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Effects of Chemical and Mechanical Treatments on the Surface Roughness and Aerodynamic Performance of FDM-Fabricated ABS Airfoils

Efectos de tratamientos químicos y mecánicos en la rugosidad superficial y el desempeño aerodinámico de perfiles aerodinámicos de ABS fabricados por FDM

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ABSTRACT

Fused deposition modeling (FDM) is a fabrication technology that offers significant advantages for the wind energy industry, particularly in the areas of product design, prototyping, and manufacturing. However, parts produced via FDM often exhibit a relatively rough surface finish due to the intrinsic layer-by-layer process. This study assessed chemical and mechanical treatments aimed at reducing the surface roughness of airfoils fabricated using acrylonitrile-butadiene-styrene (ABS), one of the most widely used polymers in FDM. Surface roughness was characterized using scanning electron microscopy (SEM) and profilometry. Two chemical treatments were evaluated: acetone immersion and acetone vapor exposure. SEM and profilometry revealed crack formation in samples treated by immersion, while vapor exposure resulted in a significantly smoother finish without cracks. Wind tunnel tests demonstrated a 27% increase in the aerodynamic lift-to-drag ratio for airfoils treated with acetone vapor, indicating an improved aerodynamic performance.

Keywords: roughness, wind tunnel, airfoil, surface finishing, fused deposition modeling

RESUMEN

El modelado por deposicion fundida (FDM) es una tecnologıa de fabricacion que ofrece ventajas significativas para la industria de la energıa eolica, especialmente en el diseño de productos, la creacion de prototipos y la manufactura. Sin embargo, las piezas fabricadas mediante FDM suelen presentar un acabado superficial aspero debido al proceso intrınseco de fabricacion capa por capa. Este estudio evaluo tratamientos quımicos y mecanicos para reducir la rugosidad superficial de perfiles aerodinamicos fabricados con acrilonitrilo-butadieno-estireno (ABS), uno de los polımeros mas utilizados en FDM. La rugosidad superficial se caracterizo mediante microscopıa electronica de barrido (SEM) y perfilometrıa. Se analizaron dos tratamientos quımicos: inmersion en acetona y exposicion a vapor de acetona. El SEM y la perfilometrıa revelaron la formacion de grietas en las muestras tratadas por inmersion, mientras que la exposicion a vapor produjo un acabado significativamente mas liso y sin grietas. Pruebas realizadas en un tunel de viento mostraron una mejora del 27% en la relacion sustentacion-resistencia para los perfiles tratados con vapor de acetona, indicando un mejor desempeño aerodinamico.

Palabras clave: aspereza, tuneles de viento, perfiles aerodinamicos, acabado superficial, modelado por deposicion fundida

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Introduction

Fused deposition modeling (FDM), also known as *3D printing*, is widely applied in different fields due to its advantages, including ease of use, reproducibility, and automation capabilities. The materials processed via FDM are mainly thermoplastic polymers that are deposited layer-by-layer by means of an extruded filament. The filament is fused at a temperature slightly higher than the melting point of the material, using high-performance equipment, and subsequently solidifies during cooling. The print head precisely extrudes the molten polymer according to a 3D CAD model [1, 2]. For instance, FDM is a versatile manufacturing process for the design and testing of turbine rotor blades in wind energy research. It enables the fabrication of functional prototypes with complex geometries that are often unattainable through traditional machining, while enabling the easy incorporation of design modifications into the CAD model without additional process adjustments [3].

A current limitation of FDM is the high surface roughness of the fabricated parts [4]. Some defects commonly observed in FDM include overlapping, holes and incorrect contours, which degrade the surface finish and directly impact the costs, aesthetics, and functionality of the final piece [5, 6]. Wind turbines are particularly affected by surface irregularities, as they reduce the power conversion

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efficiency of the system [7]. Various techniques have been developed in the industry to improve surface finish quality [8]. For example, aerodynamic experiments have been carried out in wind tunnels to determine the impacts of these treatments on blade performance [9, 10]. The results indicate that greater surface roughness leads to earlier flow detachment on the blade [11].

