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New approach to minimise surface roughness in Polytetrafluoroethylene (PTFE) through robotic spindle speed control

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ABSTRACT

Machining Polytetrafluoroethylene (PTFE) is increasingly popular due to its chemical resistance, low friction, and high-temperature stability. These properties make PTFE crucial to industries that need fine surface finishes, such as aerospace, biomedical devices, and electronics. However, achieving practical surface quality remains challenging, particularly in robotic machining processes. This research examines the impact of spindle speed on the surface roughness of PTFE during robotic milling operation using KUKA KR120 R2700. Spindle speed was selected as the primary process parameter, and the experimental trials were conducted at four spindle speed levels: 4,500 RPM, 9,000 RPM, 13,500 RPM, and 18,000 RPM. The average roughness (Ra), root mean square roughness (Rq), and maximum peak-to-valley roughness (Rz) were measured through profilometry. Concurrently, a Scanning Electron Microscope (SEM) detected surface features with microscopic imperfections. The findings demonstrate a clear trend: a significant decrease in surface roughness values with a very high spindle speed, wherein 18,000 RPM provided the best results regarding the least surface defects and finer scratch lines. Moreover, the Ra value was the most significant in the present study and validated the trend between the spindle speed and surface finish quality. This research focuses on a new direction in enhancing the machinability of PTFE materials using a robotic milling technique in which spindle speed is optimised to improve the surface finish required in many industries. The research offers essential information for manufacturers desiring greater accuracy and control in PTFE processing and expands the knowledge base of robotic manufacturing technology for polymeric material. This research establishes the scene to address concerns about using robotic systems to improve surface finishes in various engineering applications.

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1. INTRODUCTION

Polytetrafluoroethylene (PTFE) or Teflon is a polymer that can be used extensively for several industrial applications due to its high coefficient of friction, high-temperature characteristics, and chemical stability. Note that comparable materials, including Polyethylene (PE) and Polypropylene (PP), do not possess the same thermal stability or chemical resistance as PTFE, making PTFE valuable for sensitive or more specialised applications. According to Dhanumalayan [1], some application areas of PTFE are coatings, insulation, heat sealing, lubrication, bearings, and clinical application due to its low cost, high durability, and recyclable nature. Furthermore, PTFE is whole-some in electronics, automobile, aircraft, and food industries, where there is a need to maximise efficiency, minimise friction, and guarantee durability.

The major difficulty of mechanical processing, such as milling and drilling of PTFE, is obtaining low surface roughness [2]. Mechanical processing involves working or altering materials through mechanical actions, such as cutting, milling, or drilling. In particular, excessively low surface roughness negatively impacts PTFE performance by reducing friction force and wear, which are crucial for applications requiring dimensional accuracy and stability [3]. According to Ghosh et al. [4], similar substances exhibit unreliable coefficients of wear and friction. In addition, higher surface roughness does not always result in better machining precision, especially in dimensional accuracy and geometrical consistency. At the same time, Moder [5] mentioned that similar substances demonstrate unreliable coefficients of wear and friction while raising surface roughness does not necessarily improve precision. Hence, there is a strong need to enhance the machining parameters, including spindle speed, feed rates, and depth of cut, to achieve lower surface roughness and improve PTFE-based product performances.

Although most studies have evaluated metal machining parameters, research on non-metal or soft materials, specifically on PTFE, remains limited. Ni [6] investigated the mechanical processing of PTFE, particularly in drilling, and concluded that higher spindle speeds with lower feed rates enhance surface quality and machining consistency. Despite that, studies on PTFE machining using robotics, which offers enhanced flexibility and accuracy, still need to be made available. In particular, this research investigates the relationship between spindle speed and PTFE surface roughness using the KUKA KR120 R2700 robotic milling system. In line with this, Verl et al. [7] emphasised that robots provide several advantages, including precision, flexibility, and adaptability in machining processes. However, challenges such as accurate modelling, process control, and parameter identification remain unresolved.

