Fabrication and Testing of a Vapor Polishing Device for ABS 3D-Printed Parts

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ABSTRACT

Post-processing plays a significant role in improving the surface and mechanical properties of 3D-printed parts. One of these post-processing methods is vapor polishing which utilizes acetone to polish 3D-printed Acrylonitrile Butadiene Styrene (ABS) specimen. This process is usually done using an improvised vapor polishing set-up to achieve the desired surface finish of parts. Hence, in order to accomplish a uniform and standard polishing procedure for laboratory use, a vapor polishing device has been developed in this study. To assess the efficiency of the said device, the resulting surface roughness, dimensional accuracy, and tensile strength of ABS 3D-printed polished specimens have been evaluated and compared to unpolished specimen. The surface roughness of the cube specimen was captured using a Trinocular Microscope and was uploaded to the Mountains9 Topography software. Further, the dimensional accuracy of both polished and unpolished specimen has been measured using a digital Vernier Caliper. The data demonstrated that the polished specimen's surface was enhanced while its shape, geometry, and dimension were preserved. Tensile tests on two (2) sample sets of polished and unpolished specimens revealed that polishing with acetone vapor using this developed device could improve the specimen's tensile strength.

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KEYWORDS

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INTRODUCTION

Additive Manufacturing (AM) more commonly known as 3D printing is now a subject of interest in different industries, research, and academia (Dizon et al., 2018). It is now being used in different types of applications such as electronics (Espera et al., 2019; Espera et al., 2022), satellites (De Leon et al., 2022), robotics (Delda et al., 2021), oil and gas (Caldona et al., 2021), aerospace (Martinez et al., 2022), automotive (Tuazon et al., 2022), medicine (Advincula et al., 2020), agriculture (Crisostomo and Dizon, 2021) and others. This is due to the many advantages offered by AM including fabrication of components with complex geometries, opportunity in supply chain simplification, reduced material wastes, and promotion of the efficient use of resources (Pereira et al., 2019; Rosen, 2014). Recently, more studies are being conducted to investigate the environmental aspects of 3D printing, as a way to adapt to a more sustainable and economical manufacturing applications (Caldona et al., 2022). However, despite the opportunities offered by AM, there are still downsides and limitations that should be addressed.

For instance, the Fused Filament Fabrication (FFF) 3D printer, one of the most widely used consumer-level printers that utilize polymers in building prototypes and actual products (Dizon et al., 2018; Rahim et al., 2019), commonly uses Acrylonitrile Butadiene Styrene (ABS). This is due to its acceptable thermal shrinkage, chemical resistance, durability, and relatively high strength (with the ability to be subjected to functional tests on sample parts) (Chaudhari et al., 2017; Selvamani et al., 2019). Nonetheless, ABS parts printed through FFF technology, still have disadvantages commonly identified as stepped layers, overhang and bridging, stringing, warping, hygroscopicity, and structural inhomogeneity, caused mainly by printing layer-by-layer (Bryll et al., 2018; Daminabo et al., 2020). Although this can sometimes be controlled by reducing the layer thickness of 3D prints, it still requires additional manual post-processing (Dizon et al., 2021; Lalehpour and Barari, 2016). According to Dizon et al., post-processing refers to other processes or procedures applied to 3D-printed parts upon removal from the printer (Dizon et al. 2021). One of the most effective post-processing methods for ABS material is acetone vapor polishing (Lalehpour and Barari, 2016; Dizon et al., 2021). The process is done by exposing the 3D-printed parts to chemical vapor, causing its surface to flow, thereby improving its surface finish (Chaudhari et al., 2017).

