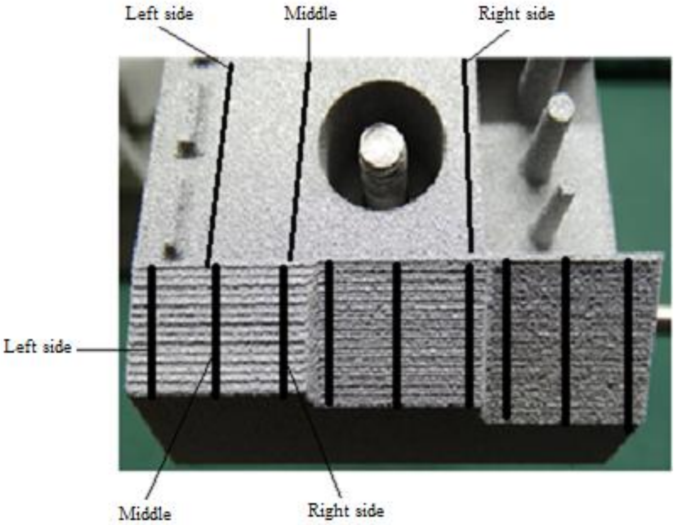

Fig. 4: Approximate zones for surface finish measurements

A visual inspection showed a significant dissolving effect of acetone on the surfaces of ABS test pieces while for nylon and Alumide® test pieces, acetone did not dissolve the surfaces, hence the surface roughness of chemically treated nylon nor Alumide® test pieces were not measured.

IV. RESULTS AND INTERPRETATION

A. Results of measurements of surface roughness for nylon test pieces

Figure 5 shows the results of measurements of the surface roughness of "as built", tumbled (a), shot peened (SPe) (b), hand finished (HF) (c), spray-painted (SP) (d) and CNC machined (e) nylon test pieces.

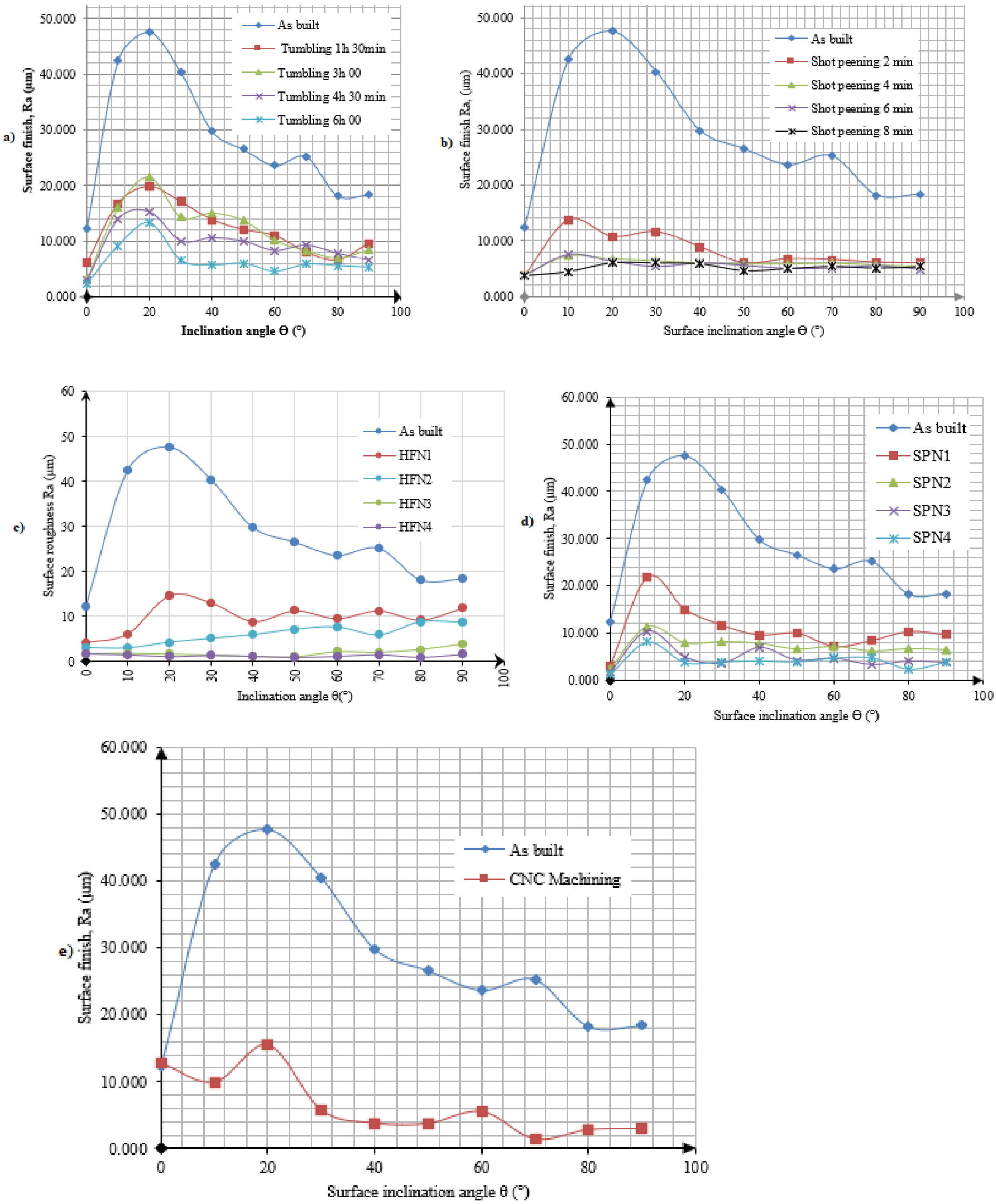

Fig. 5: Progressive improvement of surface finish though tumbling (a), shot peening (b), hand finishing (c), spray painting (d) and CNC machining (e) of nylon test pieces

