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The Effect of Acetone Vapor Smoothing Duration and Printing Orientation on The Mechanical Properties and Surface Characteristics of ABS Specimens from Fused Deposition Modeling 3D Printing

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Abstract

Fused Deposition Modeling (FDM) 3D printing technology is one of the additive manufacturing methods widely used due to its relatively low production costs, ease of processing, and compatibility with various thermoplastic materials such as Acrylonitrile Butadiene Styrene (ABS). However, FDM products generally exhibit high surface roughness due to layer formation during printing and display mechanical properties influenced by printing orientation. Acetone vapor smoothing (AVS) is commonly applied to improve the surface quality of ABS components, although excessive exposure may affect mechanical performance. This study aims to analyze the effect of acetone vapor smoothing duration and printing orientation on the mechanical properties and surface characteristics of ABS specimens produced using FDM. Specimens were printed with vertical and horizontal orientations and treated with acetone vapor smoothing for 0, 20, 40, and 60 minutes. Tensile testing was conducted according to ASTM D638 Type IV, while surface characteristics were evaluated based on layer line visibility and edge rounding. The results indicate that printing orientation has a significant influence on tensile performance, with horizontal specimens consistently exhibiting higher strength than vertical specimens due to better load distribution along the extrusion direction. A 20-minute acetone vapor smoothing treatment provided the most balanced condition by improving surface quality while maintaining mechanical properties. Longer exposure durations further reduced layer line visibility but caused greater edge rounding and a decline in tensile performance. These findings demonstrate that controlling both printing orientation and post-processing duration is essential to achieve a balance between surface quality and mechanical reliability of FDM-printed ABS components.

Keywords: Fused Deposition Modeling, ABS, acetone vapor smoothing, printing orientation, tensile strength, surface quality.

1. Introduction

The development of additive manufacturing (AM) technology has driven the utilization of three-dimensional printing processes across various fields, ranging from rapid prototyping to the production of functional components [1]. Compared with conventional manufacturing methods, AM enables the fabrication of complex geometries, reduces material waste, and accelerates product development [2], [3]. Among various AM technologies, Fused Deposition Modeling (FDM) is widely used due to its low investment cost, simple operation, and compatibility with thermoplastic materials. The establishment of ISO/ASTM 52900 further supports AM implementation by providing standardized terminology and fundamental principles for additive manufacturing processes [4], [5].

Acrylonitrile butadiene styrene (ABS) is one of the most commonly used FDM materials for engineering applications due to its good mechanical properties, impact resistance, dimensional stability, and higher thermal resistance compared with PLA [6]. Additionally, ABS can be chemically softened using acetone, enabling surface finishing processes such as acetone vapor smoothing (AVS), which are difficult to apply to other FDM materials [7].

However, FDM-printed components generally exhibit rough surfaces due to layer formation during material deposition. These layer lines can reduce surface quality, dimensional accuracy, and product performance. Surface characteristics are influenced by several printing parameters, including layer height, nozzle diameter, printing speed, and printing orientation [8].

Printing orientation also significantly affects the mechanical properties of FDM components. Horizontal printing generally provides higher tensile strength because the applied load is aligned with the extrusion path, whereas vertical printing depends on weaker interlayer adhesion [9]. This behavior causes FDM materials to exhibit anisotropic mechanical properties, where performance varies according to build orientation [10]. Recent result also identified printing orientation as one of the dominant parameters affecting tensile strength.

Acetone Vapor Smoothing (AVS) has been widely applied to improve ABS surface quality by reducing visible layer lines [11]. During acetone vapor exposure, acetone molecules diffuse into the ABS surface and increase polymer chain mobility, causing partial surface dissolution and polymer redistribution [1]. This process allows adjacent layers to merge and produces a smoother surface. However, excessive exposure may cause deeper polymer dissolution, dimensional changes, edge rounding, and potential reduction of mechanical performance due to changes in interlayer bonding and structural integrity.

Although previous studies have investigated the effects of FDM parameters on mechanical properties and surface quality, studies combining the influence of printing orientation and AVS duration on ABS performance remain limited [12]. It was hypothesized that increasing acetone vapor smoothing duration would improve surface quality, while excessive exposure could negatively affect mechanical properties due to excessive polymer softening and dimensional changes.

Therefore, this study aims to analyze the effect of printing orientation and acetone vapor smoothing duration on the mechanical properties of ABS specimens fabricated using FDM technology. Surface characteristics of vertically oriented specimens were evaluated through layer line observation and edge rounding measurement, while tensile testing was conducted according to ASTM D638 Type IV [13]. The results are expected to provide a reference for determining an optimal combination of printing orientation and AVS duration to achieve a balance between mechanical performance and surface quality.

2. Methods

2.1 Type of Research

This study is a quantitative experimental research aimed at analyzing the effect of variations in acetone vapor smoothing time on the mechanical properties and surface quality of ABS specimens printed using Fused Deposition Modeling (FDM) technology. The independent variable in this study is the acetone vapor smoothing time, namely 0 minutes (control), 20 minutes, 40 minutes, and 60 minutes. The dependent variables include mechanical characteristics such as Maximum Load, Ultimate Tensile Strength (UTS), Breaking Load, Tensile Strength at Break (Rt), and Elongation at Break, as well as visual surface characteristics namely layer line visibility and edge rounding.