Some of the previous studies emphasized the testing and evaluation of polished and unpolished ABS 3D-printed parts, which reports the effectiveness of vapor polishing procedure in improving its surface and mechanical properties. However, a standard polishing procedure that might be achieved through a vapor polishing device has not been fabricated in these studies (Gao et al., 2017; Lalehpour and Barari, 2016). In a study conducted by Tuazon et al., aside from proving the effectiveness of vapor polishing through testing and evaluation, an improvised set-up of an acetone vapor bath system was also used to conduct their test procedure (Tuazon et al., 2020). The improvised set-up consists of multiple components, particularly an aluminum plate, bowl, acetone-wet tissue, and beaker. Although the vapor polishing set-up works, it does not conform to a chemically-safe environment and operation. On the other hand, some studies focused on the fabrication of a vapor polishing device for 3D-printed parts, however, with only limited testing and evaluation of the specimen (Chaudhari et al., 2017; Xu et al., 2019). Hence, in this study, a vapor polishing device has been developed to provide an efficient standard polishing procedure and a safe working environment for laboratory use. It works by incorporating a mist maker that emits vapor inside the glass chamber where the 3D-printed specimen is placed. Furthermore, in testing the efficiency of the said device, sample sets were printed and vapor-polished to determine some physical properties such as surface roughness, dimensional accuracy, and tensile strength. The measured values have been compared to the measured values using unpolished specimens. Table 1 lists some of the above-mentioned relevant studies, with the objectives and the types of testing performed, in order to serve as a guide in the conduct of the present study.

Table 1: Summary of relevant studies about acetone vapor polishing.

References	Fabrication of Acetone Vapor Polishing Device	Experimental Testing			
		Surface Roughness	Tensile Test	Impact Test	Dimensional Accuracy
Gao et al., 2017	✗	✗	✓	✗	✗
Lalehpour and Barari, 2016	✗	✓	✗	✗	✗
Chaudhari et al., 2017	✓	✓	✗	✗	✗
Xu et al., 2019	✓	✗	✗	✗	✗
Tuazon et al, 2020	✗	✗	✗	✓	✗
Present study	✓	✓	✓	✗	✓

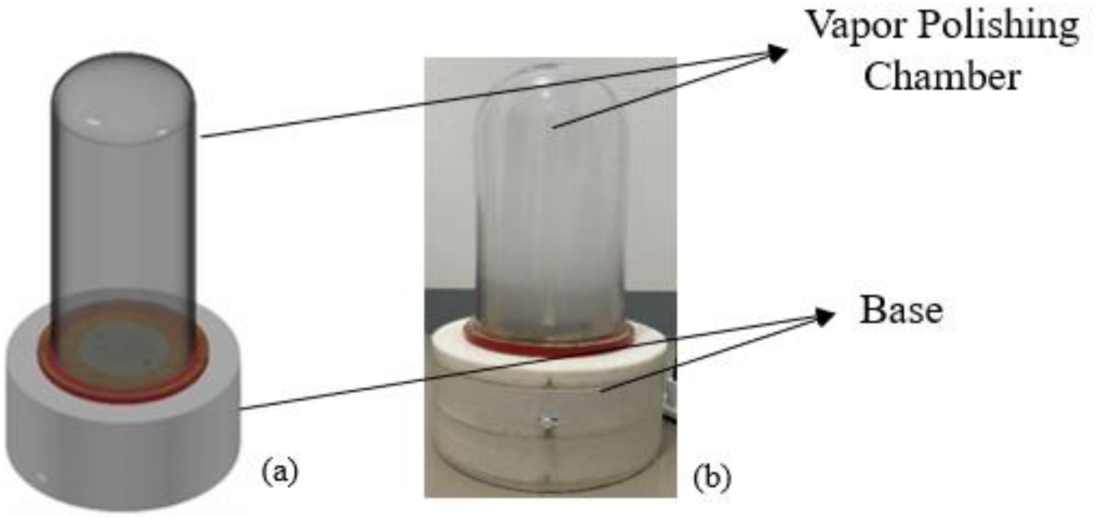

Figure 1: Image of the (a) 3D CAD Model, and (b) Actual Acetone Vapor Polishing Device

METHODOLOGY

Materials and Fabrication Procedure

Figure 1 shows the CAD model and the prototype of the device. The device could be divided into two (2) major parts namely, the *vapor polishing chamber* and the *base*. The acetone vapor polishing device was designed using CAD software and some parts (especially the base) were fabricated using the 3D printing technology. Figure 2 shows the basic construction of the fabricated acetone vapor polishing device showing the different components. The fabrication was executed according to the initial design and modified based on the adjustments needed for more effective vapor polishing.

The *vapor polishing chamber* contains a dome-type glass chamber, polishing plate, and wooden cover. This part is responsible for the stability of the specimen during the process. It also serves as an enclosure that balances the air pressure to maintain the circulation of acetone vapor thereby creating a constant polishing process. While an aluminum vapor polishing plate was customized to function as a filter, allowing acetone mists to evaporate from the container to the glass chamber. And a dome-type glass chamber was used to balance the movements of the acetone mists resulting in more interaction with the surface of the 3D-printed object.