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A preliminary comparison of effectiveness of the post processing techniques can be performed by rating the percentage of improvement of the surface roughness (starting by the highest percentage) on a particular surface and analyzing the degree of repeatability of the rating through all the surfaces. Table 2 summarizes the percentages of improvement for nylon test pieces and the following abbreviations are used to indicate the post processing techniques applied: **T**-Tumbling, **SPe**-Shot peening, **HF**-Hand Finishing, **SP**-Spray-Painting, **CT**-Chemical Treatment and **CNC-**CNC Machining.

TABLE II: RATING OF PERCENTAGE IMPROVEMENT OF SURFACE FINISH FOR NYLON TEST PIECES

Surface inclination angle θ (°)	Tumbling (T)	Shot peening (SPe)	Hand finishing (HF)	Spray-painting (SP)	CNC machining (CNC)	Rating of post processing technique
	% Improvement of surface roughness					
0	81.0	70.1	86.2	89.8	-2.9	SP,HF,T,SPe,CNC
10	78.3	89.5	96.4	80.8	76.6	HF,SPe,SP,T,CNC
20	72.1	87.2	97.6	92.1	67.5	HF,SP,SPe,T,CNC
30	83.7	85.0	96.6	90.2	85.8	HF,SP,CNC,SPe,T
40	80.8	80.1	96.0	86.0	87.2	HF,CNC,SP,T,SPe
50	77.3	82.6	96.4	85.1	85.9	HF,CNC,SP,SPe,T
60	80.5	78.7	95.1	79.9	76.4	HF,T,SP,SPe,CNC
70	76.7	78.5	93.9	80.8	94.3	CNC,HF,SP,SPe,T
80	69.1	71.9	94.6	87.0	84.3	HF,SP,CNC,SPe,T
90	71.0	70.8	91.3	79.1	83.5	HF,CNC,SP,T,SPe
Standard deviation	**2.929**	**0.764**	**0.268**	**1.783**	**4.698**	N/A

Table 2 shows that the hand finishing (HF) process with the lowest standard deviation of 0.268 occupies the first position on eight angled surfaces (from 10° to 60°, 80° and 90°), and it occupies the second position on the other two remaining surfaces (0 and 70°). The lowest percentage of improvement of surface finish is 86.2% on 0° surface angle while the highest being 97.6% on 20° angled surface. From Figure 5c, a progressive improvement of surface finish across all surfaces is observed from "as built" to hand finished nylon (HFN) test piece HFN1, from HFN1 to HFN2, from HFN2 to HFN3 and from HFN3 to HFN4 test pieces. It can be observed that for HFN4 test piece, the surface finish across the surface inclination angle is significantly reduced and becomes almost constant to an average value of 1.314 µm R_a. This is reflected by the small standard deviation of 0.268 of the surface roughness on the entire piece.

The spray-painting (SP) process also produced a progressive improvement of surface finish between 79.1 and 92.2%. (Figures 5d and 6b). Table 2 shows that the spray painting occupies from first to third position with a standard deviation of 1.783 indicating that the produced surface finish does not show big differences from one surface to another. An optimal surface finish was achieved in the case of SPN4 test piece where it can be observed that from 20 to 60° surface inclination angle, the surface finish is stabilized and remains practically at a constant value of 4.166 µm R_a, with exception of the surface finish of 2.364 µm R_a measured at 80° surface inclination angle.

The shot-peening (SPe) process produced a very good progressive improvement of surface finish varying from 70.1 to 89.5% with a small standard deviation of 0.764 indicating that the roughness is not widely dispersed across the surface inclination angles. This can be observed from Figure 5b where the shot peening technique performed for 6 and 8 minutes produced an almost constant surface finish of 6 µm R_a on 20 to 90° angled surfaces. However, the shot peening technique appears mostly in the third, fourth and fifth position in Table 2, showing that comparatively to hand finishing and spray-painting techniques, the percentage of improvement of surface finish is a bit lower.