2.2 Materials and Equipment

The ABS filament used in this study was a commercial-grade ABS filament with a diameter of 1.75 mm. Since the mechanical characteristics of ABS filament can vary depending on polymer composition and manufacturing process, the filament source and handling conditions were controlled throughout the experiment. Before printing, the filament was stored in a sealed container at room temperature to reduce potential moisture absorption that could influence extrusion stability and specimen performance. The printing parameters are shown in **Table 1**. All specimens were printed according to the ASTM D638 Type IV standard for tensile testing of plastic materials.

Table 1. Specimen Printing Parameters

Parameter	Specification/Amount
Material	ABS
Diameter nozzle	0,4 mm
Layer height	0,20 mm
Nozzle temperature	250°C
Bed temperature	100°C
Print speed	50 mm/s
Infill density	100%
Infill pattern	Grid
Cooling fan	0%
Build orientation	Vertical dan Horizontal

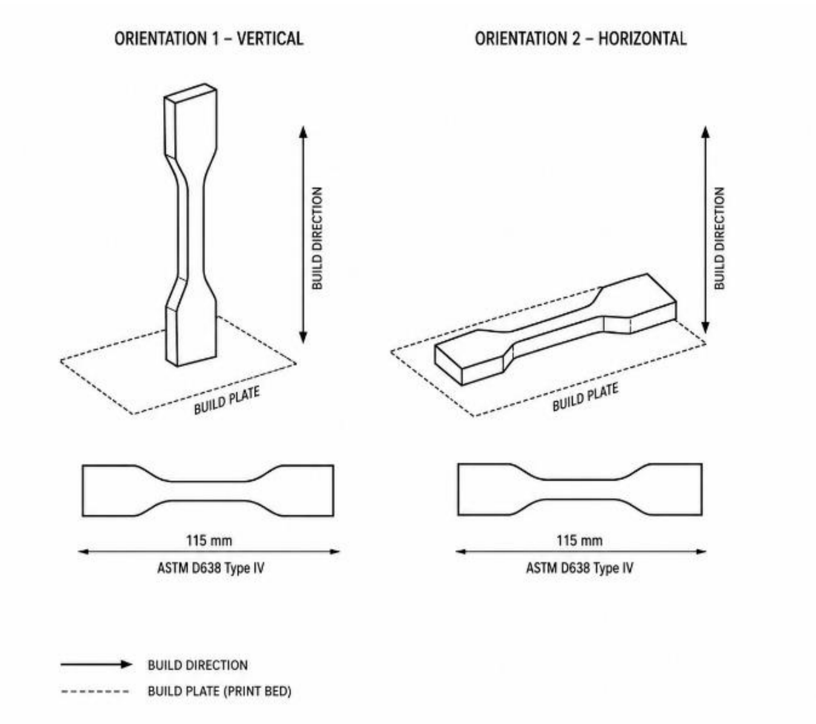

Figure 1. Illustration of Sample Printing Orientation

2.3 Specimen Preparation

The specimen model was created using CAD software based on ASTM D638 Type IV standard dimensions, then exported in STL format and processed using slicer software. After the slicing process was complete, specimens were printed using an FDM printer with the predetermined parameters. After the slicing process was complete, specimens were printed using an FDM printer with the predetermined parameters. A total of eight specimens were fabricated, consisting of four vertical-oriented specimens and four horizontal-oriented specimens. Each printing orientation was prepared with four acetone vapor smoothing conditions, namely 0, 20, 40, and 60 minutes, with one specimen assigned to each treatment condition. Tensile testing was performed individually for each specimen, and the results were analyzed descriptively by comparing the effect of printing orientation and acetone vapor smoothing duration.

2.4 Acetone Vapor Smoothing Process

The finishing process was carried out using the acetone vapor smoothing method. Approximately 50–100 mL of technical-grade acetone was poured onto a tissue placed at the bottom of a stainless steel container. A support was placed in the center of the container so that the specimen did not come into direct contact with the acetone liquid. The container was then covered with a glass dome to maintain vapor concentration during the process.

Figure 2. Acetone Vapor Smoothing Process

Heating was performed using an electric stove set to level 2 until stable acetone vapor formed. Once the vapor condition was achieved, specimens were exposed for the predetermined time variations 20 minutes, 40 minutes, and 60 minutes while the control group received no vapor smoothing treatment. After the process was complete, specimens were cooled at room temperature until all residual solvent evaporated before tensile testing or visual observation was conducted.

2.5 Tensile Testing

Tensile testing was carried out using a Universal Testing Machine (UTM) according to the ASTM D638 Type IV standard. The test aims to obtain the mechanical characteristics of ABS specimens after acetone vapor smoothing treatment.