On the other hand, the *base* of the device, as shown in Figure 3, is responsible for the production of acetone mist in the chamber. Particularly, it includes the set-up and arrangement of the circuit board which is primarily responsible in turning the acetone liquid to an acetone vapor using a mist maker. And since the base contains the acetone solution, it should therefore be separated from the other components and sealed properly. The mist maker was attached in 50 mm vertical tubes to reach the chamber much better and easier. The capacity of the petri dish is 100 ml, equivalent to ~5 hours of acetone vaporization. Moreover, the base was 3D-printed using a large-scale FFF 3D printer (Modix Big-Meter) using polylactic acid (PLA) material because it is less sensitive to acetone vapor, more robust, and more appropriate for initial design testing.

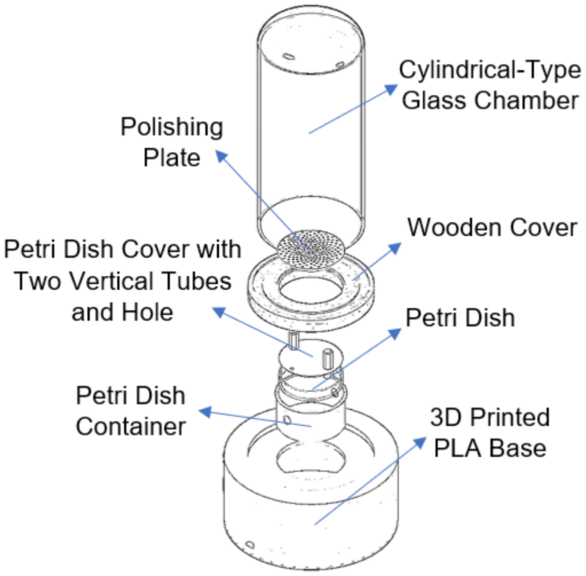

Figure 2: Basic construction of acetone vapor polishing device

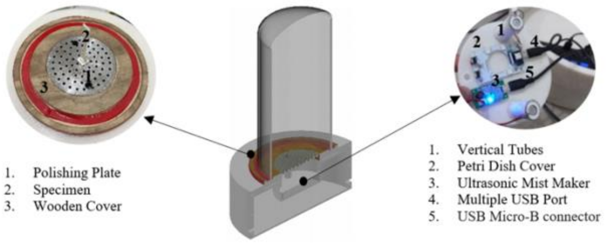

Figure 3: Internal components of the base

Vapor Polishing Procedure. Initially, the glass chamber was removed for the placement of 3D-printed specimen on the polishing plate before refilling the acetone container. Note that a syringe was used to measure the exact amount of acetone injected on the tube connected to the container. After placing the 3D-printed specimen and putting back the glass chamber, the vapor polishing device was plugged in to a power source to activate the mist maker, and with this, acetone vapor was produced. The generated acetone vapor automatically and immediately filled the enclosed glass chamber, allowing the 3D-printed specimen to absorb the acetone vapor. The specimen was removed as soon as the glass chamber became transparent (which serves as an indicator that the acetone has already ran out). Lastly, a curing (waiting) time of 30 minutes was used to allow the specimen to fully absorb the acetone before subjecting it to a particular testing procedure.

Experimental Design and Procedures

Surface Roughness. To measure the effects of acetone vapor polishing on the surface roughness of ABS 3D-printed parts, a 10 mm cube specimen with a dimension of 10 mm x 10 mm x 10 mm was printed. The cube specimen was 3D-printed with 90% infill density and layer thickness of 0.19 mm, using a FFF 3D printer (Zortrax M200). Before polishing the cube specimen, its surface was captured using a Trinocular Microscope (AMScope). The captured image of the surface was uploaded to the Mountains9 Topography software to analyze and measure its surface roughness parameter, such as the maximum peak height, maximum pit height, and maximum height. Maximum peak height (Sp) is the height between the highest peak and the mean plane, and maximum pit height (Sv) is the depth between the mean plane and the deepest pit/valley. While maximum height (Sz) is the height between the highest peak and the deepest pit/valley (Stach et al., 2016).