This article presents research to fill these gaps by establishing the best spindle speed of robotic machining in enhancing PTFE surface roughness on polymeric material. PTFE is highly relevant due to its extensive use in engineering applications, especially where a smooth surface is required, and factors such as thermal stability, low friction, and chemical inertia are desirable. Similarly, Ayanleya [8] highlighted its applicability to surface coatings to enhance hydrophobicity, wear resistance, and energy efficiency. Consequently, this research contributes to extending knowledge of improving PTFE machining approaches for industries requiring high-performance materials with superior surface finishes.

2. LITERATURE REVIEW

Machining processes using robotic milling technology are increasingly preferred over traditional Computer Numerical Control (CNC) milling due to robots' enhanced flexibility, adaptability, and accuracy in diverse machining operations. Dubey [9] highlighted that robotic manufacturing technology offers a flexible and reconfigurable system, overcoming CNC machining's limitations regarding fixed workpiece size and shape constraints while improving accuracy and repeatability.

In contrast, CNC milling machines are typically restricted to movements along three linear axes—X (horizontal), Y (vertical), and Z (depth), limiting their ability to machine complex geometries. Robotic

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milling, however, enables multi-axis movements, often incorporating six or more axes of motion. This capability allows the robotic cutting tool to manoeuvre with greater freedom in three-dimensional space, facilitating the machining of complex structures, such as curved aerospace components, turbine blades, or custom biomedical implants.

According to Chen [10], robotic milling offers superior flexibility in managing irregular workpieces, adjusting to varying work environments, and accommodating diverse tool paths. In addition, Chen also noted that the lower rigidity of robotic systems often constrains the accuracy of robotic milling compared to traditional CNC machines. Murthy et al. [11] supported this view, emphasising that robotic milling can overcome the fixed size and shape constraints of CNC systems while maintaining improved adaptability for intricate machining tasks.

This lower rigidity makes robotic milling especially ideal for machining polymeric materials such as PTFE, which require strict surface roughness control. Karl [12] stated that due to the opportunities of the PTFE's outer layer being rough to the touch, PTFE needs unique methods of working for technical application of those surfaces that matter most, for instance, when it is being used in precision seals, for biomedical purposes, or electronic insulation. Using the KUKA KR120 R2700 robot, other machining factors, including spindle speed, feed rate, tool position, and depth of cut for the materials, can be fine-tuned to enhance the surface quality depending on the needs of the targeted application area.

(a) (b)

Fig. 1. (a) Robotic CNC milling; (b) CNC milling

Fig. 1 compares Robotic CNC Milling (a) and CNC Milling (b). Robotic CNC Milling, KUKA KR120 R2700, offers enhanced flexibility and adaptability through multi-axis movements (6 or more axes), enabling the machining of complex geometries such as curved aerospace components, custom biomedical implants, and intricate moulds. This flexibility allows the tool to maneuver in various orientations for three-dimensional surfaces. In contrast, Traditional CNC Milling machines, like the vertical milling machine in Fig. 1(b), are constrained to three linear axes (X, Y, and Z), making them ideal for high-precision and repetitive operations with simpler geometries. However, their rigidity limits the machining of irregular or intricate workpieces. Hence, CNC machines are preferable for their accuracy and reliability. Nevertheless, robotic CNC milling is preferable due to flexibility, amplitude range, and price, which is beneficial in industries with complex structures and unique designs.

Over the years, plastic materials have been widely used in automotive, aerospace, medical, and manufacturing industries for their strength, flexibility, high-temperature resistance, and chemical inactivity. Abedsoltan [13] stated that plastics play a major role in the automotive industry and misted by helping to reduce weight, safety, and fuel efficiency. Likewise, Park [14] noted that engineering plastic foams with

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low density and good mechanical and thermal shocks were used in the aerospace, aircraft, and automobile industries. According to Moshkbid et al. [15], plastics are used ithe medical sector implants, bioresorbable, and equipment packaging. The healthcare sector also has gained a lot from the versatility of plastics. Moreover, Sohn et al. [16] have highlighted that thermoplastic polymers have been widely incorporated in electronics, aerospace, and automotive industries due to their low cost, low-temperature processability, and recyclable properties, which make them highly suitable for additive manufacturing applications.