The additive manufacturing industry is currently searching for a fast and low-cost solution to improve the surface finish of FDM-fabricated materials. Two post-treatments have been studied, *i.e.*, mechanical and chemical methods, which can smooth the surface and minimize its roughness [12, 13]. The chemical treatment consists of immersing the manufactured part in an acetone bath. It is simple, fast, cost-effective, and reliable. Nevertheless, in the chemical pretreatment method, factors such as part orientation, frequency, cooling, and exposure time must be balanced to optimize surface quality [14]. On the other hand, the low-cost mechanical method employs different sandpaper grain sizes to polish the surface [15].

Despite the increasing use of FDM for functional parts fabrication, the inherent surface roughness of printed airfoils remains a significant challenge that negatively impacts aerodynamic performance, particularly in wind turbine applications. Although chemical and mechanical post-treatments have been individually studied, there is a lack of comprehensive comparisons regarding their effects on both surface roughness and aerodynamic efficiency during controlled wind tunnel testing. This study systematically evaluated chemical treatments (acetone immersion and vapor) and mechanical polishing on ABS airfoils produced via FDM, quantifying their influence on surface morphology and aerodynamic behavior. The results provide valuable insights into the improvement of FDM-fabricated parts in renewable energy systems, contributing to advances in both manufacturing processes and practical applications.

The objective of this work was to study chemical and mechanical methods for reducing the surface roughness of an airfoil fabricated via FDM in wind turbine design applications. In this vein, ABS was selected due to its high tensile strength and Young's modulus [9], [16]. The effect of surface treatments on surface roughness was studied through profilometry and scanning electron microscopy (SEM), while the aerodynamic performance of the airfoil was assessed through wind tunnel experiments.

To further distinguish this work from prior studies, Table 1 summarizes representative research on the chemical post-processing of FDM-printed ABS, as well as on the aerodynamic testing of rough surfaces, using only references already cited in this manuscript. While prior works primarily quantify surface quality, dimensional effects, or mechanical responses after acetone-based treatments [17, 18, 19], and others relate surface condition to aerodynamic penalties in wind-tunnel campaigns [10], our study uniquely integrates chemical and mechanical post-processing with direct, quantitative lift-to-drag (L/D) measurements on FDM airfoils.

This comparative table emphasizes that, unlike previous studies, our work not only evaluates surface roughness but also directly correlates post-processing treatments with aerodynamic performance under controlled wind tunnel conditions.

The working hypothesis of this study is that chemical and mechanical surface treatments, specifically acetone immersion and acetone vapor exposure, are capable of significantly reducing the surface roughness of ABS airfoils fabricated via FDM, thereby improving their aerodynamic L/D ratio as measured in wind tunnel tests.

Materials and methods

Airfoil design

ABS airfoils were designed using AutoCAD 2021 and SolidWorks 2021, based on the Giguere SG6043 wind turbine airfoil, with chord and width dimensions of 20 and 10 cm, respectively [20]. A total of six airfoils were fabricated: one reference (REF) and five subjected to different surface treatments (Fig. 2).

3D printing of ABS airfoils

The airfoils were printed using ABS filament (ABS ZYLtech) with a melting temperature between 240 and 260 °C, a filament diameter of 1.75 ± 0.05 mm, and a filament roundness of ± 0.05 mm, at a deposition rate of 90 mm/s [9, 21]. Printing was performed on a Zortrax M200 desktop 3D printer, using the Z-suite software [22, 23].

Chemical and mechanical surface treatments

Treatments were applied to reduce the surface roughness, as summarized in Table 2:

- **Acetone immersion.** Two samples were immersed at room temperature for 1 min (IM2510) and 2 min (IM2523).
- **Acetone vapor.** Two samples were exposed to vapor at 56 °C for 4 min (VAP40) and 5 min (VAP50).
- **Mechanical/acetone vapor.** One sample was first sanded with grit-80 sandpaper, and then exposed to acetone vapor at 56 °C for 5 min (VAPM5).

High-purity acetone (99.9%) was used to prevent the porosity caused by commercial diluents in hygroscopic ABS [21, 24]. The immersion chambers contained 200 mL acetone, and the vapor temperature was maintained at 56 °C to prevent boiling.

Surface characterization

The surface roughness (Ra) of each airfoil was measured using a profilometer (Zeta-20, ZETA instruments), with 15 random measurements performed for each sample (Figs. 1g to 1l) [25]. SEM (Denton Vacuum Desk IV) was used to examine the airfoil topography (Figs. 1a to1f).