After measuring the surface of the unpolished cube specimen, it was acetone vapor-polished using the device. The acetone volume used was 20 ml, and the specimen was exposed for approximately one hour and a curing time of 30 minutes. Following the same procedure, the surface of the polished specimen has been measured, analyzed, and compared to the previous results obtained from the unpolished cube specimen. The test specimen and set-up during surface digital imaging can be seen in Figure 4.

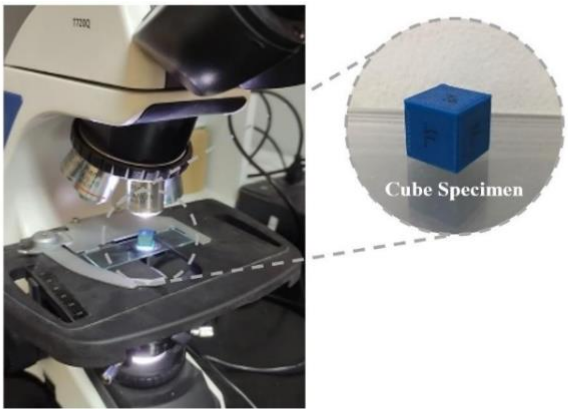

Figure 4: Digital imaging of surface roughness of 10 mm cube specimen

Dimensional Accuracy. The dimensional changes between 3D-printed polished and unpolished specimens were measured to test the effectiveness of the fabricated acetone vapor polishing device. Three (3) cube specimens with different dimensions of 10 mm, 15 mm, and 20 mm were 3D-printed using the ABS material (Robles et al., 2022a; Robles et al., 2022b), as shown in Figure 5. The cube specimens were prepared similarly as described in the previous section. Meanwhile, the initial dimensions of each specimen were measured and recorded using a Vernier Caliper (Mitutoyo Digimatic) in three (3) positions (top-to-bottom, front-to-back, and left-to-right) as shown in Figure 6, in order to obtain the average dimension before polishing. Afterwards, it was then polished using the acetone vapor polishing device with the same procedure performed on the previous test. The dimension of the polished specimen has also been measured and compared to the values obtained from the unpolished cube specimen.

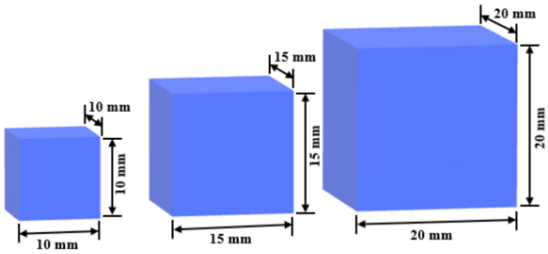

Figure 5: Three (3) ABS 3D-printed cube specimens with different dimensions

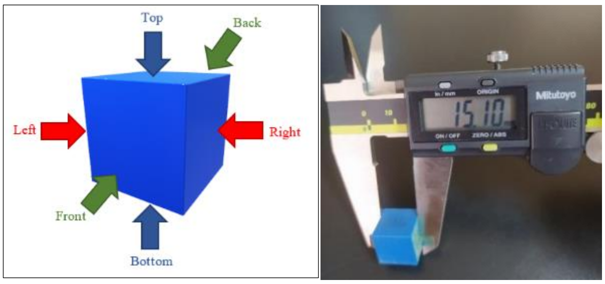

Figure 6: Guide in dimensional measurement of cube specimen and photo of actual measurement

Tensile Test. Tensile tests were performed on two (2) test samples using a Universal Testing Machine (Shimadzu AGS-X Series) with 10 kN capacity following the ASTM D638-14 test procedure. The ABS tensile specimen was prepared following the ASTM D638-14 Type IV explicitly designed to measure the tensile strength of rigid plastics (for both reinforced and non-reinforced specimens). The specimens were 3D-printed by batch, three (3) test specimens for polished and unpolished specimens. The print settings were set with an infill density of 90%, honeycomb printing pattern, 0º raster angle, and was printed edgewise (i.e. edge build orientation). The ABS 3D-printed specimen was vapor-polished using the procedures mentioned above. The tensile test set-up and the specimen configuration are shown in Figure 7.