Compared to other forms of plastics, PTFE is relatively unique, and its qualities include lower friction, heat stability, and non-stick surfaces; thus, it is used in non-stick coatings, electronics, and automobiles. Existing studies by Qi [17]suggested that incorporating fluoro silicone and silicone rubbers improved the friction of PTFE composites at high temperatures and their application in high-temperature sealing systems. Similarly, Deshwal [18] mentioned that incorporating metallic and carbon-based materials enhance PTFE's wear and thermal stability, making it acceptable in low-speed and low-load applications, especially in bearing technologies. Notably, its demand has significantly grown over the years, and its unique characteristics make it a significant material in cutting tool development in many engineering and various industries to enhance machining. Table 1 compares the applications of PTFE in domestic and industrial sectors. It highlights differences in primary use, material function, common products, operating conditions, and key benefits, showcasing PTFE’s versatility from household convenience to industrial durability.

Table 1. Applications of PTFE in domestic and industrial sectors [1]

Criteria	Domestic Applications	Industrial Applications
Primary Use	Everyday household tasks and convenience	Heavy-duty and precision engineering
Examples	Non-stick cookware, dental floss, fabric coatings	Gears, seals, fasteners, and pipe fittings
Material Function	Non-stick, easy-to-clean surfaces	Chemical resistance, heat resistance, low friction
Common Products	1. Frying pans	1. Industrial gears
	2. Dental floss	2. Chemical hoses and pipelines
	3. Iron soleplates	3. Conveyor belts and rollers
	4. Insulated cables	4. Anti-corrosion fasteners
	5. Plumbing tapes	5. Electrical insulators and gaskets
Operating Conditions	Moderate temperature and pressure	High temperature, pressure, and corrosive environments
Key Benefits	Ease of use, hygiene, and convenience	Enhanced durability, stability, and performance

The influence of machining parameters on surface roughness is significant in determining the quality of the final product, especially for polymeric materials such as PTFE. Abellán-Nebot et al. [19] emphasised that understanding cutting and process parameters is important in improving machining sustainability and reducing CO_2 emissions. This indicates that more energy- and material-efficient machining processes can be achieved by controlling parameters such as spindle speed and feed rate. According to Işleyen et al. [20], it was recorded that surface roughness can be reduced when the spindle speed is increased and the feed rate is reduced. However, increasing tool diameter can increase durability and accuracy while increasing surface roughness.

Additionally, Balakrishna et al. [21] stated that an optimal surface finish can be reached with high cutting speed, low feed rate, and shallow depth of cut. The author emphasised that feed rate has the greatest impact on surface roughness, particularly when applied to specific surface segments. In this investigation, three primary parameters, spindle speed, feed rate, and depth of cut, were examined to determine the surface roughness of PTFE. In particular, spindle speed affects cutting efficiency, with higher speeds typically producing smoother surfaces since the cutting tool moves faster through the material. Meanwhile, feed rate refers to the relative speed between the cutting tool and the material, which can affect the depth of the scratch on the surface. At the same time, the depth of cut determines how much material will be cut at a time, which affects the surface defects and roughness produced. These parameters must be determined to obtain the best PTFE surface with minimal roughness.

Previous research has established that machining parameters are very significant in defining surface roughness, which controls the performance of materials in technical applications. Zhao et al. [22] proved that if spindle speed and cutting tool positioning are not appropriately controlled, the surface roughness is incurred, and the performance of the surface degrades. Similarly, Ridwan et al. [23] concluded that variation in the accurate machining parameters could lead to tool failure, ineffective surface finish, and even equipment deterioration. Hence, it marks the significance of exerting control to achieve stable machining surface finish and integrity. Kant et al. [24] also established other critical machining parameters, namely, feed rate, depth of cut, and cutting speed, as essential to reducing surface roughness and optimising energy consumption in machining operations. The parameters, which include feed rate and cutting speed, can be adjusted to enhance surface finish and material properties and reduce manufacturing costs. Altogether, these results highlight the significance of parameter optimisation in providing the best possible surface quality and effective machining results.

