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Design Optimization of DR3AM Vapor Polishing Device for ABS 3D-Printed Parts

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Abstract. 3D printing is an additive manufacturing method that turns digital design into an actual product. A 3D-printed part sometimes requires post-processing to enhance its physical and mechanical properties. Acetone vapor polishing is one of those techniques which is highly beneficial in smoothing 3D-printed parts made of acrylonitrile butadiene styrene (ABS). Previously, an acetone vapor polishing device using a mist maker was developed at the Bataan Peninsula State University. However, for a more efficient polishing method, an optimized vapor polishing device using heat has been developed in this study. Using a heating device, which is an insulated nichrome coil, shows a more gradual and fine vaporization of acetone unlike the mist maker. To further assess the efficiency of the optimized device, the researchers tested the dimensional accuracy, surface roughness, tensile strength, and impact strength of polished and unpolished ABS 3D-printed specimens. The findings showed that the change in surface roughness of the polished cube specimens did not significantly alter their physical geometry. The tensile test reveals that the overall elasticity of the polished tensile specimens has increased noticeably. The impact test also shows that the polished specimen can absorb more impact from a swinging pendulum compared with unpolished specimen. Thus, all testing procedures indicated that post-processing using the optimized vapor polishing device improved the overall physical and mechanical properties of the polished ABS 3D-printed specimens.

Keywords: 3D printing, acrylonitrile butadiene styrene, dimensional accuracy, surface roughness, tensile properties, impact strength

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1. Introduction

3D printing is becoming known globally, and one of the types of this technology is the Fused Filament Fabrication (FFF). FFF is analogous in using a computer-controlled hot glue gun in its most basic form.

In contrast to traditional hot glue guns, 3D printers have a nozzle that is about 0.1 mm to 2.0 mm in diameter. Nowadays, FFF technology is one of the most popular 3D printing techniques [1]–[6]. However, post-processing is sometimes required for this type of technology to improve the layer adhesion strength and surface finish of 3D-printed parts [2].

One of the most commonly-used filaments for FFF 3D printers is the Acrylonitrile Butadiene Styrene (ABS). It is a thermoplastic polymer that has made a significant contribution in high-performance engineering applications [3]–[6]. However, poor layer bond strength and rough surface consistency are common characteristics of FFF 3D-printed ABS materials that sometimes require post-processing techniques [6]. Heat treatment and vapor-polishing are some examples designed to address these issues. Heat treatment is a post-processing procedure that enhances the mechanical properties of 3D-printed polymers and improves surface finish [7]. On the other hand, acetone vapor polishing is another way to smoothen the surface without altering the object's features and improve the mechanical properties of a 3D-printed ABS part through acetone vapor [2], [3], [8]. Furthermore, employing acetone vapor to ABS 3D-printed parts also ensures a high degree of process stability [9]. The application of heat treatment and acetone vapor polishing procedures are proven to be effective in improving both the mechanical and physical properties of 3D-printed materials [2], [3], [7].

Previously, an acetone vapor polishing device was developed by researchers of Bataan Peninsula State University (BPSU) which uses a mist maker [3]. However, for a more efficient vapor polishing method, an optimized vapor polishing device using heat has been fabricated in this study. This study was focused on developing an acetone vapor polishing device that utilizes the heat produced from an insulated nichrome coil. The insulated nichrome coil is a core heating element commonly used in various industrial and scientific applications. This type of metal is highly resistive, with a voltage current applied to the coil, which produces heat [10]. Additionally, this study used a new cover for the vapor polishing device using T6 6061 aluminum as it is one of the strongest alloys on the market. It is a highly corrosion-resistant and strong material used to make lightweight products and components, making it ideal for various structural components and industrial goods applications [11].

2. Methods

2.1. Design Optimization of DR3AM Vapor Polishing Device

2.1.1 Materials.

This optimized the existing vapor polishing device for ABS 3D-printed parts at BPSU's DR3AM Center. According to the recommendation from the paper of Gache et al. (2022), the device's design should be optimized. For instance, it was observed that the wooden cover of the device can expand and be affected by the chemical reagent acetone. Additionally, the mist maker of the vapor polishing device is of poor quality [3]. With this, the researchers considered various criteria in proposing a new method of optimizing the existing vapor polishing device. The availability of materials and components has a significant factor in improving the design and functionality of the device.