Wind tunnel testing

Aerodynamic performance was evaluated in an axial wind tunnel with a 30 x 30 cm test section and a 0.75 hp axial fan (Fig. 2c). The drag and lift forces were measured for each airfoil at angles of attack of -10, -5, 0, 5, 10, 15, and 20^{o}, as schematically illustrated in Fig. 3. The forces were sampled for 30 s at 2 Hz, enough for the response to be time-independent.

Table 1. Comparison of related studies.

Reference	Treatment/focus	Evaluated effects	Distinction of this study
[17]	Acetone immersion	Surface smoothing; dimensional changes; improved aesthetics	Combines chemical and mechanical finishing with direct L/D measurements on airfoils
[18]	Acetone vapor smoothing	Roughness reduction; improved bonding; possible mechanical impact	Links vapor treatment to wind-tunnel airfoil performance for multiple exposure times
[19]	Chemical post-processing of FDM parts	Roughness reduction; exposure time effects; uniformity	Uses optimized exposure to enhance aerodynamic efficiency with quantified L/D ratios
[10]	Wind-tunnel testing of rough surfaces	Relationship between surface texture and drag	Integrates surface finishing evaluation with direct aerodynamic quantification on FDM airfoils

Source: Authors

Table 2. Treatments applied to the FDM-fabricated ABS airfoils in order to reduce their roughness.

Test	Code	Temperature (°C)	Time (min)	Sandpaper treatment
1	IM2510	25.0	1.0	No
2	IM2523	25.0	2.0	No
3	VAP40	56.0	4.0	No
4	VAP50	56.0	5.0	No
5	VAPM5	56.0	5.0	Yes
6	Reference	N/A	N/A	N/A

Source: Authors

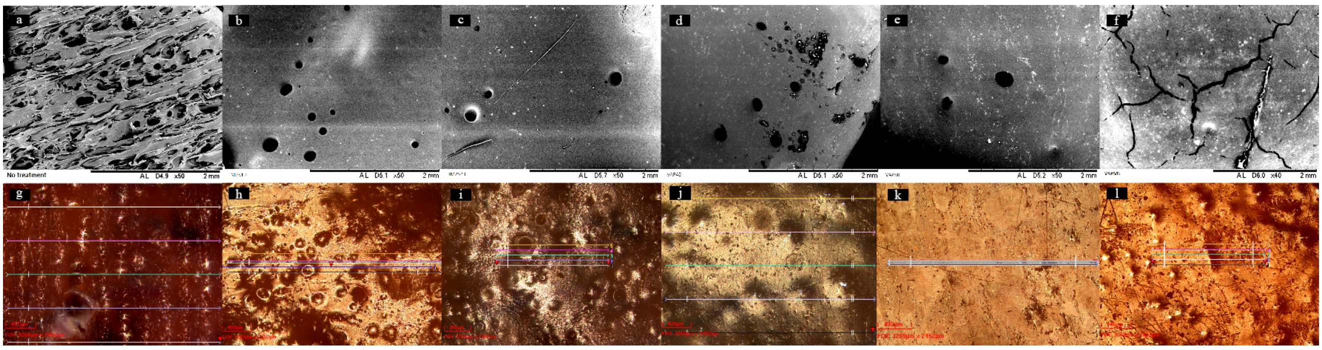

Figure 1. Results of SEM analysis: a) REF, b) IM2510, c) IM2523, d) VAP40, e) VAP50, f) VAPM5. Results of profilometer analysis: g) REF, h) IM2510, i) IM2523, j) VAP40, k) VAP50, l) VAPM5.
Source: Authors

The Reynolds number was 2×10^5, a relevant value for small wind turbine research [26, 27].

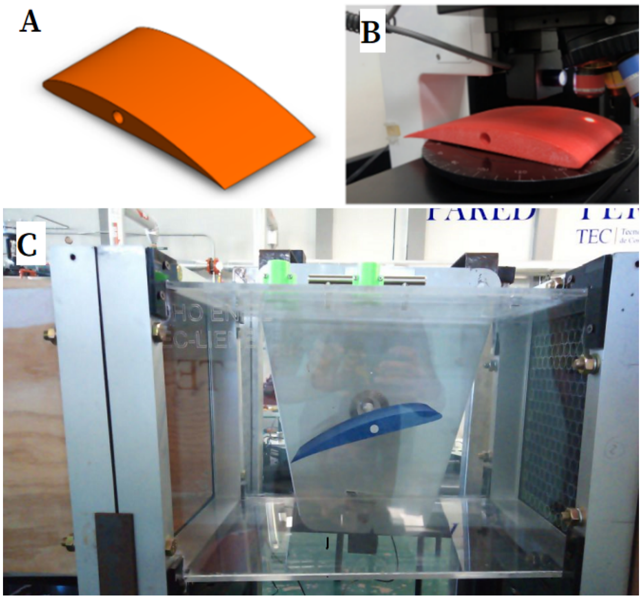

Figure 2. a) Airfoil CAD design, b) printed ABS airfoil, c) Wind tunnel setup. **Source:** Authors