Fig. 2 illustrates the relationship between key machining parameters and surface roughness in milling processes. The main factors, spindle speed (n) and feed rate (Vf), influence surface roughness and determine the tool's interaction with the workpiece. The diagram also highlights key surface texture characteristics, and these irregularities occur due to improper machining parameters, tool wear, or material properties. Surface roughness is defined by roughness height (vertical deviations) and roughness width (spacing between irregularities), both critical in determining surface quality and performance. Essentiallyoptimising spindle speed and feed rate reduces surface flaws and waviness, resulting in smoother surfaces with minimal defects. These relationships are essential for controlling machining conditions to achieve high-quality surface finishes, particularly in precision applications.

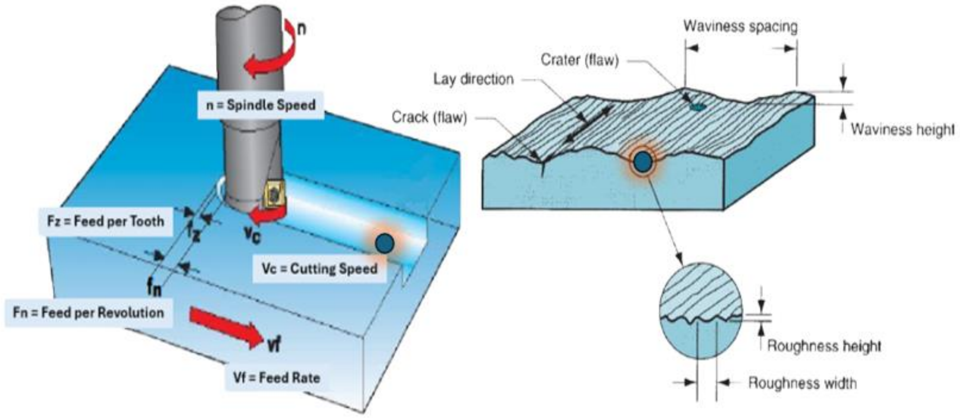

Fig. 2. Influence of cutting parameters on surface roughness in machining processes

By synthesising findings from previous studies and analysing key machining parameters, this research aims to address the gap in the literature regarding the influence of spindle speed on PTFE surface roughness, particularly in robotic machining applications. Furthermore, this study isolates the effect of spindle speed while keeping other parameters, such as feed rate and depth of cut, constant to eliminate additional variations. The synthesis highlights critical relationships between spindle speed and surface quality, providing deeper insights into the robotic milling of PTFE. It also introduces a novel approach for determining optimal machining parameters for PTFE, a polymer material widely used in industries that demand smooth, high-quality surfaces, such as aerospace, electronics, and medical. This approach is expected to provide valuable insights for improving machining performance and surface finish, critical for enhancing the material’s functional performance in precision applications.

3. METHODOLOGY

The methodology is designed to evaluate the effect of spindle speed on the surface roughness of PTFE, focusing on measurements obtained through robotic machining techniques. This study the relationship between spindle speed and surface quality to identify optimal machining conditions that minimize surface roughness minimised . The experimental process includes precise control of machining parameters such as spindle speed, feed rate, and cut depth while leveraging robotic technology's flexibility to achieve consistent and repeatable results. Additionally, surface roughness measurements will be conducted using advanced tools like profilometers and Scanning Electron Microscopy (SEM) to assess surface characteristics and defects at micro-level precision. Accordingly, this approach seeks to enhance the understanding of machining behaviour for PTFE and provide insights into improving its surface quality, which is critical for industrial applications requiring high-performance and smooth surface finishes.

3.1 Experimental work

This experimental work aims to evaluate the effect of machining parameters on machined surface roughness. The workpiece used in the experiment was a PTFE thermoplastic polymer sheet manufactured by Rochling. The test specimen is square and size 50 mm x 50 mm x 50 mm. The mechanical and physical properties of PTFE materials are described in Table 2. A two-flute carbide flat-end mill with a diameter of 10 mm and a total length of 70 mm was used for the face-cutting test. In addition, face milling cutting tests using a 6-axis KUKA KR120 R2700 milling robot investigated surface roughness concerning varying spindle speed while maintaining a constant feed rate and depth of cut. After machining, the surface roughness values were measured using a Mitutoyo SJ-401 Surface Profilometer and TM3030 Tabletop Microscope with SwiftED3000 to analyse the SEM image. Moreover, SEM is used to analyse surface morphology, microstructure, and material composition at high magnification.