Parameters obtained from the test include:

- Maximum Load (Fmax)

- Ultimate Tensile Strength (UTS)
- Breaking Load (Fbreak)
- Tensile Strength at Break (Rt)
- Elongation at Break

Figure 3. Universal Testing Machine

The Ultimate Tensile Strength (UTS) value is calculated using Equation (1).

$$UTS = \frac{F_{max}}{A_0} \tag{1}$$

where:

Fmax = maximum load (N)

A_0 = initial cross-sectional area of the specimen (mm^2)

The Tensile Strength at Break (Rt) value is calculated using Equation (2).

$$R_t = \frac{F_{break}}{A_0} \tag{2}$$

where:

Fbreak = load at specimen fracture (N)

A_0 = initial cross-sectional area of the specimen (mm^2)

The Elongation at Break value is calculated using Equation (3).

$$\varepsilon = \frac{L_u - L_0}{L_0} \times 100\% \tag{3}$$

where:

L_0 = initial gauge length of the specimen (mm)

Lu = gauge length of the specimen after fracture (mm)

2.6 Surface Characteristic Evaluation

Surface characteristic evaluation was performed using a digital microscope to observe morphological changes in the specimen surface before and after the acetone vapor smoothing process. Images were captured with constant magnification, specimen position, and lighting conditions so that the observation results could be compared consistently across each treatment time variation:

The surface characteristics evaluated include:

1. Layer line visibility: the degree of visibility of layer lines from the FDM printing process on the specimen surface. Evaluation was performed descriptively based on digital microscope images by comparing changes in layer line visibility for each variation of acetone vapor smoothing time.
2. Edge rounding: the change in specimen edge geometry due to surface layer melting during the acetone vapor smoothing process. The degree of edge rounding was analyzed quantitatively based on the edge radius value using image analysis methods on digital microscope images. The radius value was obtained by fitting the specimen edge contour to a circular arc, so a larger radius value indicates a higher degree of edge rounding.

The results of the surface characteristic evaluation were then compared across each variation of acetone vapor smoothing time to analyze the effect of the treatment on morphological changes in the surface of FDM-printed ABS specimens.

2.7 Data Analysis

Tensile test data were analyzed descriptively by comparing the values of Maximum Load, Ultimate Tensile Strength (UTS), Breaking Load, Tensile Strength at Break (Rt), and Elongation at Break for each variation of acetone vapor smoothing time and specimen printing orientation.

Surface characteristic evaluation data were analyzed based on digital microscope images. Analysis was performed descriptively for changes in layer line visibility, while the degree of edge rounding was analyzed quantitatively using edge radius values obtained through the image analysis method.

Subsequently, the results of mechanical and surface characteristic analyses were compared to evaluate the effect of acetone vapor smoothing time variations on the surface quality and mechanical performance of FDM-printed ABS specimens.

3.Results and Discussion

3.1 Tensile Test Results

Tensile testing was performed on ABS specimens printed using FDM technology and subjected to acetone vapor smoothing treatment with time variations of 0, 20, 40, and 60 minutes. Testing used the ASTM D638 Type IV standard to obtain values for Ultimate Tensile Strength (UTS), elongation at break, and Young's modulus. All values used in this study are actual test results. **Table 2** shows a summary of tensile test results for each vapor smoothing time variation.

Table 2. Tensile Test Results of ABS Specimens

Sample		Fmax (kN)	UTS (MPa)	Fbreak (kN)	Rt (MPa)	Elongation (%)
0 Minute (Control)	Vertical	0,542	26,13	0,542	26,13	6,82
	Horizontal	0,817	39,39	0,800	38,57	8,45
20 Minutes	Vertical	0,560	27,00	0,560	27,00	6,82
	Horizontal	0,813	39,20	0,710	34,23	9,36
40 Minutes	Vertical	0,544	26,23	0,544	26,23	6,70
	Horizontal	0,781	37,66	0,682	32,88	9,85
60 Minutes	Vertical	0,523	25,22	0,523	25,22	6,73
	Horizontal	0,782	37,70	0,729	35,15	8,82

In general, specimens with horizontal orientation show higher tensile strength compared to vertical orientation across all time variations. This difference is due to the loading direction being parallel to the extrusion path (raster), so the load is absorbed more by continuous filaments rather than interlayer bonds. Conversely, in vertical orientation, loading acts perpendicular to the layers, making material failure more likely to occur through interlayer delamination. This phenomenon has been widely reported in studies on the mechanical characteristics of FDM-printed products [14], [15].

Among the investigated parameters, printing orientation showed a stronger influence on tensile strength compared with acetone vapor smoothing duration. The difference between horizontal and vertical orientations remained consistent across all treatment conditions, with horizontal specimens showing substantially higher tensile strength values due to the load being transferred along the filament deposition direction. In contrast, the effect of acetone vapor smoothing duration resulted only in relatively small changes in tensile strength values. Short-duration exposure up to 20 minutes maintained or slightly improved the tensile properties, while longer exposure caused gradual strength reduction due to excessive solvent interaction with the ABS surface layer. These results indicate that the mechanical anisotropy caused by the FDM printing orientation is the dominant factor determining tensile performance, whereas acetone vapor smoothing mainly affects surface-related characteristics and provides secondary modification to mechanical behavior.

In addition to the effect of printing orientation, variations in acetone vapor smoothing time also showed an effect on tensile strength values. In both orientations, treatment for 20 minutes produced a small increase in UTS values compared to untreated specimens. However, increasing the exposure time to 40 and 60 minutes caused a decrease in tensile strength, especially in the vertical orientation.

3.2 Effect of Acetone Vapor Smoothing Duration on Mechanical Properties

The following figures show the relationship between acetone vapor smoothing (AVS) duration and the Ultimate Tensile Strength (UTS) values of ABS specimens with vertical and horizontal printing orientations.