Before achieving the ideal function of the optimized device, the researchers conducted several testing and experiments to obtain the appropriate type of vaporizer (the part that creates vapor) to use for the acetone vaporization. Considering the advantages and disadvantages of different vaporizers, an insulated nichrome coil indicates its edge over other vaporizers as shown in Table 1.

Table 1. Advantages and Disadvantages of Different Vaporizers

	Vaporizers	Advantages	Disadvantages
Initial Design	Mist Maker	Easier to use. Focuses on a specific area, preventing acetone wastage.	Perfect for water-based but not effective for acetone solvent. It makes too much pressure which makes the acetone evaporation uncontrolled.

			Acetone mist directs at the top of the glass dome, making the polishing time longer
Improved Design	Peltier Module	Smaller in size. Gradual acetone evaporation.	One side of the Peltier module gets cold, which makes it incompatible with the device since its cold side might affect the electronic components inside the base. Dependent on the Arduino system to operate utterly.
Final Design	Insulated Nichrome Coil	Good conductor of heat. Gradual and fine acetone evaporation.	Electrical wires are sensitive.

The vapor polishing device was initially optimized and designed using computer-aided design software. The 3D-printed base made of PLA and glass cover of the device are similar from the existing device. The wooden cover of the existing device was replaced with aluminum to prevent deformation. The researchers used an insulated nichrome coil instead of a mist maker to make the acetone evaporation process more effective and for a longer lifespan of the device. In addition, the researchers decided to install a digital thermostat temperature alarm and time relay module for a better system function. This component aids in determining the average temperature of insulated nichrome coil to achieve smooth acetone evaporation, the standard amount of acetone, and the time required for vapor polishing of 3D-printed parts. The following figures show the comparison between the existing and optimized design of the vapor polishing device. Figure 1 shows the CAD model of the existing vapor polishing device using a mist maker. Figure 2 shows the CAD model of the optimized vapor polishing device using the insulated nichrome coil. To set up the insulated nichrome coil, the researchers made a customized aluminum cover using T6 6061, which has three layers to make it more durable. These are the measurements: 8.10 x 4.1 inches, 8.10 x 7.5 inches, and 7.45 x 4.25 inches, respectively. Since the base of the device contains circuits, the acetone was designed to have its own container so that it could be stored properly. This container was placed at the center of the device which is covered with a 5 x 5 inches receptacle as support, and placed under it is the insulated nichrome coil.

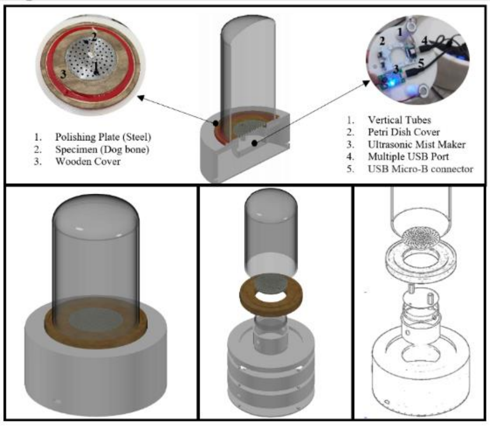


Figure 1. CAD Model of the Existing Vapor Polishing Device Using Mist Maker [3]

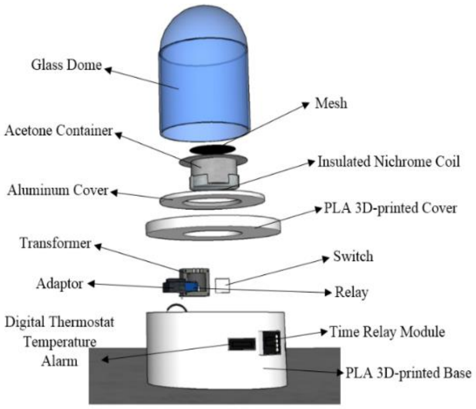


Figure 2. CAD Model of the Optimized Vapor Polishing Device Using Insulated Nichrome Coil

2.2. *Experimental Design and Procedures*

2.2.1. *Material*

Acrylonitrile Butadiene Styrene (ABS) material is known for its flexibility, durability, adaptability, and high heat tolerance; although it has interface lines between layers, there are ways how it can be polished. The commonly-used post-processing technique for ABS material is acetone vapor smoothing, as the acetone can polish or reduce the visible raster layer on the surfaces of the 3D-printed parts [3], [4], [6]. This study used Polymaker PolyLite ABS filament which has a much lower volatile component compared with standard ABS polymers. Thus, providing an outstanding print quality and excellent post-processing capabilities [12]. All test specimens in this study were 3D-printed using Zortrax M200 FFF 3D printer with a printing temperature of 275 °C.