Table 2. PTFE workpiece properties used in the experiment

Properties	
Tensile Strength (MPa)	25
Young’s Modulus (GPa)	0.5
Rockwell Hardness (N/mm^2)	54–60
Density (g/cm^3)	2.7
Melting Point (°C)	327
Coefficient of Thermal Expansion	120×10^{-6}
Low-Temperature Resistance (°C)	-200 to +260

These experiments were conducted under controlled experiments to reduce variation to the least possible in other machining operations for accurate results. A vertical milling cutting pattern was used to study the effect of machining parameters on the surface roughness of PTFE. Fig. 3 illustrates the experimental setup for robotic milling. The PTFE workpiece was securely clamped to ensure stability and minimise vibrations during machining. Moreover, Mundim et al. [25] highlighted that shorter tools reduce vibrations by minimising the cutting length and preventing re-machining caused by vibrations. This is particularly beneficial when machining soft materials, where lower stiffness demands reduced force, enhancing stability in milling processes. Additionally, Niu et al. [26] confirmed that shorter tools exhibit reduced stiffness, which lowers cutting forces and vibrations during machining. The setup highlights the advanced control capabilities of robotic milling, enabling consistent and reliable experimentation under controlled cutting conditions.

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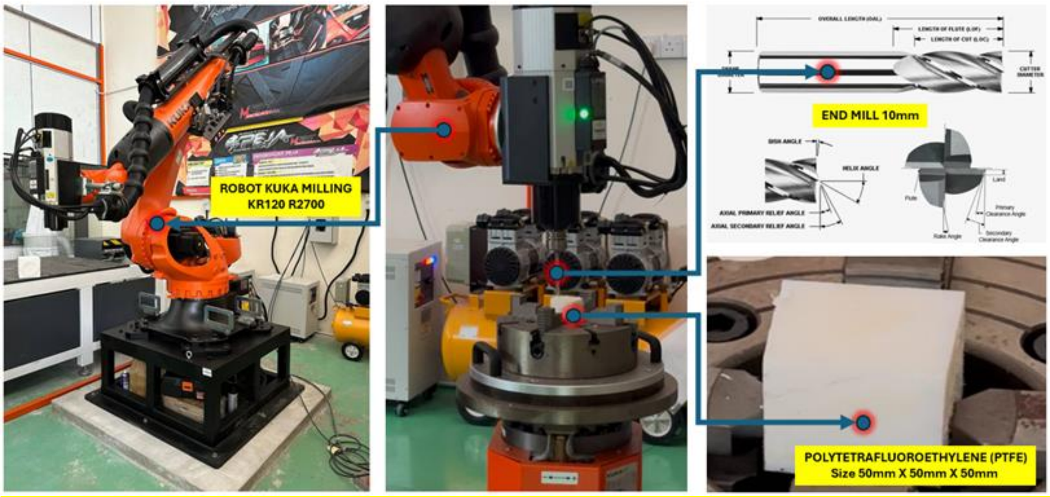
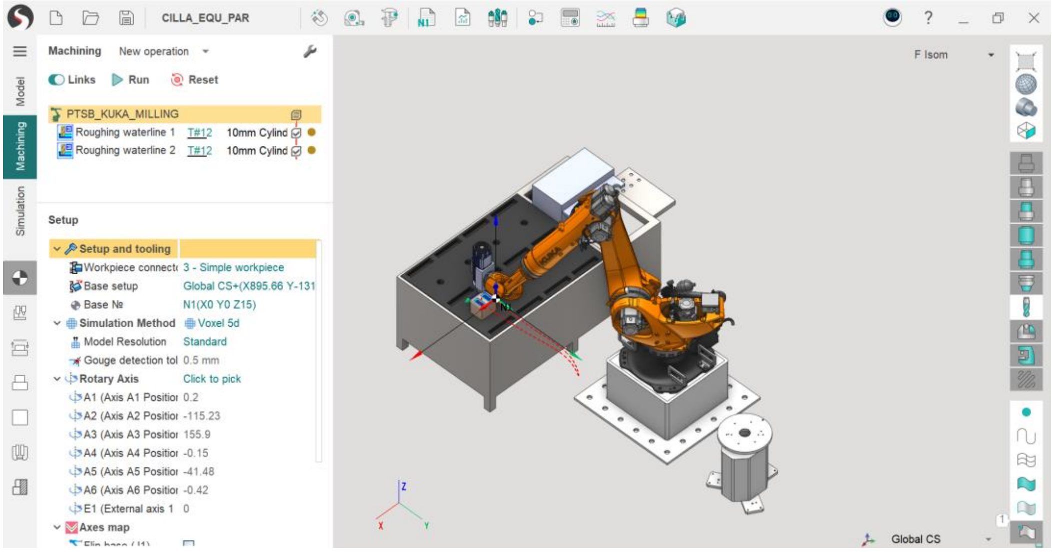