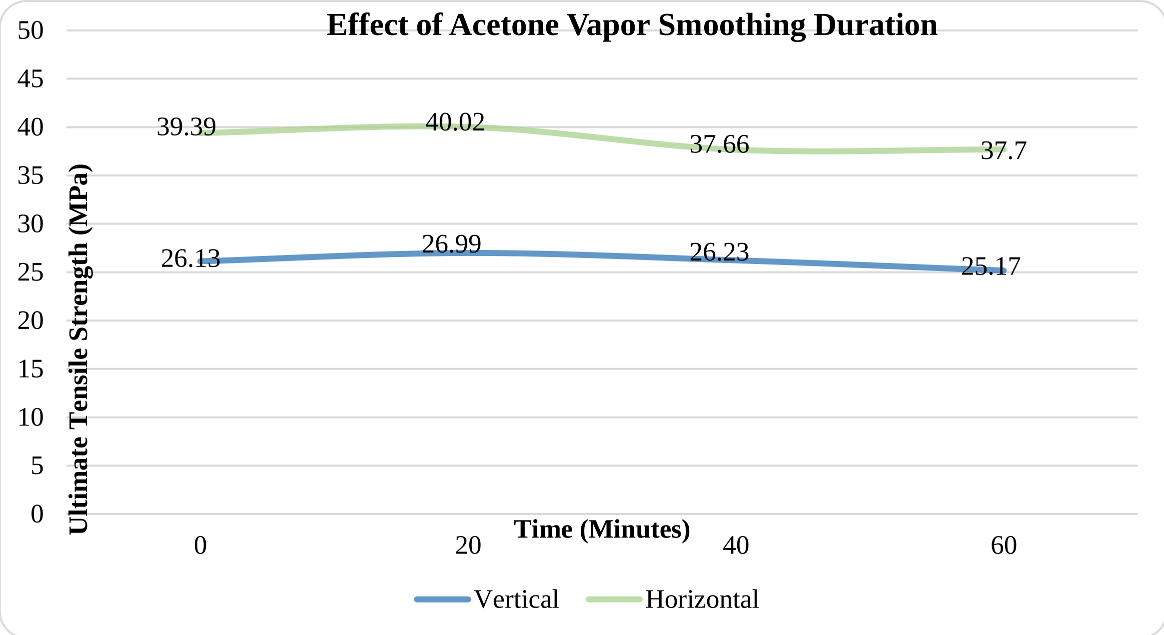

Figure 4. Graph of UTS vs. AVS Duration

In the vertical orientation, the UTS value increased from 26.13 MPa in the untreated condition to 27.00 MPa after acetone vapor smoothing treatment for 20 minutes. This increase indicates that short-duration acetone vapor exposure can improve specimen surface conditions without causing a reduction in mechanical strength. However, when the treatment duration was increased to 40 minutes and 60 minutes, the UTS value decreased to 26.23 MPa and 25.22 MPa. This decrease indicates that excessively long acetone exposure can reduce the specimen's ability to withstand tensile loads [1], [16].

A similar trend also occurred in the horizontal orientation. The UTS value of 39.39 MPa in untreated specimens slightly decreased to 39.20 MPa after 20-minute treatment, then further decreased to 37.66 MPa and 37.70 MPa for 40 and 60-minute treatments. Nevertheless, specimens with horizontal orientation still showed higher UTS values compared to vertical orientation across all treatment variations. This is due to the horizontal printing orientation producing a loading direction more parallel to the filament deposition direction, so interlayer bonding does not become the main weak point during tensile testing [17].

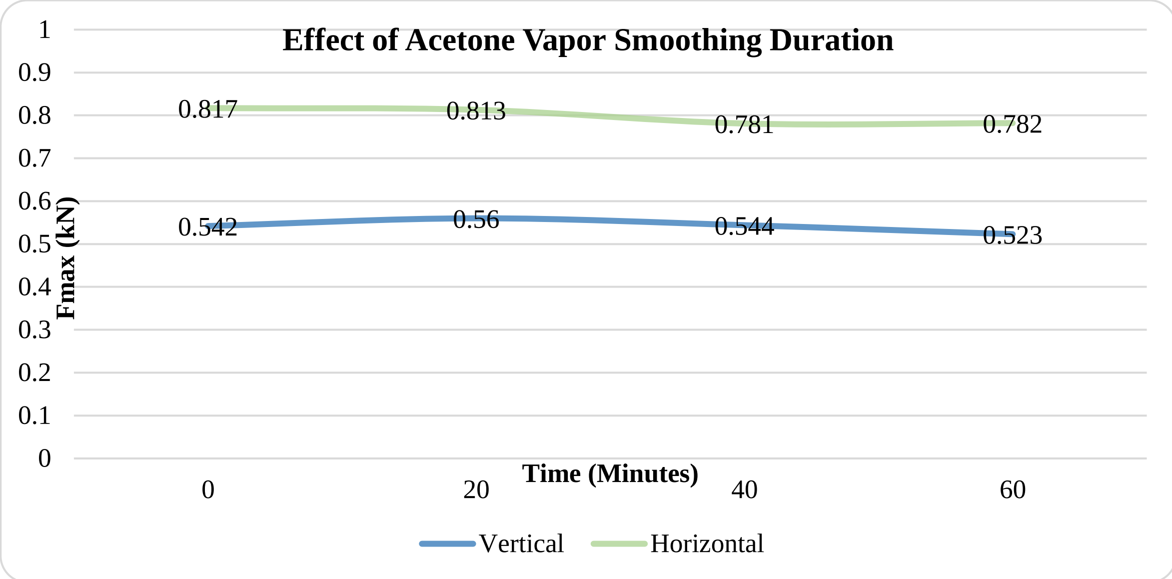

Figure 5. Graph of Maximum Load (Fmax) vs. AVS Duration

The trend in UTS value changes is consistent with changes in Maximum Load obtained for each treatment variation. In the vertical orientation, the Maximum Load value increased from 0.542 kN to 0.560 kN after 20-minute treatment, then decreased to 0.544 kN and 0.523 kN for 40 and 60-minute treatments. Meanwhile, in the horizontal orientation, the Maximum Load value slightly decreased from 0.817 kN to 0.813 kN, then dropped to 0.781 kN and 0.782 kN for 40 and 60-minute treatments. This indicates that increasing acetone vapor smoothing duration beyond 20 minutes tends to reduce the specimen's ability to withstand maximum load before failure [18].