With improvement ranging from 69.1 to 83.7%, the tumbling technique (T) dominated the fourth and a fifth position, indicating that the surface finish improvement was reduced across the surfaces when a comparison is made against hand finishing, spray-painting and shot peening (Table 2). It should be noted that the improvement of surface finish through the tumbling technique is not progressive (Figures 5a and 6c). It can be observed that the tumbling applied for a period of 3 h increased the surface finish obtained compared to a tumbling period of 1 h 30 min. This can be explained by the fact that the tumbling technique, being a material removal process, occurs where there is a transition period where fine burrs are generated. These burrs can be later removed if the pieces were subjected to a relatively longer tumbling period. Figure 6 shows the effects of post processing techniques on improvement of surface roughness on 10°, 20° and 30° angled surfaces of the nylon test pieces

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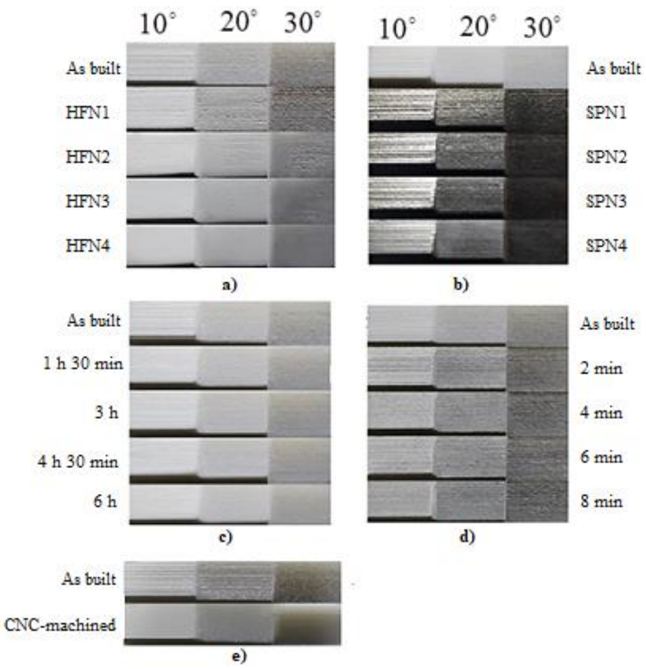

Fig. 6: Hand finishing (a), spray-painting (b), tumbling (c), shot-peening (d) and CNC-machining (e) improvement of surface finish of nylon test pieces

With the highest standard deviation of 4.698, CNC machining occupies the first to fifth positions, with the second and fifth positions being dominant in Table 2, indicating that the surface finish is widely dispersed across surfaces and the level of improvement of surface finish across the surfaces being reduced compared to hand finishing or spray-painting techniques. The CNC machining technique (Figures 5e and 6e) could exhibit a negative effect on the horizontal surface where the surface roughness increased by 2.9%. Compared to the shot peening and tumbling techniques, CNC machining exhibited a low percentage of surface finish improvement on 10 and 20°angled faces where the stair step effect is more pronounced; whereas on 30° surface angle, the level of improvement of the three techniques is approximately the same and equal to 85%. From 40 to 90° surface angles, the improvement of surface finish produced by CNC machining increases compared to shot peening or tumbling. Figure 5e shows that the CNC machined surface finish follows the trend of the surface finish of "as built" test piece which keeps changing across surfaces. This behavior can be explained by the fact that the cutting parameters were kept identical for all surface inclination angles and the inherited surface finish from the "as built" test piece influenced the final surface finish of CNC machined test piece.

B. Results of measurements of surface roughness for Alumide® test pieces

The rating of the percentage of improvement of the surface finish of the five post processing techniques across the surface inclination angles on the Alumide® test pieces is presented in Table 3.

Table III: Rating of percentage improvement of surface finish for Alumide® test pieces

Surface inclination angle θ (°)	**T**	**SPe 3 min**	**HF**	**SP**	**CNC**	**Rating of post processing techniques**
	% improvement of surface roughness					
0	74.5	47.8	87.7	88.5	63.0	SP, HF, T, CNC,SPe
10	74.7	50.4	94.7	79.2	77.9	HF, SP, CNC, T,SPe
20	78.2	71.1	95.9	92.3	69.1	HF, SP, T, SPe,CNC
30	80.4	65.9	95.6	88.8	86.2	HF, SP, CNC, ,T,SPe
40	81.9	68.1	95.3	89.9	84.7	HF, SP, CNC, T,SPe
50	79.7	68.8	96.0	92.2	85.5	HF, SP, CNC, T,SPe
60	80.7	65.9	95.6	90.6	88.2	HF, SP, CNC, T,SPe
70	71.6	56.6	90.2	83.5	89.2	HF, CNC, SP, T,SPe
80	71.1	50.8	92.7	84.6	85.8	HF, CNC, SP, T,SPe
90	64.6	48.4	89.7	80.9	81.5	HF, CNC, SP, T,SPe
Standard deviation	1.279	2.202	0.274	1.326	2.693	

Table 3 indicates that the hand finishing appears in first positions for all angled surfaces of the Alumide® test pieces, with exception to the horizontal surface where HF occupies the second position. With the lowest standard deviation of 0.274, the improvement of the surface finish across the angled surfaces varies from 87.7 to 96%. From Figure 7c, it can be observed that the surface roughness of the test pieces decreases progressively with the further application of sanding and priming with exception observed on the 70° surface inclination angle where the surface finish of HFA1 test piece is less than the surface finish of the HFA2 test piece. Finally, the surface finish across all surfaces on the HFA4 test piece could be stabilized at a value close to 2 µm Ra. Figure 8 illustrates the progressive improvement of surface roughness from "as built" to tumbled, shot peened, hand finished, spray painted and CNC machined Alumide® test pieces on 10°, 20° and 30° surface inclination angles.