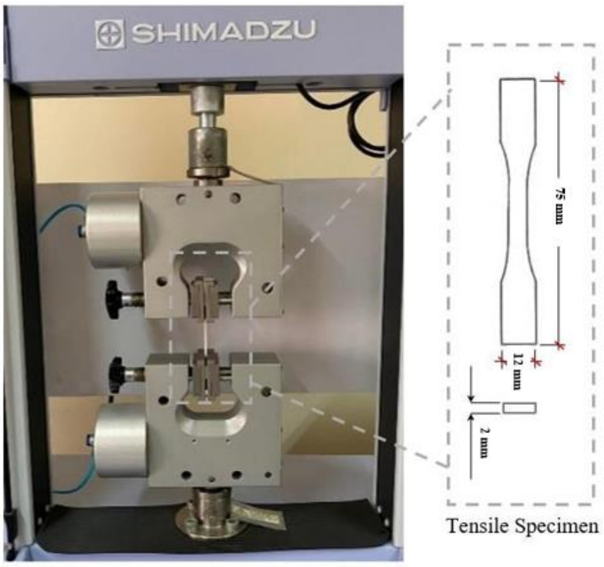

Figure 7: Tensile test set-up and test specimen configuration based from ASTM D638-14 Type IV

RESULTS AND DISCUSSION

Effectiveness of Acetone Vapor Polishing Device

Figure 8 shows the images of (a) Unpolished Cube Specimens and (b) Polished Cube Specimens. Using plain eyesight, the surface of the polished specimens shows some improvement, demonstrating that the developed device was able to polish the ABS 3D-printed specimens. The effectiveness of the said device was further evaluated using the following test procedures: (a) surface roughness, (b) dimensional accuracy, and (c) tensile test.

Figure 9 shows the digital images of the surfaces of cube specimen before and after vapor polishing. Results showed that there has been a significant difference on the surface roughness of the vapor-polished specimen compared to the unpolished specimen. The stepped layers due to 3D printing are noticeable in the digital images of unpolished specimen while the images from the polished specimen showed the layers were smoothened.

Also, Table 2 summarizes the results obtained from the Mountains9 Topography software, where a difference in the maximum peak height of 221.56 µm and maximum pit height of 234.42 µm were obtained between unpolished and polished specimens, respectively. This reveals a 75.20% decrease in unpolished specimens' maximum peak height after being subjected to the vapor polishing procedure. This is due to acetone reacting on the surface of ABS 3D-printed specimen during the polishing procedure, which causes the higher areas (peaks) to gradually subside and flow to the surface pit of the specimen resulting in the reduction of the height differences between the surface peaks and pits of the specimens of each case. Hence, it indicates that the vapor polishing procedure could significantly improve the surface roughness of the specimen.

In addition, results obtained from the dimensional accuracy test shows that the acetone vapor-polished ABS 3D-printed test cubes have negligible changes in dimension and volume reduction, with approximately ±0.2 mm and ~2.5%, respectively. This was done by determining the difference in dimensions and percentage in volume reduction of unpolished and polished test samples as shown in Table 3. The volume reduction in percent was calculated using Eq. 1, where the volume difference between unpolished and polished samples was divided by the volume of the unpolished sample. This demonstrates that the volume of acetone used in vapor polishing the specimen is sufficient to polish parts without significantly altering its dimension. The dimensional accuracy of acetone vapor-polished parts could depend on the volume of the acetone used, and the time it takes to polish the parts. Note that over-exposure to acetone vapor could melt the surface of the specimen and may affect the geometrical shape and dimension of the ABS 3D-printed specimen. Thus, proper control is necessary.

$$\text{Volume Reduction (\%)} = \frac{\text{Volume}_{\text{unpolished}} - \text{Volume}_{\text{polished}}}{\text{Volume}_{\text{unpolished}}} \quad (1)$$

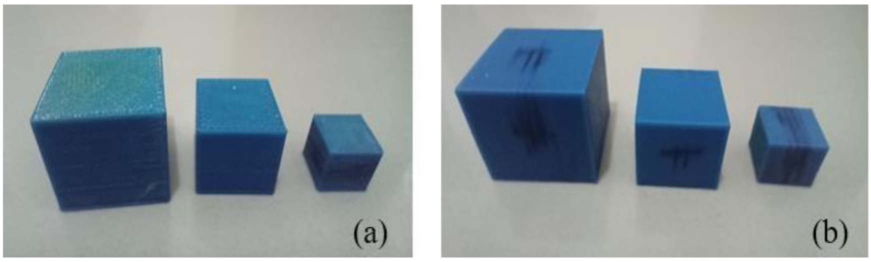

Figure 8: Images of (a) Unpolished Cube Specimens and (b) Polished Cube Specimens