Fig. 3. Experimental setup

Fig. 4 displays the SprutCAM software that facilitates tool path planning and collision detection, ensuring smooth, optimised tool engagement during machining. It enables the adaptive control of machining parameters, such as spindle speed, feed rate, depth of cut, and tool orientation, to minimise errors. This virtual simulation reduces trial-and-error in actual experiments, improving machining efficiency and surface finish outcomes. Integrating SprutCAM with KUKA robotics highlights advanced programming flexibility and accuracy in robotic milling operations.



PTSB_KUKA_MILLING
Roughing waterline 1 T#12 10mm Cylind
Roughing waterline 2 T#12 10mm Cylind

Setup

Setup and tooling	
Workpiece connect	3 - Simple workpiece
Base setup	Global CS+(X895.66 Y-131
Base №	N1(X0 Y0 Z15)
Simulation Method	Voxel 5d
Model Resolution	Standard
Gouge detection tol	0.5 mm
Rotary Axis	Click to pick
A1 (Axis A1 Positio	0.2
A2 (Axis A2 Positio	-115.23
A3 (Axis A3 Positio	155.9
A4 (Axis A4 Positio	-0.15
A5 (Axis A5 Positio	-41.48
A6 (Axis A6 Positio	-0.42
E1 (External axis 1	0
Axes map	

Fig. 4. SprutCAM simulation and programming setup

The three significant independent variables considered in this study were spindle speed, feed rate, and depth of cut set at 1.0 mm, as summarised in Table 2. Each independent variable was varied in four values determined based on the recommendations of the cutting tool's manufacturer and the knowledge gathered

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through contemporary literature on machining polymeric-based material. This study aims to demonstrate that the robotic milling process can achieve spindle speeds of up to 18,000 RPM, focusing on minimising surface roughness. However, based on the specifications of the KUKA KR120 R2700 robot, the maximum spindle speed is 24,000 RPM.

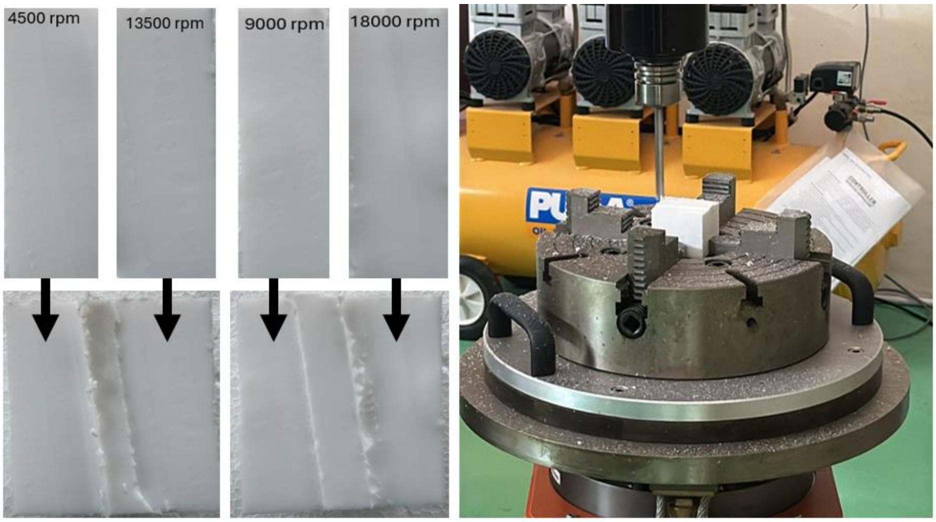
Table 2. Cutting parameters setting

Spindle Speed (rev/min)	Depth of Cut (mm)	Feed per Tooth (mm)
4500	1.0	0.111
9000	1.0	0.056
13500	1.0	0.037
18000	1.0	0.028