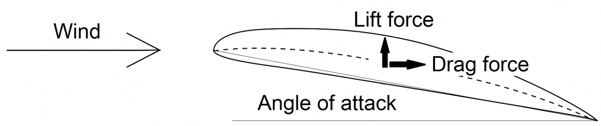

Figure 3. Airfoil schematic with relative wind and angle of attack. **Source:** Authors

Results and discussion

Surface roughness

In this work, ABS airfoils fabricated via FDM were subjected to five different chemical and mechanical surface treatments aimed at improving their aerodynamic properties for wind turbine applications. Fig. 1 shows the optical and electron micrographs of a non-treated reference and the treated samples. The topography of the samples was significantly altered by the treatments applied [28]. Fig. 1a shows a very rough, irregular, and porous surface|typical of FDM manufacturing|for the non-treated sample. The surface roughness was remarkably reduced for the treated samples in Figs. 1b to 1f.

The samples subjected to acetone immersion and vapor treatment for longer periods (Figs. 1c and 1e) are less porous than the samples exposed for shorter times (Figs. 1b and 1d). The sample subjected to combined mechanical and acetone vapor treatment (Fig. 1f) shows pronounced cracks, which were not present in the samples that were only chemically treated.

The Ra measurements of each sample were taken with a profilometer and are statistically represented in Fig. 4. The non-treated sample exhibits a high roughness due to the stacking of the extruded filament, which solidifies in an uncontrolled manner after leaving the nozzle. All the different chemical and mechanical treatments applied reduced the intrinsic roughness resulting from the FDM process. An analysis of variance (ANOVA), performed using Minitab, confirmed that the arithmetic means of the samples are significantly different, with a p-value of less than 0.05. The VAP50 resulted in the most significant change in Ra (-80.05%), followed by VAPM5 with -69.97%, VAP40 with -36.22%, IM2523 with -27.30%, and IM2510 with -23.02%. The chemical treatments grew more effective as the exposure time was extended. The immersion treatment (IM2510 and IM2523) resulted in the highest Ra dispersion, as well as in unwanted dimensional changes, which can be attributed to the rapid and heterogeneous dissolution rate [29, 17, 18]. For the samples processed with acetone vapor, a temporary solution of ABS and warm acetone formed on the surface of the part, allowing for the immediate reaction and reflux of the solution. This led to flattening and a reduced Ra dispersion, which further decreased as the exposure time increased [30], [31].

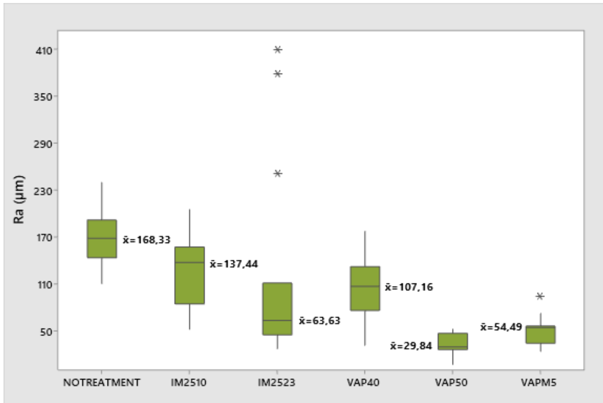

Figure 4. Boxplot of the arithmetic mean roughness (Ra) of ABS airfoils fabricated via FDM and subjected to different chemical and mechanical surface treatments. **Source:** Authors

While our results demonstrate that acetone vapor treatments (particularly VAP50) significantly reduce surface roughness, some previous studies have reported contrasting outcomes. For instance, [4] observed only limited improvements in surface finish under similar chemical treatments, possibly due to differences in exposure time and ABS filament types. Similarly, [5] reported that certain polymer grades may exhibit swelling or cracking under prolonged solvent exposure, which aligns with our observation of cracks in VAPM5. These contrasting results highlight the importance of process parameters and material characteristics in achieving effective roughness reduction, emphasizing that the optimal treatment depends strongly on the specific context of application.