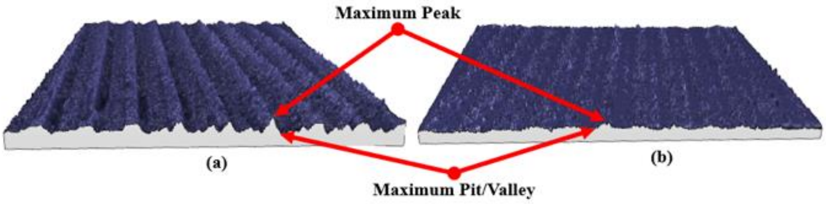

Figure 9: Microscopic images of (a) Unpolished and (b) Polished Cube Specimen

Table 2: Results obtained by Mountains9 Topography Software.

3D-Printed Cube Sample	Max. Peak Height, Sp	Max. Pit Height, Sv	Max. Height, Sp + Sv = Sz
Unpolished	289.1 µm	317.3 µm	606.4 µm
Polished	67.54 µm	82.88 µm	150.4 µm

Table 3: Summary of dimensional changes for the Unpolished and Polished cube specimen.

Cube Dimension (mm)	Top to Bottom		Front to Back		Left to Right		Volume Reduction (%)
	Unpolished	Polished	Unpolished	Polished	Unpolished	Polished	
10	10.06	10.06	10.1	10.02	10.15	10.12	1.0853
15	15.06	15	15.08	14.91	15.19	15.05	2.42887
20	20.05	20.02	20.02	20	20.18	20.14	0.4471

Table 4: Tensile Strength of Unpolished and Polished Specimens.

Test Samples	Tensile Specimen No.	Tensile Strength (MPa)	Average Tensile Strength (MPa)
Unpolished	1	41.141	40.722
	2	40.900	
	3	40.126	
Polished	1	41.520	44.482
	2	47.768	
	3	44.158	

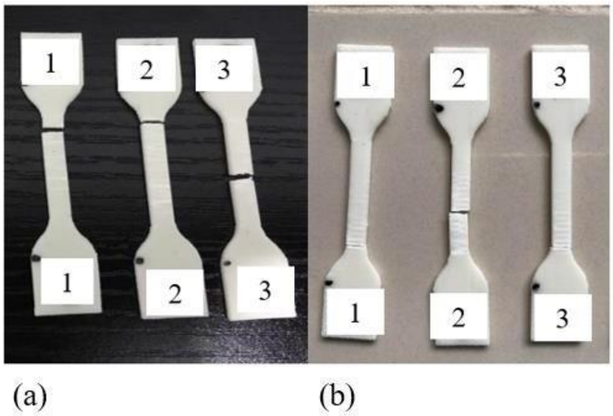

Figure 10: ABS 3D-printed Tensile Specimen: (a) Unpolished and (b) Polished

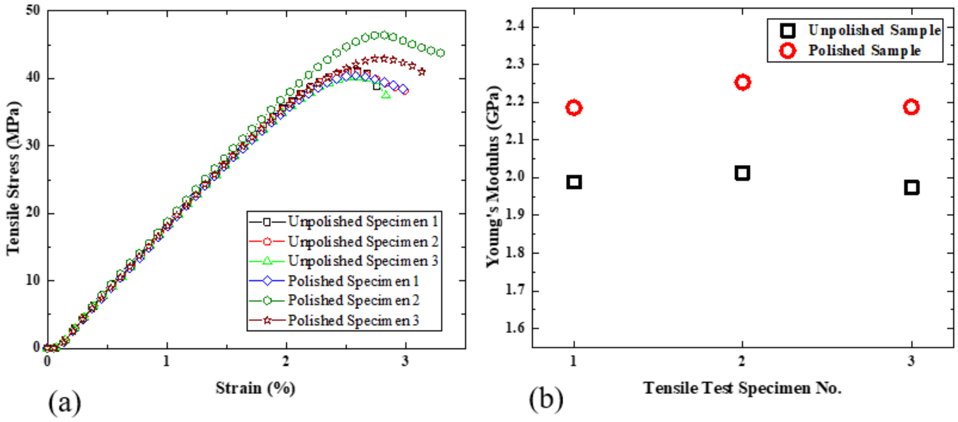

Figure 11: Summary of (a) Stress-Strain Curve and (b) Young's Modulus of Unpolished and Polished Test Specimens