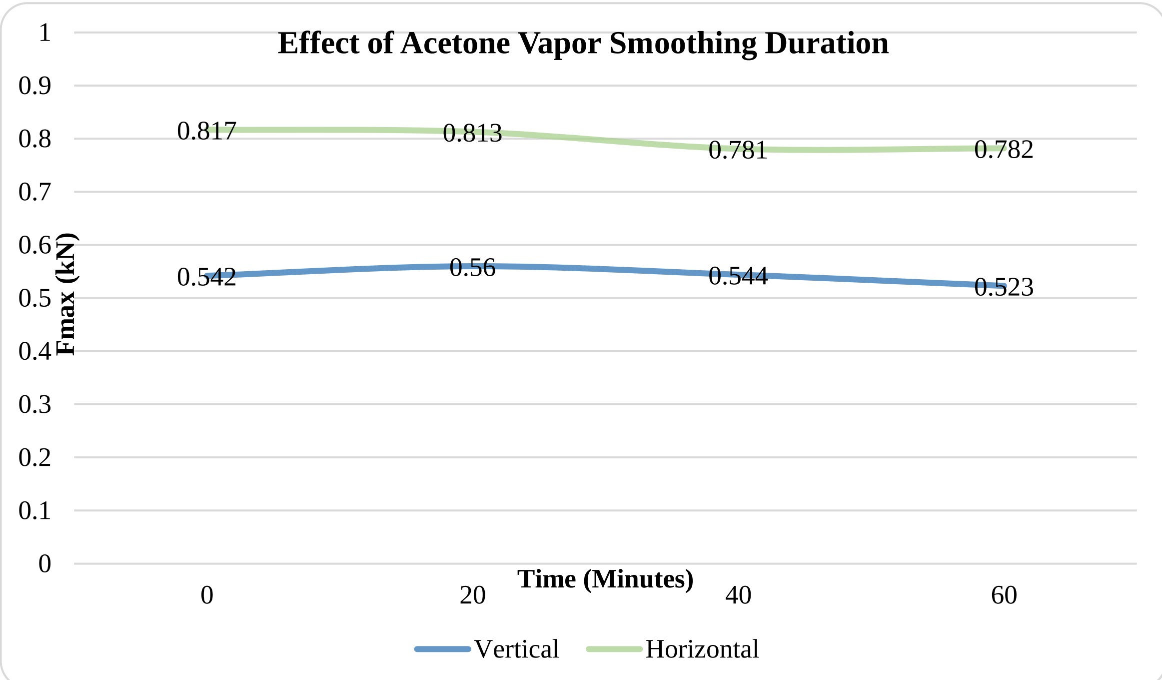

Figure 6. Graph of Breaking Load (Fbreak) vs. AVS Duration

Similar changes were also observed in the Breaking Load and Tensile Strength at Break (Rt) values. In the vertical orientation, the Breaking Load value was identical to the Maximum Load across all treatment variations, so the Rt trend was identical to UTS. This condition indicates that the specimen fractured immediately upon reaching the maximum load without experiencing significant plastic deformation after the peak load point. Conversely, in the horizontal orientation, the Breaking Load decreased from 0.800 kN in the untreated specimen to 0.710 kN, 0.682 kN, and 0.729 kN for 20, 40, and 60-minute treatments. This decrease was accompanied by a reduction in Rt from 38.57 MPa to 34.23 MPa, 32.88 MPa, and 35.15 MPa. These results indicate that although specimens can still reach a relatively high maximum load, the material's ability to sustain load until fracture tends to decrease after receiving acetone vapor smoothing treatment of longer duration [19].