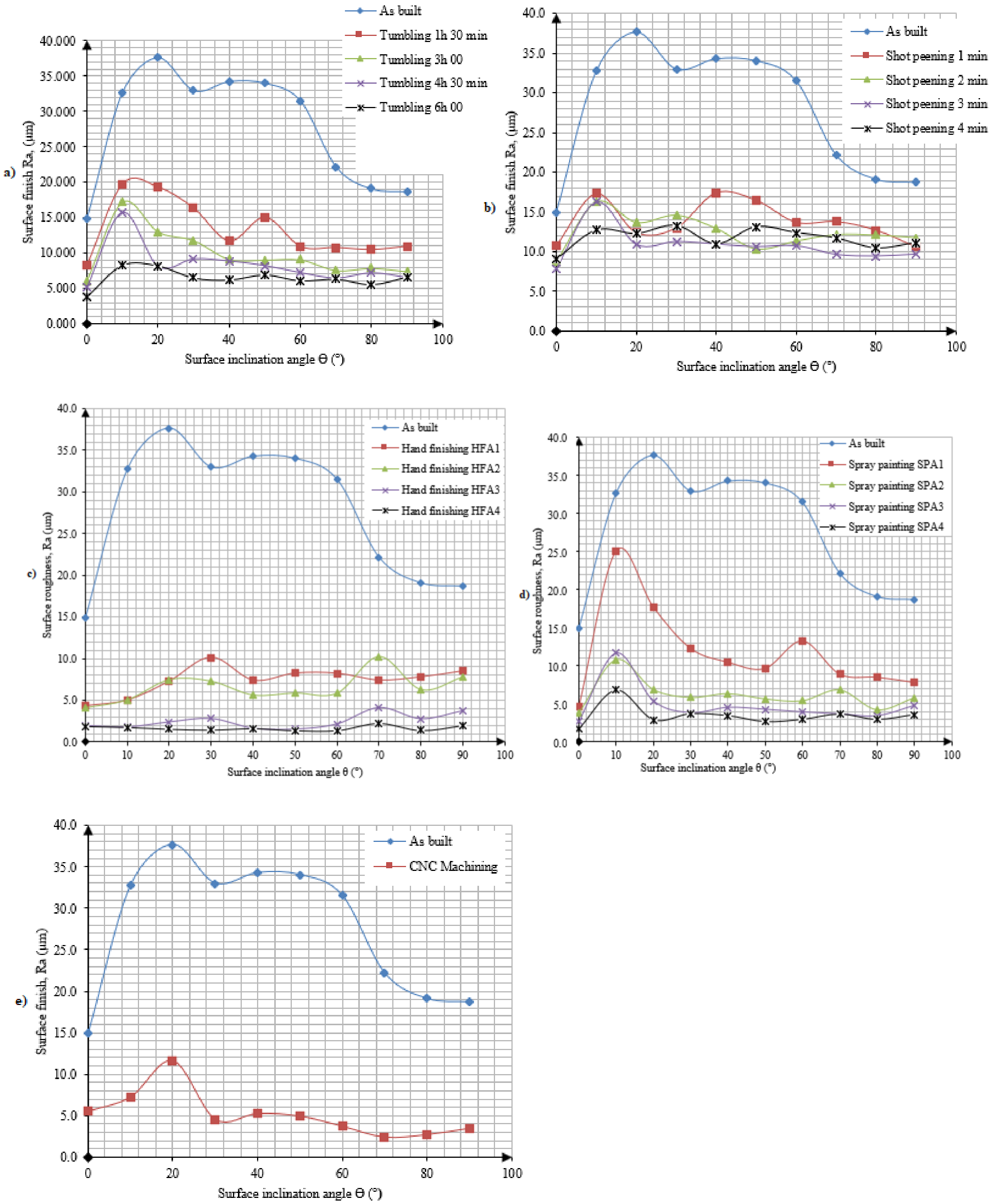

Fig. 7: Progressive improvement of surface finish though tumbling (a), shot-peening (b), hand finishing (c), spray painting (d) and CNC machining (e) of Alumide® test pieces

From Figure 8, it can be observed that with different levels of improvement of the surface roughness, the final surface roughness obtained by each technique produced an almost uniform surface roughness across the 10°, 20° and 30° surface inclination angles. A similar trend is observed on the other angled surfaces of the test pieces.