4. RESULT AND DISCUSSION

The results in Fig. 5 illustrate the influence of spindle speed on the surface roughness of PTFE during machining. The PTFE surface exhibits greater roughness at lower spindle speeds, such as 4,500 RPM, due to increased friction and cutting resistance. This is attributed to PTFE's low hardness, which makes it prone to deformation and material tearing at slower speeds, resulting in an uneven surface finish. The surface roughness significantly decreases as the spindle speed increases to 9,000 RPM and 13,500 RPM. The elevated spindle speed generates higher frictional heating, softening the PTFE material and facilitating smoother cutting with reduced surface resistance.

The surface quality improves at the maximum spindle speed of 18,000 RPM, achieving the smoothest finish. This is due to the controlled heat generation, which lowers surface tension and material hardness, enabling uniform material removal. The results highlight that increasing spindle speed enhances machining efficiency, reduces surface roughness, and minimises defects. This demonstrates that PTFE's low hardness and thermal sensitivity can be effectively leveraged for precision machining.



(a) (b)

Fig. 5. (a) PTFE after machining in different spindle speeds; (b) PTFE during machining

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After completing the machining process at various spindle speeds, the PTFE surface quality was evaluated through two key measurements: surface roughness and microscopic image analysis. Surface roughness was quantified using the Mitutoyo SJ-401 Surface Profilometer, which provided three critical roughness parameters: average roughness (Ra), root mean square roughness (Rq), and maximum height average (Rz). Measurements were taken at multiple points across the machined surface to ensure data uniformity and reliability. Each experiment was repeated three times to enhance accuracy, minimise experimental error, and confirm the consistency of the results. Furthermore, microscopic image analysis further complemented the roughness measurements by capturing surface defects and structural characteristics, comprehensively evaluating the PTFE surface after machining.

Ra, Rq, and Rz are essential in assessing surface roughness and functional performance in precision machining. Ra is the average roughness, which offers a surface texture characterisation by calculating the mean displacement of peaks and valleys and is, therefore, useful in most applications requiring low surface roughness and low surface roughness coefficient of friction. Meanwhile, Rq is the root mean square roughness, increasing more significant deviations and providing the significance of amplitude-weighted measures of surface irregularities contributing to wear rate and energy transfer. Simultaneously, Rz, the average maximum height, calculates the highest and the lowest peaks of a surface with varying heights over the sampling length, making it useful in ascertaining defects on the surface and its general structure.

Fig. 7 illustrates the relationship between spindle speed and surface roughness parameters (Ra, Rq, and Rz) for PTFE, demonstrating a consistent reduction in surface roughness as spindle speed increases. At 4,500 RPM, surface roughness values are highest due to increased friction and cutting resistance, resulting in rougher surfaces. As spindle speed rises to 9,000 RPM and 13,500 RPM, the surface roughness decreases significantly, particularly for Rz, indicating fewer deep peaks and valleys caused by more stable tool-material interactions. Conversely, the reduction in Ra and Rq reflects an improvement in overall surface texture due to better material removal efficiency at higher speeds. At 18,000 RPM, surface roughness reaches its lowest values, with minimal deviations across all parameters. This is attributed to the higher spindle speed that generates uniform heating, which softens PTFE and reduces cutting resistance, enabling consistent and smooth material removal. Thus, the findings affirm that improving the spindle speed improves the machining rate and increases the surface finish for PTFE.