2.2.2. *Dimensional Accuracy*

Five (5) cube specimens were 3D-printed with 90% infill density and 0.19 mm layer thickness with different dimensions starting from (10 mm)^3, (15 mm)^3, (20 mm)^3, (25 mm)^3, and up to (30 mm)^3. The dimensions of each specimen were measured and recorded using the Mitutoyo Digimatic Vernier Caliper, following the study of Robles et al. [13], [14]. Accordingly, the cubes were polished to the optimized vapor polishing device. Figure 3 shows the procedure for obtaining the measurements of dimensions of the unpolished and polished cube specimens.

2.2.3. *Surface Roughness.*

Mixing hot chemical vapors with heated air accelerates the vapor polishing technique and produces an excellent surface finish [15]. The changes in surface roughness after the polishing process was measured using the cube specimens. The specimen's surface was captured and analyzed with an AMScope MU503 T-720-Q and Mountains Topography software. The researchers measured the 3D-printed sample before being subjected to the optimized vapor polishing device with an acetone of 20 mL for 30 minutes and a curing time of another one hour. Figure 4 shows the use of AMScope trinocular microscope to capture a digital image of the surface of a 3D-printed specimen.

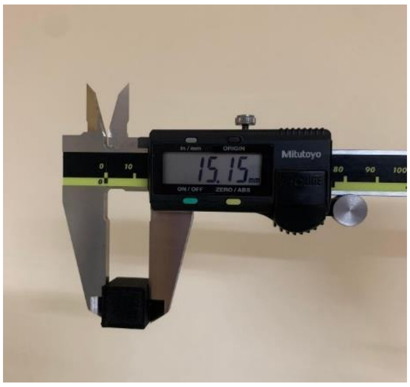


Figure 3. Cube Specimen Measurement

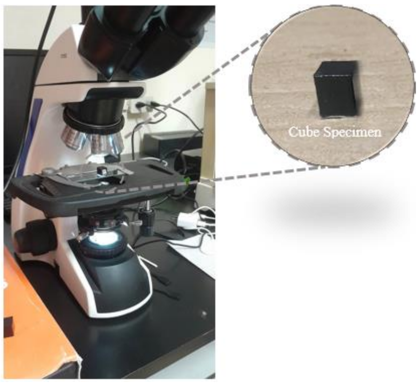


Figure 4. Actual Setup to capture the Digital Topography of 10mm cube

2.2.4. *Tensile Test*

In determining the effect of the vapor polishing device on the tensile properties of the ABS 3D-printed parts, the study tested two (2) sets of samples: unpolished and acetone vapor polished. Five (5) specimens were printed and manufactured for each sample in accordance with ASTM D638 Type IV [16]. Each tensile test specimen was 3D-printed with a honeycomb infill pattern, 90% infill density, 0° raster angle, and edgewise orientation. Acetone vapor polished specimens were subjected to the optimized vapor polishing device using 40 mL of acetone. The acetone vapor polishing process was estimated to be 30 minutes followed by a curing time of 30 minutes. Tensile test was conducted using the Shimadzu AGS-X Series Universal Testing Machine (UTM) with 10kN capacity. Figure 5 displays the tensile test setup and the specimen’s dimension.

2.2.5. Impact Test

The researchers used ASTM D256 test method E to obtain the difference in impact resistance of unpolished and acetone vapor-polished 3D-printed specimens, using a pendulum-dial Izod testing machine. This ASTM standard test method is a single-point assessment of the resistance of material from breaking using a swinging pendulum [17]. For preciseness, the equipment was thoroughly tested and calibrated in line with ASTM D256 before conducting the experiment. The Izod Type E test specimens have a layer thickness of 190 microns and an infill density of 70%. Figure 6 depicts the actual impact test set-up. Table 2 summarizes the amount of acetone used, vapor polishing time, and curing time of the specimen from the dimensional accuracy, surface roughness, tensile strength, and impact test. As observed by the researchers, these are the data needed to smoothen each ABS 3D-printed parts.