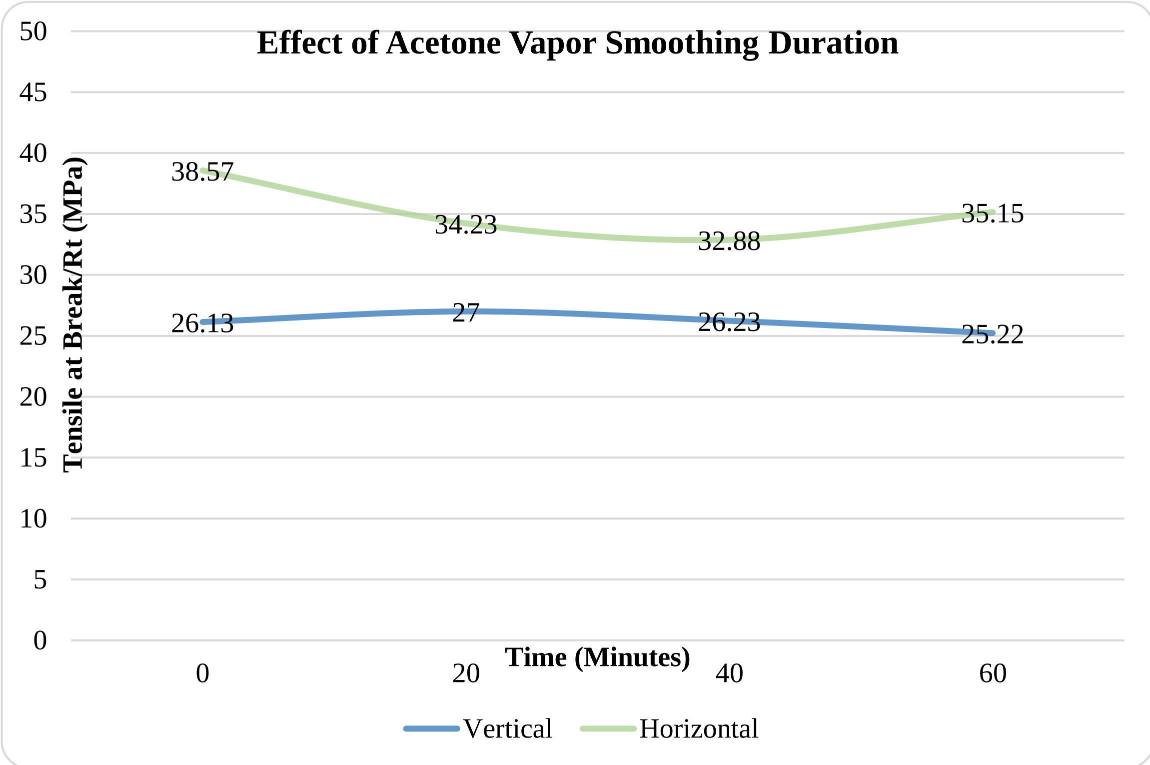

Figure 7. Graph of Tensile Strength at Break (Rt) vs. AVS Duration

Analysis of Elongation at Break values shows a different trend compared to tensile strength parameters. In the horizontal orientation, elongation values increased from 8.45% in the untreated condition to 9.36% at 20-minute treatment and reached the highest value of 9.85% at 40-minute treatment, before decreasing again to 8.82% at 60-minute treatment. Conversely, in the vertical orientation, changes in Elongation at Break values were relatively small, ranging from 6.70–6.82% across all treatment variations. The increase in elongation in the horizontal orientation indicates that acetone vapor smoothing treatment increases the specimen's ability to deform before fracture, while in the vertical orientation this effect was relatively insignificant [20].

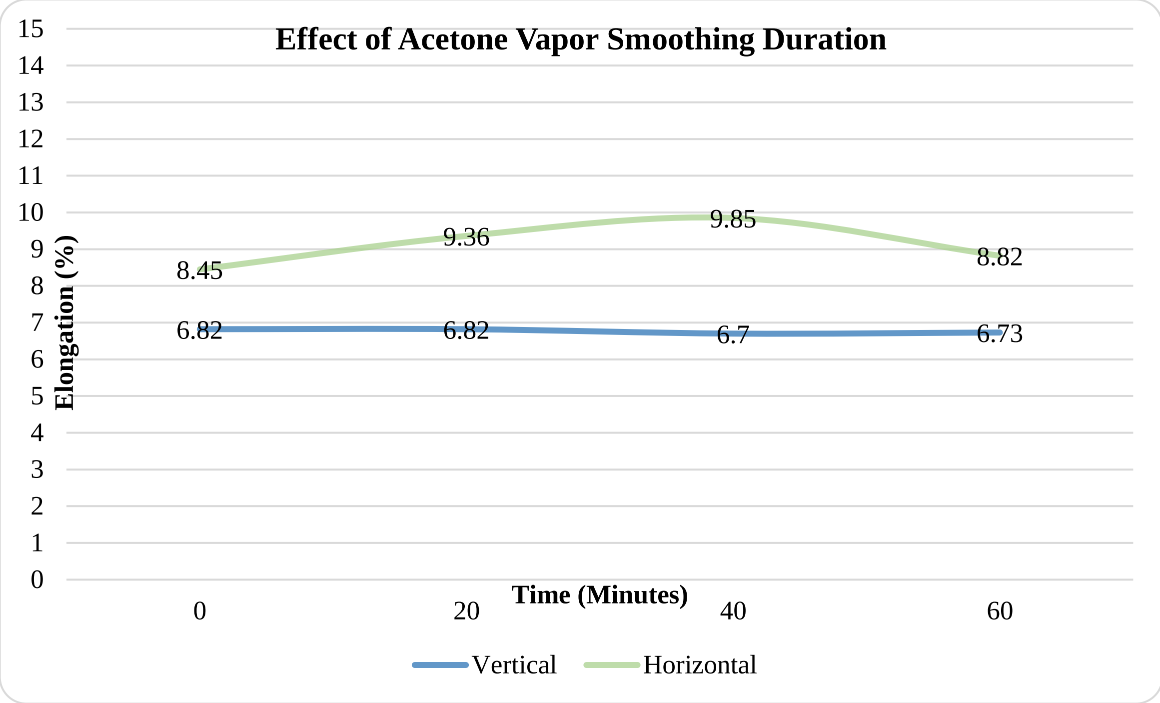

Figure 8. Graph of Elongation vs. AVS Duration

3.3 Effect of Acetone Vapor Smoothing on Surface Characteristics

In addition to affecting mechanical properties, acetone vapor smoothing treatment also produced noticeable changes in the surface characteristics of ABS specimens. Evaluation was performed using a digital microscope to observe changes in layer line visibility, while the degree of edge rounding was analyzed quantitatively through edge radius measurements using image analysis methods. The observation results are shown in Figure 7 and 8.