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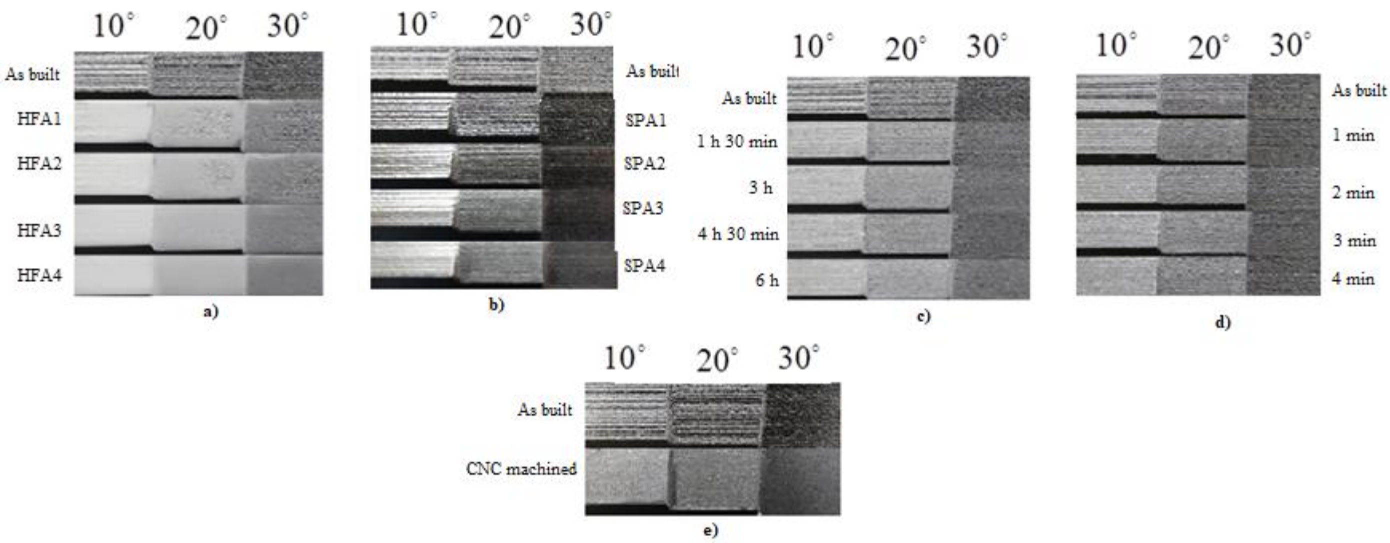

Fig. 8: Improvement of surface finish through hand finishing (a), spray painting (b), tumbling (c), shot peening (d) and CNC machining of Alumide® test pieces

C. Results of measurements of surface roughness for ABS test pieces

In addition to the five post processing techniques performed on nylon and Alumide® test pieces, ABS test pieces were subjected to chemical treatments consisting of a controlled immersion into an acetone bath solution at a room temperature for a period of 60 seconds (CT1), heated at 50°C for a duration of 60 seconds (CT2) and subject to acetone vapour at 110°C for 20 minutes (CT3). The rating of the percentage of improvement of the surface finish of the six post processing techniques across the surface inclination angles on the ABS test pieces is presented in Table 4.

TABLE IV: RATING OF PERCENTAGE OF IMPROVEMENT OF SURFACE FINISH FOR ABS TEST PIECES

Surface inclination angle θ (°)	Tumbling (T)	Shot peening (SPe)	Hand finishing (HF)	Spray painting (SP)	Chemical treatment (CT)			CNC machining (CNC)	Rating of improvement of post processing techniques
					CT1	CT2	CT3		
	% Improvement of surface finish								
0	37.2	55.7	95.4	92.6	85.5	85.6	89.2	75.0	HF, SP, CT3, CT2, CT1, CNC, SPe, T
10	26.6	49.2	97.3	83.1	66.4	91.0	92.4	92.0	HF, CT3, CNC, CT2, SP, CT1, SPe, T
20	28.2	69.7	98.3	94.1	92.7	93.1	93.3	92.9	HF, SP, CT3, CT2, CNC, CT1, SPe, T
30	31.9	74.2	97.7	95.3	89.2	89.4	88.1	93.0	HF, SP, CNC, CT2, CT1, CT3, SPe, T
40	40.9	76.8	97.4	94.9	87.3	91.7	80.2	82.8	HF, SP, CT2, CT1, CNC, CT3, SPe, T
50	37.5	75.0	96.8	95.2	88.3	87.8	84.6	86.5	HF, SP, CT1, CT2, CNC, CT3, SPe, T
60	43.7	61.2	96.7	93.4	89.7	87.5	88.6	78.1	HF, SP, CT1, CT3, CT2, CNC, SPe, T
70	50.9	69.0	95.0	91.6	87.0	87.3	93.8	79.3	HF, SP, CT3, CT2, CT1, CNC, SPe, T
80	39.9	66.6	94.1	92.0	87.4	89.1	90.3	90.4	HF, SP, CT3, CNC, CT2, CT1, SPe, T
90	49.2	67.3	94.5	86.6	80.0	86.3	77.3	73.3	HF, SP, CT2, CT1, CT3, CNC, SPe, T
Stand. Dev.	**12.79**	**6.674**	**0.199**	**2.274**	**4.515**	**0.861**	**2.297**	**1.223**	N/A

Table 4 shows that the hand finishing technique occupies first positions across all surfaces of the test pieces. With a very small standard deviation of 0.199, an improvement of surface finish ranging from 94.1 to 98.3% was achieved with application of 9 sanding steps and 6 layers of epoxy primer. The small standard deviation indicates that there exist negligible differences between the values of surface finish across all surfaces. This can be observed from Figures 9c and 10a where the surface finish across all surface angles for all hand finished test pieces can be practically equated to an average value of 1.082 μm Ra.