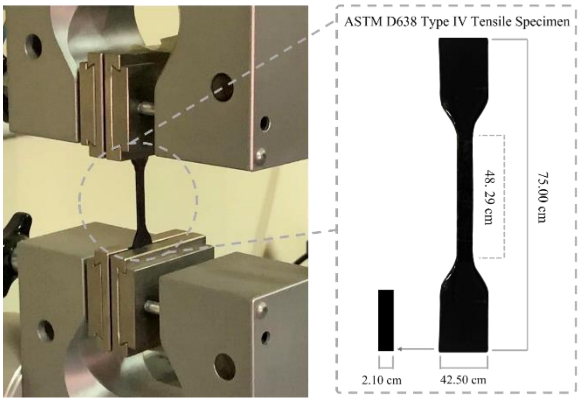


Figure 5. Tensile Test Set-up and Tensile Specimen's Dimension

Figure 6. Actual Impact Test Set-up

Table 2. Summary of Amount of Acetone Used, Vapor Polishing Time, and Curing Time

Type of Test	Specimen	Amount of Acetone Used (mL)	Vapor polishing time (sec)	Curing time (hour)
Dimensional Accuracy and Surface Roughness Test	10mm cube	20	14.28	1
	15mm cube	20	14.28	1
	20mm cube	30	24.95	1
	25mm cube	40	30.15	1
	30mm cube	40	30.15	1
Impact Test	ASTM Izod Type E	30	24.95	1
Tensile Test	ASTM Tensile Type IV	40	30.15	1

3. Results and Discussion

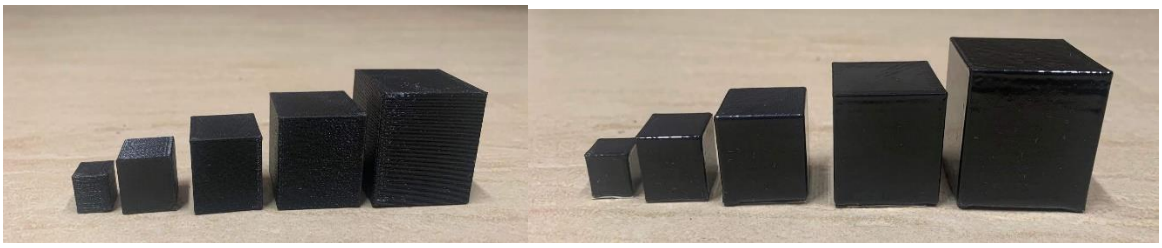
3.1. Effectiveness of the Optimized DR3AM Vapor Polishing Device

The optimized vapor polishing device has proven its effectiveness based on various testing procedures done. As mentioned in the previous section, the effectiveness of the optimized vapor polishing device was assessed by having a comparative test between the dimensional accuracy, surface roughness, tensile strength, and impact resistance of unpolished and polished specimens. The vaporization mechanism of the optimized vapor polishing device clearly shows the possibility of effectiveness using other heating methods which was crucial to the improvement of the vapor polishing device. Figure 7 shows the final CAD design and actual photo of the device used for vapor polishing. Since the focus of this study was to develop an acetone vapor polishing device which optimizes the vapor polishing device previously done by Gache et al., its effectiveness was measured by comparing the test results of both studies. However, this study used ABS PolyLite filament from the Polymaker brand. This material is different in terms of melting point and composition (blend), to the material used by Gache et al., the Z-Ultrat ABS filament from Zortrax brand. Hence, the result and mechanical response to various tests of these materials were expected to be different. This difference in result was initially observed through visual inspection. ABS PolyLite already has a smoother surface after 3D printing compared to ABS Z-Ultrat even though both filaments underwent the same printing parameter. This is because ABS PolyLite specimen was printed at temperature 10 °C higher than its maximum melting temperature. Unlike the ABS Z-Ultrat which was printed within its required melting temperature range.