Lastly, under tensile test, Table 4 shows the summary of the variation of tensile strengths of unpolished and polished specimens. Data comparison and analysis revealed that polished test samples have greater tensile strengths than unpolished test samples. This is due to the melting of the surface layers of the polished test samples during the acetone vapor polishing procedure, which made it more compact by filling the air gaps between the layers, thus resulting in a greater layer-by-layer adhesion (Gao et al., 2017). The surface has also been smoothened removing potential sources of cracks, i.e. the very deep pits at the interface of all the layers. Figure 10 shows the actual specimens after the tensile tests. And as shown in Figure 11, the tensile stress-strain curve and average Young's Modulus obtained from testing clearly indicate that polished specimens have higher strength, ductility, toughness and stiffness (modulus of elasticity) compared with unpolished specimens. Changes in tensile properties could be due to stronger adhesion between layers on the surface of the polished test samples during the acetone vapor polishing procedure.

Hence, the fabricated acetone vapor polishing device has been demonstrated to be an effective tool in improving the surface quality and strength of the 3D-printed ABS parts.

CONCLUSION AND RECOMMENDATIONS

A vapor polishing device to smoothen ABS 3D-printed specimens has been developed. The device uses a volume-based ratio of acetone in vapor polishing the specimens. Using 20 ml volume of acetone to vapor polish the 3D-printed specimens, it was observed that it enhances the surface roughness and tensile strength without significantly altering its dimension. Specifically, the surface roughness test shows a significant reduction of both the polished specimen's maximum peak and pit height, which reduces the surface roughness of the ABS 3D-printed specimen. Further, the dimensional accuracy assessment shows a difference of approximately ±0.2 mm and ~2.5% volume change in the polished cube specimens, which suggests that it improves the quality of the surface without completely altering the geometrical shape and dimension of 3D-printed specimen. Moreover, the tensile test shows a significant increase in the overall tensile strength and stiffness of the 3D-printed specimen, which is due to the melting of the surface as acetone flows in between the layer gaps on the surface of the polished specimen resulting in greater layer-by-layer adhesion. The developed device is effective in improving the surface quality and strength of the 3D-printed ABS parts. However, it is recommended to include a timer to monitor and control the process, and a vapor absorption mechanism attached to the glass chamber to prevent the acetone vapor from leaking.

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CONTRIBUTIONS OF INDIVIDUAL AUTHORS

All authors contributed to the design and fabrication of the device, the testing and analysis of the results, and the writing of the manuscript.

CONFLICT OF INTEREST

The author(s) declare(s) that there is no conflict of interest.

REFERENCES

Advincula RC, Dizon JRC, Chen Q, Niu I, Chung J, Kilpatrick L, Newman R. Additive manufacturing for COVID-19: devices, materials, prospects, and challenges. MRS Communications 2020; 10(3): 413–427.

Bryll K, Piesowicz E, Szymański P, Slaczka W, Pijanowski, M. Polymer composite manufacturing by FDM 3D printing technology. MATEC Web of Conferences 2007; 237:0–6.

Caldona EB, Dizon JRC, Espera AH, Advincula RC. On the economic, environmental, and sustainability aspects of 3D printing toward a cyclic economy. American Chemical Society 2022; 507–525.

Caldona EB, Dizon JRC, Viers RA, Garcia VJ, Smith ZJ, Advincula RC. Additively manufactured high-performance polymeric materials and their potential use in the oil and gas industry. MRS Communications 2021; 11: 701–715.

Chaudhari AA, Godase AM, Ravindra J, Abhijit N. Acetone vapor smoothing: A postprocessing method for 3D printed ABS parts. International Journal of Research and Scientific Innovation (IJRSI) 2017; IV(V): 123–127.