These results not only corroborate prior findings regarding the effectiveness of acetone vapor treatments [30, 31]; they also highlight differences that may arise due to filament composition, printing orientation, and treatment duration. Compared to studies such as [4] and [5], this study suggests that the careful optimization of exposure times is critical to maximize surface smoothing while avoiding structural damage. These findings have practical implications for industrial applications: by selecting appropriate treatment parameters, manufacturers can improve aerodynamic efficiency without compromising dimensional accuracy, which is especially relevant for the prototyping and low-volume production of wind-turbine components.

Table 3. Number of tests performed in the wind tunnel based on the studied variables. **Source:** Authors

Variables	Levels	Number
Forces (N)	Drag and lift	2
Airfoils	One without treatment and five with treatment	6
Angle of attack (º)	-10, -5, 0, 5, 10, 15, 20	7
Total number of tests		84

Aerodynamic performance of surface-treated ABS airfoils

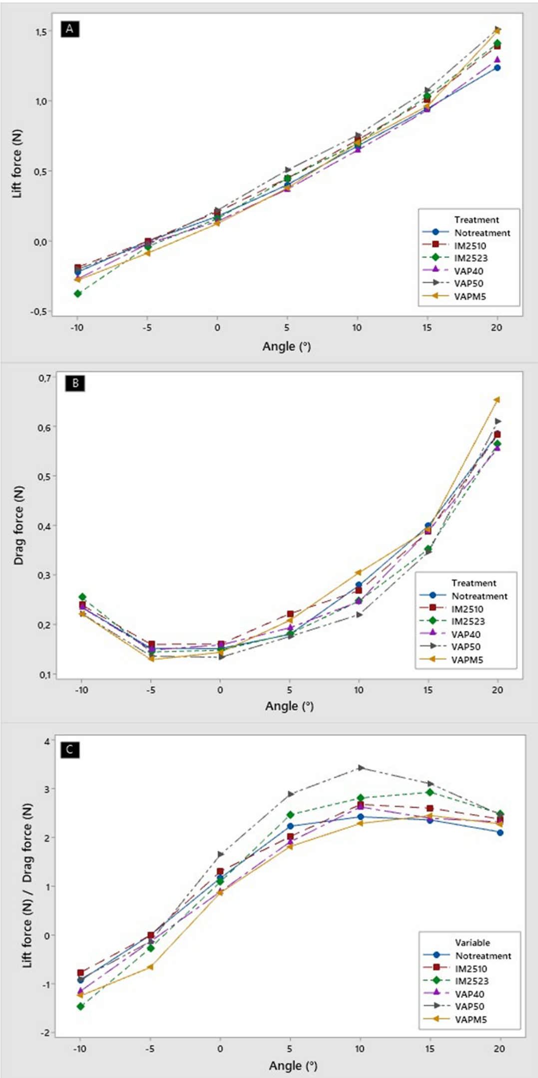

Figure 5. Aerodynamic performance parameters for ABS airfoils fabricated via FDM and subjected to different surface treatments in order to reduce their surface roughness. **Source:** Authors

The measurements of the lift and drag forces generated on the treated airfoils were obtained at different angles in wind tunnel experiments, as presented in Fig. 5. The variation percentages for each sample are presented in Table 4. The VAP50 airfoil reported the greatest lift force improvement and, at the same time, the lowest drag force. This is the treatment that produced the lowest surface roughness. This result indicates that acetone vapor exposure for 5 min constitutes the best treatment for roughness reduction in ABS airfoils, leading to improved aerodynamic efficiency, with an average of 27% compared to the non-treated reference. The IM2510 airfoil also showed an improvement of 9% in aerodynamic performance. Three other procedures had a non-significant or a counterproductive effect on the aerodynamic performance of the airfoil.

The correlation between reduced surface roughness and improved aerodynamic performance observed herein aligns with the general trends reported in previous works [17], but there are notable discrepancies. For example, other studies have shown that minor roughness variations may have negligible effects on lift and drag for certain airfoil geometries, whereas, in our experiments, the VAP50 treatment consistently enhanced performance across the tested angles. This emphasizes the importance of considering both material-specific behavior and manufacturing conditions when scaling these treatments to larger or differently shaped airfoils. From an industrial design perspective, these results suggest that acetone vapor treatment could be integrated into FDM-based prototyping pipelines to achieve more aerodynamic surfaces, potentially reducing post-processing costs and improving the efficiency of small-scale wind turbines or other aerodynamic devices.