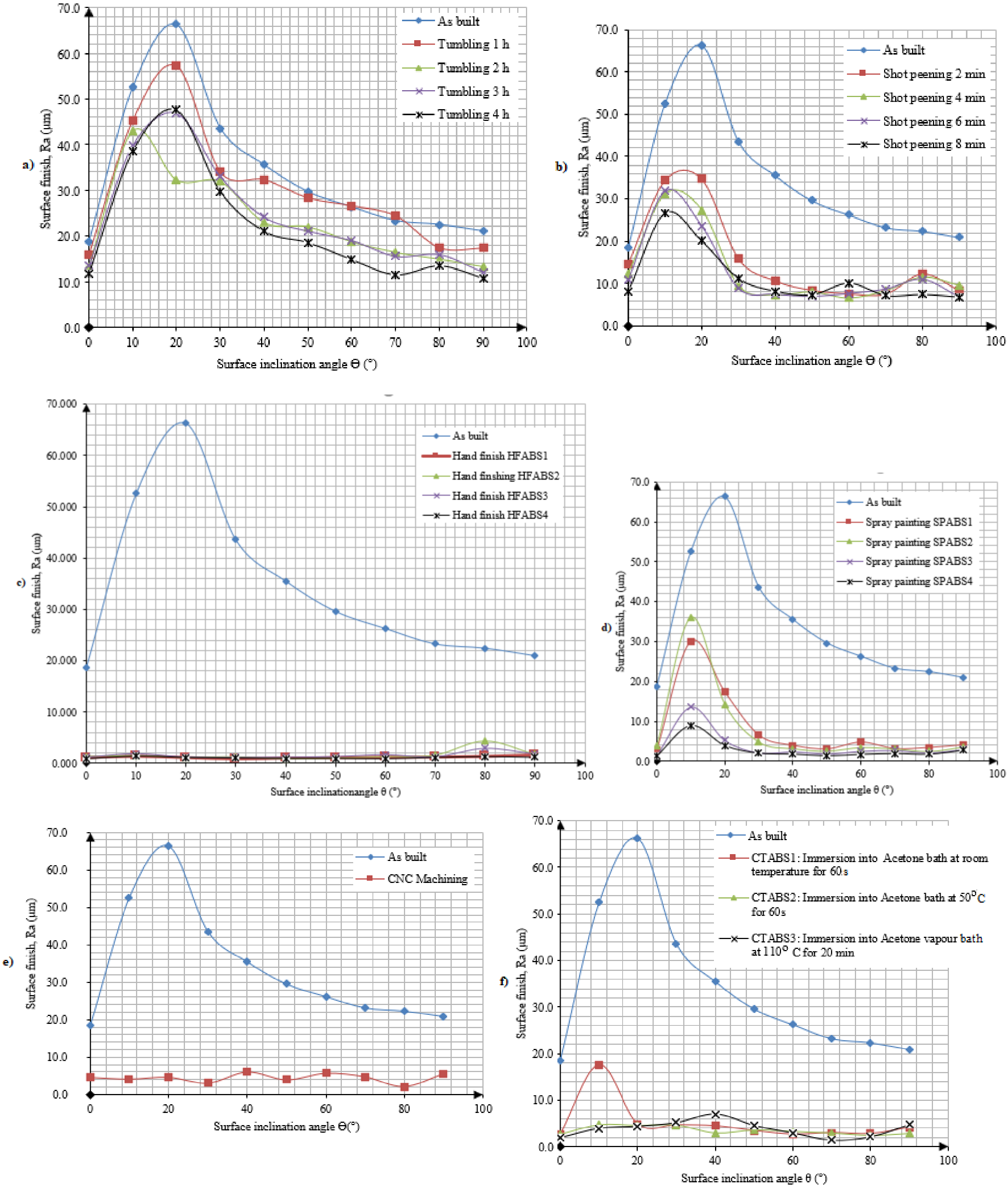

Fig. 9: Progressive improvement of surface finish though tumbling (a), shot-peening (b), hand finishing (c), spray painting (d) and CNC machining (e) of ABS test pieces