Crisostomo JLB, Dizon JRC. 3D printing applications in agriculture, food processing, and environmental protection and monitoring. Advance Sustainable Science, Engineering and Technology 2021; 3(2): 0210201.

Daminabo SC, Goel S, Grammatikos SA, Nezhad HY, Thakur VK. Fused deposition modeling-based additive manufacturing (3D printing): techniques for polymer material systems. Materials Today Chemistry 2020; 161:00248.

De Leon MB, Ante UB, Velasco MS, Ng AOS, Garcia JAV, Liza FP, Advincula RC, Dizon JRC. 3D-printing for cube satellites (CubeSats): Philippines ‘perspectives. Engineering Innovations 2022; 1: 13–27.

Delda RNM, Basuel RB, Hacla RP, Martinez DWC, Cabibihan JJ, Dizon JRC. 3D printing polymeric materials for robots with embedded systems. Technologies 2021; 9(4): 82.

Dizon JRC, Espera AH, Chen Q, Advincula RC. Mechanical characterization of 3D-printed polymers. Additive Manufacturing 2018; 20:44–67.

Dizon JRC, Gache CCL, Cascolan HMS, Cancino LT, Advincula RC. Post-processing of 3D-printed polymers. Technologies 2021; 9(3): 61.

Espera AH, Dizon JRC, Chen Q, Advincula RC. 3D-printing and advanced manufacturing for electronics. Progress in Additive Manufacturing 2019; 4(3): 245–267.

Espera AH, Dizon JRC, Valino AD, Advincula RC. Advancing flexible electronics and additive manufacturing. Japanese Journal of Applied Physics 2022; 61:SE0803.

Gao H, Kaweesa DV, Moore J, Meisel NA. Investigating the impact of acetone vapor smoothing on the strength and elongation of printed ABS parts. JOM 2017; 69(3): 580-58.

Lalehpour A, Barari A. Post-processing for fused deposition modeling parts with acetone vapour bath. IFAC-PapersOnLine 2016; 49(31): 42–48.

Martinez DW, Espino MT, Cascolan HM, Crisostomo JL, Dizon JRC. A comprehensive review on the application of 3D printing in the aerospace industry. Key Engineering Materials 2022; 913: 27-34.

Pereira T, Kennedy JV, Potgieter J. A comparison of traditional manufacturing vs additive manufacturing, the best method for the job. Procedia Manufacturing 2019; 30:11–18.

Rahim TNAT, Abdullah AM, Akil HMD. Recent developments in fused deposition modeling-based 3D printing of polymers and their composites. Polymer Reviews 2019; 59(4)5: 89–624.

Robles GS, Delda RNM, Del Rosario RLB, Espino MT, Dizon JRC. Dimensional accuracy of 3D - printed Acrylonitrile Butadiene Styrene: Effect of size, layer thickness, and infill density. Key Engineering Materials 2022a; 913:17–25.

Robles GS, Espino MT, Delda RNM, Dizon JRC. Significance of fundamental metrology of 3D-printed parts for engineering design: dimensional accuracy. Advance Sustainable Science Engineering and Technology 2022b; 4(2):0220212.

Rosen DW. Research supporting principles for design for additive manufacturing. Virtual and Physical Prototyping 2014; 9(4): 225–232.

Stach S., Sapota W., Wróbel Z., Ţălu Ş. Assessment of possibilities of ceramic biomaterial fracture surface reconstruction using laser confocal microscopy and long working distance objective lenses, Microsc. Res. Tech., 2016, 79 385-392.

Selvamani SK, Samykano M, Subramaniam SR, Ngui WK, Kadirgama K, Kanagaraj G, Idris MS. 3D printing: overview of ABS evolvement. AIP Conference Proceedings 2019; 2059(1): 10.1063-1.5085984.

Tuazon BJ, Custodio NAV, Basuel RB, Reyes LAD, Dizon JRC. 3D printing technology and materials for automotive application: A mini-review. Key Engineering Materials 2022; 913: 3-16.

Tuazon BJ, Espino MT, Dizon JRC. Investigation on the effects of acetone vapor-polishing on fracture behavior of ABS printed materials at different operating temperature. Materials Science Forum 2020; *1005*: 141–149.

Xu K, Xi T, Liu C. Design of the desktop vapor polisher with acetone vapor absorption mechanism. Journal of Physics: Conference Series 2019; 1303(1).