Figure 7. Final CAD Design (a) and (b) Actual Photo of Optimized Vapor Polishing Device

3.1.1. Dimensional Accuracy

Various cube sizes were used to examine the dimensional accuracy of the 3D-printed cube specimen after being subjected to vapor polishing. Figure 8 shows the unpolished and polished ABS 3D-printed cube specimen using the optimized acetone vapor polishing device. Results showed an insignificant change in the dimension of cube specimens in any directions, such as top to bottom, front to back, and left to right, before and after acetone vapor polishing. Table 3 shows the summary of dimensional changes in unpolished and polished specimens. It shows that each of the specimen's dimensions has retained or decreased by about ±1 mm. Equation 1 shows the formula used in determining the volume reduction in the dimensional accuracy test.



(a) (b)

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

$$Volume\ Reduction\ (\%) = \frac{Volume_{unpolished} - Volume_{polished}}{Volume_{unpolished}} \times 100\% \tag{1}$$

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

Cube Size (mm)^3	Top to Bottom (mm)		Front to Back (mm)		Left to Right (mm)		Volume Reduction (%)
	Unpolished	Polished	Unpolished	Polished	Unpolished	Polished	
10	10.25	10.20	10.13	10.10	10.12	10.07	**1.29**
15	15.15	15.15	15.05	15.03	15.07	15.05	**0.26**
20	20.21	20.18	20.07	20.05	20.15	20.08	**0.60**
25	25.15	25.02	25.12	25.06	25.14	25.07	**1.03**
30	30.10	30.10	30.20	30.16	30.10	30.05	**0.30**

3.1.2. Surface Roughness

For the surface roughness assessment, the researchers captured a digital image of the topography of unpolished and polished 3D-printed cube using the AMscope trinocular microscope and analyzed them using Mountains9 software to measure their surface roughness. The results show a significant difference in the surface roughness of the unpolished and polished 3D-printed sample. Figure 9 shows the image of an unpolished 3D-printed sample compared to a polished one after the vapor polishing procedure using the optimized vapor polishing device. Tabulated results of Maximum Peak Height (Sp), Maximum Pit Height (Sv), and Maximum Height (Sz) gathered from the roughness analysis of unpolished and polished specimens using the Mountains9 Software was shown in Table 4. It can be observed that based on the roughness analysis, a difference of 2.416 µm in maximum peak height and 2.68 µm for maximum pit height were obtained between unpolished and polished specimens. This data implies that the optimized vapor polishing device reduces the maximum peak height with 65.87%, maximum pit height with 65.24%, and maximum height with 65.52% of the surface of 3D-printed specimens. As reported by Gache et. al, this reduction is due to the flowing of melted surface peaks of ABS 3D-printed specimen to the surface pit during the acetone polishing procedure, resulting in the reduction of the specimen surface's maximum height, Sz [3]. Therefore, improvements in the surface roughness of the specimen prove the effectiveness of the optimized vapor polishing procedure.


(a) (b)

Figure 9. Digital Image of (a) Unpolished and (b) Polished Surface of 10 mm Cube Specimen

Table 4. Results obtained by Mountains9 Topography Software

Sample	Maximum Peak Height, Sp	Maximum Pit Height, Sv	Maximum Height, Sp + Sv = Sz
Unpolished	3.668 µm	4.108 µm	7.775 µm
Polished	1.252 µm	1.428 µm	2.681 µm