Limitations and replicability

Despite the positive results, this study has several limitations that must be acknowledged. Only six airfoils were tested, all fabricated with a single geometry and a single thermoplastic polymer (ABS), which limits the generalizability of our findings. Moreover, the FDM process is inherently variable due to printing parameters such as nozzle temperature, layer height, print speed, and filament quality. These factors may affect the reproducibility of the surface finish as well as aerodynamic performance across different setups or machines.

Another important source of uncertainty lies in the wind tunnel's force measurements. The axial balance used to measure the lift and drag has a resolution uncertainty of 0.01 N. Although this level of precision is acceptable for most conditions tested, small measurement errors may have occurred, especially at low force values or high angles of attack.

Additionally, this work focused only on the short-term effects of the surface treatments. Thus, the long-term impact of acetone-based treatments on the structural integrity and environmental durability of the airfoils remains unknown. Exposure to UV light, moisture, or mechanical fatigue in real operational environments may alter the material's behavior over time.

To ensure replicability, all experimental conditions and treatment parameters were carefully documented, but

Table 4. Percent variations in aerodynamic performance for each surface treatment applied to ABS airfoils fabricated via FDM.**Source:** Authors

Variation percentages								
Angles	-10 º	-5 º	0 º	5 º	10 º	15 º	20 º	Average
IM2510	18 %	-	12 %	-9 %	10 %	10 %	13 %	9 %
IM2523	-58 %	-	-7 %	11 %	10 %	24 %	18 %	1 %
VAP40	-23 %	-	-24 %	-14 %	9 %	2 %	10 %	-7 %
VAP50	3 %	-	42 %	30 %	42 %	32 %	17 %	27 %
VAPM5	-33 %	-	-26 %	-19 %	-6 %	4 %	8 %	-12 %

further research is necessary to evaluate additional airfoil shapes, other thermoplastics used in FDM, and the long-term reliability of the treatments under realistic service conditions. This will help to determine the practical feasibility of these treatments for wind turbine components and other aerodynamic applications.

Conclusions

In this work, different chemical and mechanical treatments were applied to FDM-fabricated ABS airfoils in order to reduce their intrinsic roughness. The treatments studied were acetone immersion, acetone vapor exposure, and acetone vapor combined with mechanical polishing. SEM analysis led to the conclusion that acetone immersion and vapor treatments can reduce roughness but leave a slight porosity on the material surface, while the combination of mechanical and acetone-vapor treatment generates cracks. The profilometer results revealed that the airfoil with the lowest mean roughness and data dispersion was that subjected to vapor treatment for an extended period of time. The immersion treatment reduced roughness to a lesser extent but exhibited higher data dispersion. An assessment of aerodynamic performance in a wind tunnel further supported the hypothesis that acetone vapor treatment for 5 min is the best alternative, resulting in the smallest drag forces and the greatest lift forces. This treatment yielded a 27% improvement in the aerodynamic L/D ratio, constituting the most effective procedure for obtaining a smooth surface and improved aerodynamic characteristics in the studied context.

The findings of this study demonstrate that simple and low-cost surface treatments (*e.g.*, acetone vapor exposure), can significantly enhance the aerodynamic performance of FDM-fabricated components. These treatments can be feasibly integrated into small-scale industrial workflows for the production of aerodynamic parts, such as blades for micro-wind turbines or educational wind tunnel models. Since FDM is already widely used in rapid prototyping and small-batch production, incorporating these post-processing techniques could improve product efficiency without requiring major infrastructure changes. Future work should explore the automation and scalability of these treatments to facilitate their adoption in commercial manufacturing.

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Author contributions

- **José Matamoros:** experiments, tunnel measurements, printing, analysis, methodology, edition, validation of results, conceptualization.
- **Rafael Mora:** experiments, printing, analysis, methodology, editing, validation of results, conceptualization.
- **Claudia Villareal:** supervision, revision, editing, conceptualization, methodology.
- **Gustavo Richmond-Navarro:** supervision, revision, editing, conceptualization, methodology, resources.

Conflicts of interest

The authors declare no conflict of interest.

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