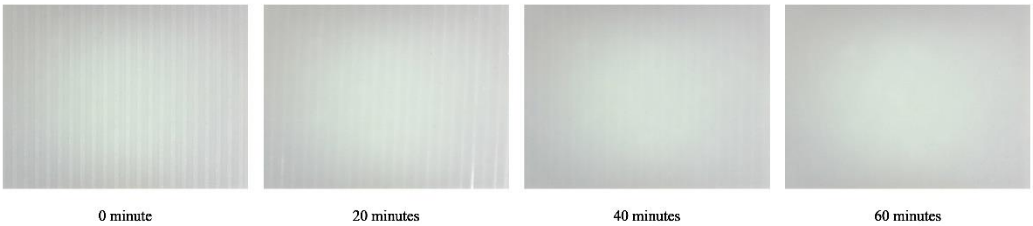

Figure 7. Changes in Layer Line Visibility

In untreated specimens, layer lines were still clearly visible across the entire surface, making the FDM printing texture easily recognizable. The specimen edges also maintained their geometric shape according to the printing process.

In untreated specimens, layer lines were still clearly visible on the entire surface, making the characteristic texture of FDM printing easily recognizable. In addition, specimen edges still maintained their geometric shape with the smallest edge radius value compared to other treatment variations. This condition shows that the specimen surface still maintained the original characteristics of the printing process.

After acetone vapor smoothing treatment for 20 minutes, layer line visibility began to decrease and the surface appeared smoother and more glossy compared to untreated specimens. Under these conditions, the change in edge geometry was still relatively small, as indicated by an insignificant increase in edge radius. This indicates that 20-minute treatment can improve surface quality without significantly altering specimen geometry.

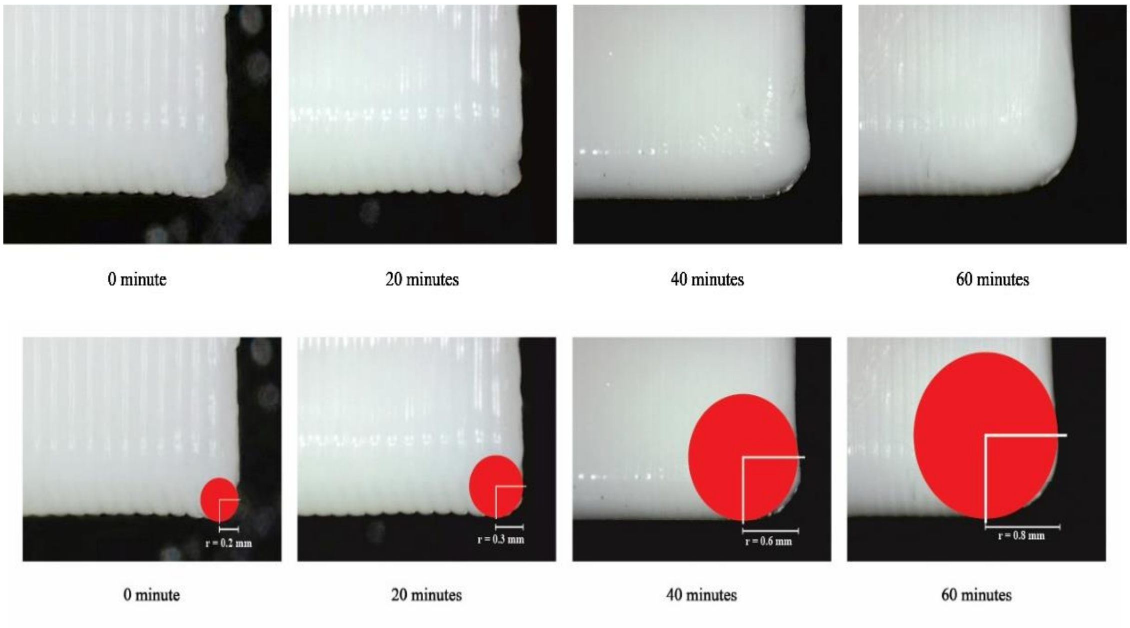

Figure 8. Specimen Edge Rounding and Radius Increase

Table 3. Edge Radius Measurement Results

Durasi AVS	Edge Radius (mm)
0 menit	0,20
20 menit	0,30
40 menit	0,60
60 menit	0,80

At 40-minute treatment, layer lines became increasingly difficult to observe and the surface became more homogeneous. At the same time, the edge radius value increased, making edge rounding more clearly visible. These results indicate that longer acetone vapor exposure not only reduces layer line visibility, but also begins to affect the geometry of the specimen edges due to softening of the surface layer.

The most noticeable change occurred at 60-minute treatment. Under these conditions, almost all layer lines were no longer visible, making the surface appear very smooth and glossy. However, the edge radius value also became the largest compared to other treatment variations, indicating that edge rounding occurred more intensively. This condition indicates that excessively long acetone vapor smoothing exposure can produce very good surface quality but is accompanied by local geometric changes at the specimen edges.