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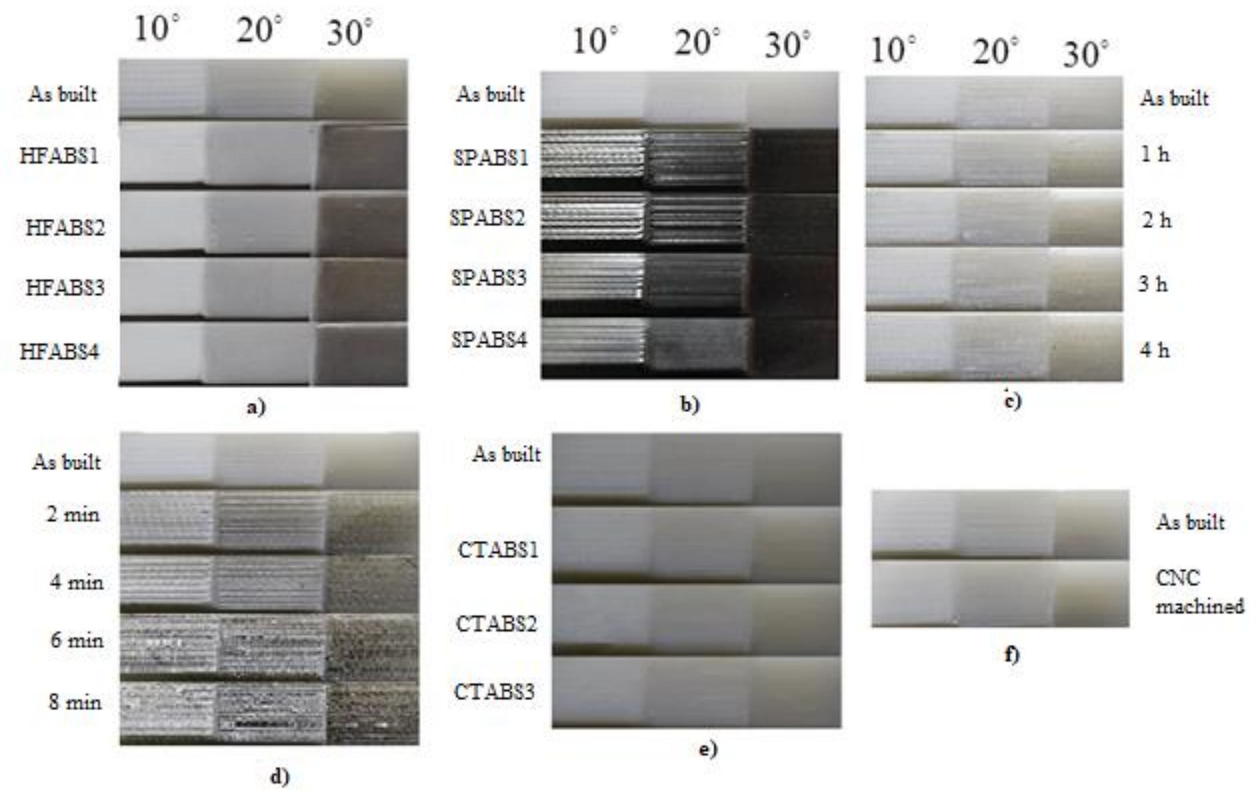

Fig. 10: Improvement of surface roughness of ABS test pieces through hand finishing (a), spray-painting (b), tumbling (c), shot peening (d), chemical treatment (e) and CNC machining (f)

The Spray painting technique occupies the second position and up to 90%. With four undercoats of priming, followed by one layer of silver paint, the spray-painting technique performed on the ABS test pieces exhibited 83.1 to 95.3% improvement of surface finish with a standard deviation of 2.274. Figures 9d and 10b showed that the surface roughness improved progressively with the increase of the number of undercoats. It can be realized that in the range of 30° to 90° surface angles, the surface finish of SPABS4 is practically stabilized to an average value of 2 µm Ra, which is an advantage for a uniform surface finish across the above surface angle range. It can be noted that the lowest improvement of surface finish is observed at 10°and 20° surface angles where the stair-step effect is more evident, the uniform undercoating and painting across the entire test piece does not provide enough coverage to eliminate the stair steps.

Among the three considered chemical treatments, CT3 showed the best performance by dissolving the stair steps on 10° surface inclination angle into acetone vapour bath, thus improving the surface finish up to 92.4%, an improvement which is a slightly higher than 91% achieved when the ABS test piece was subjected to CT2. It can be realized that the differences of percentage of improvement of surface roughness for CT1, CT2 and CT3 are not significant on 0°, 20°, 30°, 50°, 60°, 70° and 80° surface angles (Figures 9f and 10e). The three chemical treatment curves almost overlap with the exception on 10° surface angle where the immersion into the acetone bath at room temperature for a period of 60 seconds failed to scale down the surface finish with an average value of 4.343 µm Ra, thus producing improvement of surface finish ranging from 66.4 to 92.7%.

With a relatively small standard deviation of 1.223, the CNC machining of ABS test pieces produced a wide range of percentages (73.3 to 93%) of improvement of surface finish. Figure 9e shows that the final surface roughness varied from 1.144 to 6.104 µm Ra. Boschetto, Bottini and Veniali [26] showed that without having a risk of very scattered surface roughness, a surface roughness below 2 µm can be achieved if the cutting depth could be varied between 0.5 to 0.05 mm across inclination angles. In a similar manner to nylon and Alumide® CNC machined test pieces, this investigation has showed that a harmonization of surface finish across all the surface inclination angles requires the variation of the cutting parameters that will inadvently led to extra machining time, labour and cost.

Table 4 shows that the shot peening occupies seventh position indicating that hand finishing, spray painting, chemical treatments with acetone and CNC machining performing better than shot peening for the improvement of surface finish of ABS test pieces. When the shot peening period is gradually increased from 2 to 6 minutes with an increment of 2 minutes, there is a progressive improvement of surface finish for the entire range of surface angles (Figure 9b). The increase of the shot peening period up to 8 minutes led to an increase of surface finish for 30° to 60° surface angles, which was very pronounced on the surfaces inclined at 30° and 60°. For the 70° to 90° range, a progressive

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improvement of surface finish with increase of shot peening period is also observed