3.1.3. Tensile Test

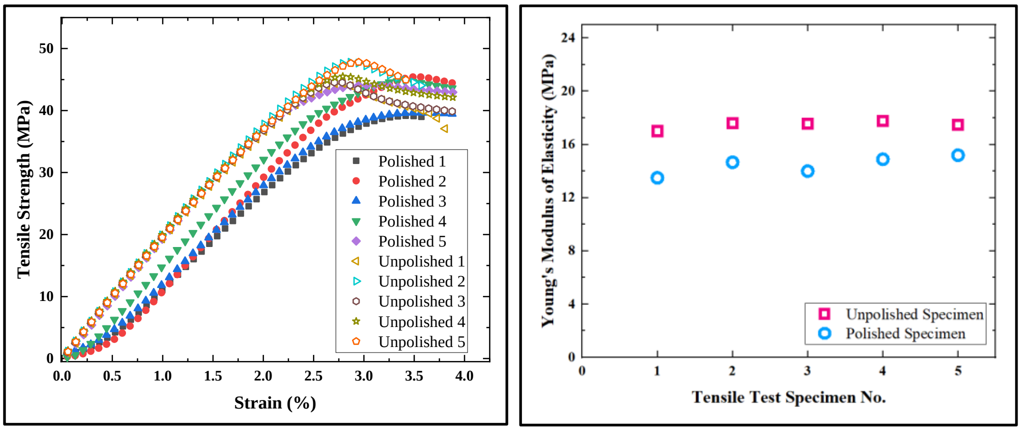
The obtained results in tensile strength and Young's Modulus for unpolished and polished specimens are shown in Table 5. The Young's modulus (E) of a material determines how it responds to external stress in terms of reversible elastic deformation and irreversible plastic deformation. Tensile strength was proportional to E, but the relationship varied with material [18].

Table 5. Tensile Strength and Young's Modulus of Unpolished and Polished Specimens

Test Samples	Tensile Specimen No.	Tensile Strength (MPa)	Average Tensile Strength (MPa)	Young's Modulus (MPa)	Average Young's Modulus (MPa)
Unpolished	1	44.520	**46.354**	17.002	**17.486**
	2	45.219		17.612	
	3	45.722		17.570	
	4	48.153		17.758	
	5	48.155		17.486	
Polished	1	36.908	**40.713**	13.496	**14.446**
	2	37.307		14.659	
	3	41.616		13.996	
	4	43.138		14.888	
	5	44.596		15.191	

After polishing the tensile specimen, it was subjected to tension using the UTM to investigate the effects of vapor polishing on the tensile strength and elasticity of the polished specimens compared to the unpolished specimens. Figure 10 and 11 show the test specimens after testing and the summary of stress-strain curves and Young's Moduli of unpolished and polished specimens, respectively. Based on the tensile test results of both the unpolished and polished specimens, polishing using the optimized vapor polishing device affected the Young’s modulus and tensile strength of the ABS 3D-printed specimens. It was observed that the stress-strain curve of polished specimen has a smoother curve compared to unpolished specimen. Specifically, the unpolished specimens showed a peak value between 2.5%-3.0% strain. This can be related to the observed higher Young’s modulus (stiffness) of unpolished specimen compared to polished specimen. And as a result of the change in Young’s modulus, the polished specimen became less resistant to elastic deformation compared to unpolished specimen. In addition, the polished specimen yielded a lower tensile strength compared to unpolished specimen. However, this was not the case observed in the obtained data by Gache et al, wherein the Young’s modulus and tensile strength of the vapor polished specimen both improved [3]. It could be due to the melting temperature of materials used, as mentioned in the previous section. Since PolyLite was printed with temperature higher than its melting point, it produced a smoother surface than Z-Ultrat even before it was vapor polished. Therefore, once vapor polished, it produced a smoother surface which means that each raster layer was bonded better to its adjacent layer. This resulted in a lower Young’s modulus and lower tensile strength, compared to Z-Ultrat when vapor polished. In addition, this could also be related to the difference in polymer blend of PolyLite and Z-Ultrat, which may be the reason for its higher susceptibility to melting during vapor polishing.

Figure 10. (a) Unpolished and (b) Polished Type IV Tensile Specimen



(a) (b)

Figure 11. Summary of (a) Stress–Strain Curve and (b) Young's Moduli of Unpolished and Polished Type IV Test Specimens

3.1.4. Impact Test

Using the Izod impact test, the researchers were able to investigate the fracture behavior of unpolished and polished 3D-printed specimen using the optimized vapor polishing device. Using Equation 2 and 3, the researchers calculated the impact resistance and impact energy that can be absorbed by the specimen from a swinging pendulum before fracture. Table 6 and Figure 12 show the tabulated and graphical representation of the calculated impact resistance and impact energy, comparing the result of polished and unpolished specimens. Generally, vapor polished specimen obtained a higher impact resistance and higher impact energy compared to those unpolished specimens. This improvement can also be related to the bonding of raster layers caused by melting of ABS plastic during acetone vapor polishing. However, some data obtained from unpolished and polished specimen were almost equal, this can be due to the defect, such as void or crack, produced during its printing which is common printing problem in FFF 3D printers. The effect of such defect cannot be out done by the effectiveness of bonding of raster layers alone during the vapor polishing process.