Overall, increasing acetone vapor smoothing duration results in decreased layer line visibility and increased edge radius. These results indicate that longer treatment duration improves specimen surface quality, characterized by smoother surfaces and reduced layer lines. However, this surface quality improvement is also accompanied by increasingly greater edge rounding, so an optimal treatment duration is needed to achieve a balance between surface quality and dimensional accuracy of FDM-printed products.

The surface evaluation in this study was primarily focused on morphological changes observed through digital microscopy and edge geometry variation. Although these approaches successfully identified the influence of acetone vapor smoothing duration on layer line reduction and edge rounding, quantitative surface roughness measurements such as Ra and Rz could provide additional numerical evidence regarding surface improvement. Future studies may incorporate three-dimensional surface profiling or advanced microscopic characterization to obtain a more comprehensive understanding of surface modification mechanisms after solvent vapor treatment [21].

3.4 Relationship between Surface Characteristics and Mechanical Properties

The research results show a trade-off between improvements in surface characteristics and mechanical properties of FDM-printed ABS specimens after acetone vapor smoothing treatment. The longer the treatment duration, the more reduced layer line visibility becomes, making the surface appear smoother, while the edge radius value increases, indicating increasing edge rounding. On the other hand, this surface quality improvement is accompanied by a tendency for some mechanical parameters to decrease, such as Maximum Load, Ultimate Tensile Strength (UTS), Breaking Load, and Tensile Strength at Break (Rt), especially at 40 and 60-minute treatments.

Under the investigated printing conditions, 20-minute acetone vapor smoothing provided the most balanced improvement between surface quality and mechanical performance. Under these conditions, layer line visibility had already decreased, making the surface appear smoother, while the increase in edge radius was still relatively small so the geometric change in the specimen was not yet significant. From a mechanical standpoint, Maximum Load and UTS values could still be maintained; in the vertical orientation, they even showed a slight increase compared to untreated specimens. This indicates that 20-minute treatment duration can improve surface quality without causing a significant reduction in specimen mechanical performance [1].

Conversely, 40-minute and 60-minute treatments produced increasingly smooth surfaces with increasingly low layer line visibility and a greater increase in edge radius. However, these conditions were accompanied by a decrease in Maximum Load, UTS, Breaking Load, and Rt values, although in the horizontal orientation the Elongation at Break increased up to 40-minute treatment before decreasing again at 60-minute treatment. These results indicate that improving surface quality through acetone vapor smoothing needs to be balanced with control of treatment duration so that geometric changes and reductions in mechanical properties remain within acceptable limits [1].

Based on these results, the selection of acetone vapor smoothing duration should be adapted to the product application requirements. For components that prioritize mechanical strength and dimensional accuracy, a shorter treatment duration of approximately 20 minutes is more recommended because it can provide surface quality improvements with minimal reduction in mechanical properties. Meanwhile, for products that prioritize surface aesthetic aspects, longer treatment duration can be considered with the consequence of greater edge rounding and some reduction in mechanical properties [1].

4. Conclusion

This study aimed to analyze the effect of acetone vapor smoothing duration on the surface characteristics and mechanical properties of ABS specimens from 3D printing using Fused Deposition Modeling (FDM) technology with the ASTM D638 Type IV standard. The acetone vapor smoothing duration variations used were 0, 20, 40, and 60 minutes on specimens with vertical and horizontal printing orientations.

Based on tensile test results, acetone vapor smoothing duration had an effect on the mechanical properties of ABS specimens. In the vertical orientation, the Ultimate Tensile Strength (UTS) value increased from 26.13 MPa to 27.00 MPa after 20-minute treatment, then decreased to 26.23 MPa and 25.22 MPa for 40 and 60-minute treatments. In the horizontal orientation, UTS slightly decreased from 39.39 MPa to 39.20 MPa at 20-minute treatment, then decreased to 37.66 MPa and 37.70 MPa for 40 and 60-minute treatments. The same trend was also shown by Maximum Load, Breaking Load, and Tensile Strength at Break (Rt) values, while the Elongation at Break value in the horizontal orientation increased up to 40-minute treatment before decreasing again at 60-minute treatment. Overall, horizontal orientation showed better mechanical properties than vertical orientation across all treatment variations.

From the aspect of surface characteristics, increasing acetone vapor smoothing duration caused layer line visibility to decrease, making the specimen surface appear smoother. On the other hand, image analysis results show that edge radius values increased with increasing treatment duration, indicating increasingly greater edge rounding. Thus, surface quality improvement was accompanied by geometric changes at the specimen edges.

Overall, the research results indicate a trade-off between improvements in surface characteristics and mechanical properties due to acetone vapor smoothing treatment. A treatment duration of 20 minutes provided the best balance because it could improve surface quality with reduced layer line visibility and still relatively small edge rounding, while maintaining specimen mechanical properties without significant reduction. Therefore, this duration can be recommended as an initial parameter for the acetone vapor smoothing process for FDM-printed ABS products requiring a balance between surface quality and mechanical performance. This study highlights the importance of controlling acetone vapor exposure duration to achieve a suitable compromise between surface enhancement and mechanical preservation in FDM-printed ABS components. The findings provide practical guidance for selecting post-processing conditions based on the required balance between surface appearance, dimensional stability, and mechanical performance.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

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