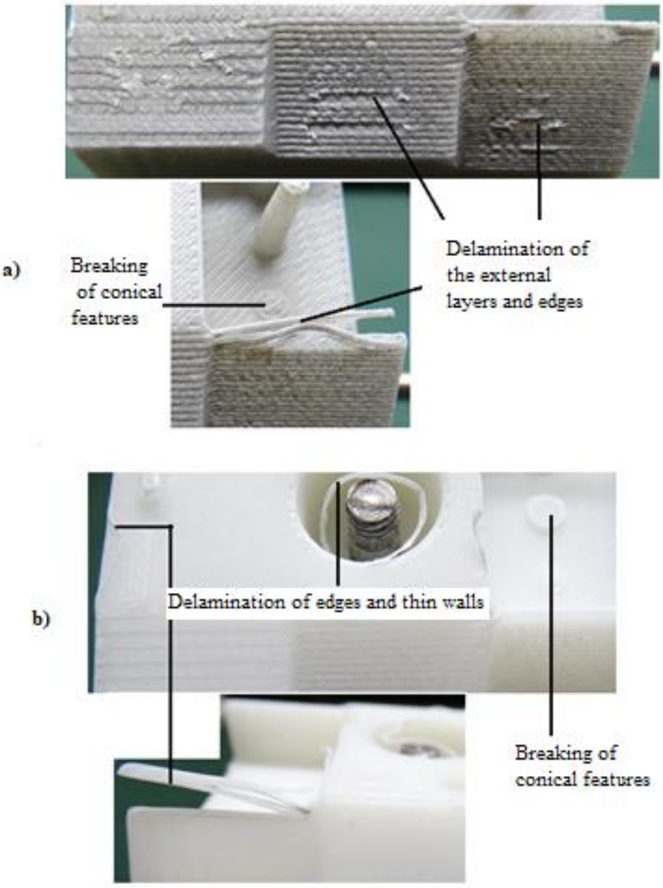

Fig. 11: Problems associated with shot peening (a) and tumbling (b) of ABS test pieces

Despite the overall progressive improvement of the surface roughness, the shot peening of ABS test pieces also saw surface damage at the middle areas of the 10°, 20° and 30° surface as well as the removal of edges and thin walls of the piece (Figure 11a).

For a short period of one hour, the tumbling technique applied to ABS test pieces also displayed the incidental and unintended removal of material in the form of fibers from the edges and thin walls; and the breaking of the conical features (Figure 11b). This showed poor to satisfactory improvement of surface finish varying from 26.6 to 50.9% with a very high standard deviation of 12.792 was observed, thus rating the tumbling technique applied to ABS test pieces in the last positions (Table 4). Figure 9a showed that with an increase of the tumbling time, the improvement of the surface finish was not progressive on 10° and 20° surface inclination angles where the stair-step effect was more pronounced. For a uniform surface finish across the entire piece, tumbling of ABS AM parts produced through MEX may not be suitable. Extensive work aimed at the improvement of surface finish of FDM ABS test pieces through chemical treatment with acetone showed better results than mechanical methods in many aspects [28]. For a uniform surface finish across the entire test piece, with the lowest standard deviation of 0.861, immersion in an acetone bath at 50°C for a period of 60 seconds was found to be the most preferable comparatively to the three considered chemical treatments and the five mechanical techniques as well. This treatment provides an advantage of requiring a shorter period at moderate temperature with less energy consumed, thus avoiding the risk associated with the heating of the acetone which is a highly flammable chemical substance. Table 5 summarizes the highest achieved percentage of improvement of surface finish along with the corresponding achieved lowest surface finish.

TABLE V: SUMMARY OF THE HIGHEST ACHIEVED PERCENTAGE OF SURFACE FINISH IMPROVEMENT AND THE CORRESPONDING LOWEST SURFACE FINISH

	Highest surface finish improvement (%) / lowest surface finish (µm)					
(Technique / Material)	**Hand Finishing (HF)**	**Tumbling (T)**	**Shot Peening (SPe)**	**Spray Painting (SP)**	**CNC machining (CNC)**	**Chemical treatment (CT)**
Nylon	97.6	83.7	89.5	92.2	94.3	Not applied
	1.314	6.577	6	4.166	1.433	
Alumide®	96	81.9	71.1	92.3	89.2	Not applied
	1.37	6.191	12.256	2.897	2.399	
ABS	98.3	50.9	76.8	95.3	93	93.8
	1.155	11.426	8.243	2.064	3.072	1.431

V. CONCLUSION AND FUTURE WORK

The six post-processing techniques improved the surface finish for nylon, Alumide® and ABS test pieces. Hand finishing and spray-painting techniques exhibited the highest percentage of improvement of surface finish of the test pieces. However, both techniques were characterized with a long period of processing time extending to 5h20min to finish a single test piece, with eventual lack of consistency for a uniform dimensional accuracy across the entire test piece. With care taken for small protrusions and sharp corners, tumbling and shot peening can be effectively applied to LS nylon and Alumide® parts. However, tumbling and shot peening could cause heavy damage on ABS pieces, thus detrimentally affecting the dimensional accuracy of ABS parts manufactured through the MEX process as found by Nsengimana et al. [35]. The chemical treatment method applied to ABS test pieces was found to be an optimal solution to dissolve stair-stepping surfaces, thus improving the surface finish. Where a uniform surface finish is required for parts with complex form and small features, CNC machining is not recommended as the setting of individual cutting parameters for each surface may not be productive and would involve a high production cost. Future work will focus on a variety of chemical treatments that will reduce the surface finish of LS nylon and Alumide® materials.

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