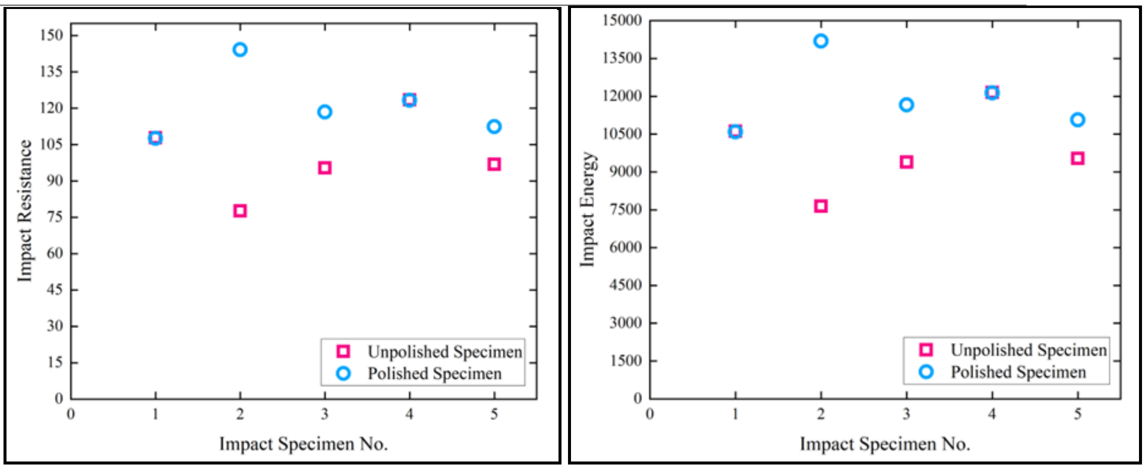
Impact Resistance, $$I_R = \frac{E_S}{\mathrm{w}} \tag{2}$$

Impact Energy, $$I_R = \frac{E_S}{\mathrm{dw}} \tag{3}$$

Table 6. Summary of Mean Experimental Results of Impact Test

Post-processing	**Impact Resistance (J/m)**	**Impact Energy ($\mathbf{J/m^2}$)**

Unpolished	107.81	10611.47
	77.61	7638.97
	95.38	9388.25
	123.44	12149.36
	96.88	9534.94
Polished	107.58	10588.17
	144.16	14188.76
	118.44	11657.56
	123.29	12134.61
	112.46	11069.10



(a) (b)

Figure 12. Summary of (a) Impact Resistance and (b) Impact Energy of Unpolished and Polished Izod Type E Specimen

4. Conclusion and Recommendation

The existing acetone vapor polishing device was optimized by incorporating an insulated nichrome coil and using a volume-based ratio to polish the different ABS 3D-printed parts. Compared to the mist-maker used in previous iterations of the device, which have more pressure in releasing the acetone vapor, the nichrome coil has they could gradually evaporate the acetone which is advantageous in terms of vapor polishing. The efficiency of the optimized DR3AM vapor polishing device was assessed using dimensional accuracy, surface roughness, tensile strength, and impact strength of polished and unpolished ABS 3D-printed specimens. The optimized DR3AM vapor polishing device significantly smoothens the surface of 3D-printed parts without completely altering the dimensional accuracy. The tensile test reveals that the overall elasticity of the polished tensile specimen has increased significantly while the impact test also shows that the polished specimens can absorb more impact from a swinging pendulum compared with unpolished specimen.

ABS 3D-printed parts might have different results depending on the amount of acetone used, the time allotted to polish each 3D-printed part, and the brand of filament used (filament brands sometimes differ in polymer blend and melting temperature). It was also observed that some parts of the polished specimen are not evenly smoothened. Thus, the researchers recommend the following:

- identify the right amount of acetone and set a standard vapor polishing time in order to determine if the polishing of the surface of a 3D-printed specimen is already enough;
- investigate the optimal curing time for the acetone vapor polished to be absorbed by the 3D-printed part.
- utilize advanced mechanisms like Arduino, to monitor the temperature of the nichrome coil after it attains the set temperature and time.

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