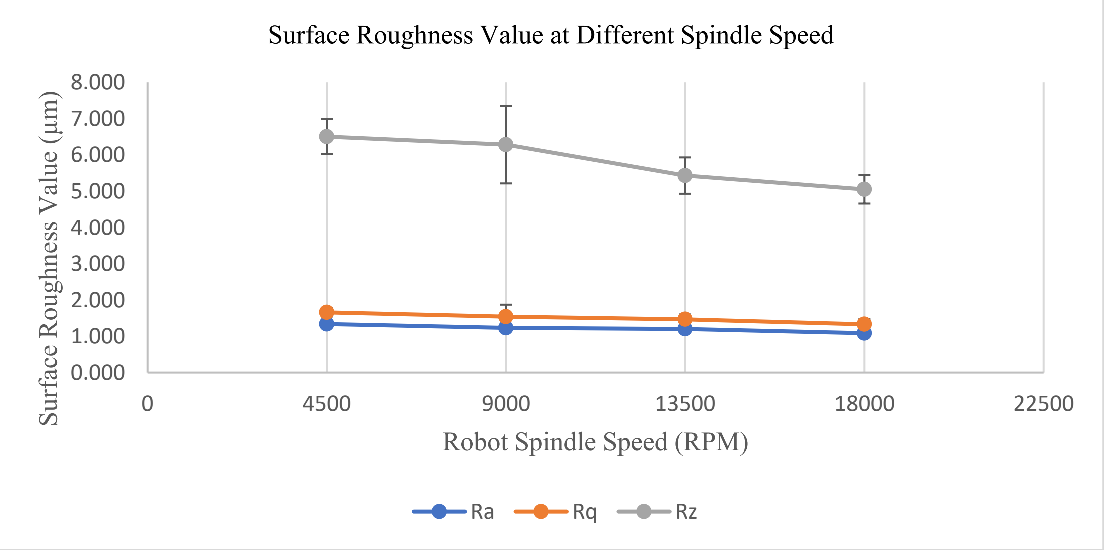

Fig. 7. Surface roughness (Ra, Rq, Rz) of PTFE at different spindle speeds with constant feed rate and depth of cut

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The SEM analysis was performed using the TM3030 Tabletop Microscope with SwiftED3000 to visually assess the surface morphology of PTFE after machining at various spindle speeds. SEM imaging provides high-magnification microstructural details, which reveal surface defects such as scratches, grooves, and micro-cracks that are not observable through standard surface roughness measurements alone. Each sample was examined under a magnification of x60, where the scale bar indicates 1 mm, corresponding to the entire horizontal width of the image. This magnification level enables detailed visualisation of surface irregularities at a microscopic scale.

The SEM images in Fig. 8 illustrate the surface morphology of PTFE machined at different spindle speeds, providing a detailed evaluation of surface roughness and defect formation. At 4,500 RPM, the surface exhibits significant roughness with visible scratches and irregular tool marks, indicating poor material removal consistency due to lower spindle speed. At 9,000 RPM, the surface demonstrates an improvement, with reduced scratches and more uniform tool marks, although micro-scratches remain visible. At 13,500 RPM, the surface texture improves further, with finer grooves and more organised tool marks, reflecting enhanced machining efficiency and more consistent material removal. At 18,000 RPM, the surface achieves the smoothest finish, with minimal visible defects and finer tool marks, indicating optimised machining conditions. The SEM analysis demonstrates that increasing spindle speed significantly improves the surface quality of PTFE by reducing surface roughness and defects, highlighting the benefits of higher machining speeds in producing refined and consistent surface finishes.

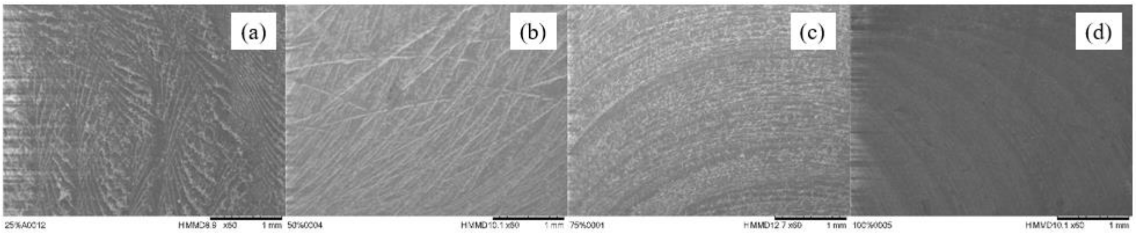

Fig. 8 SEM images of PTFE surface after machining at different spindle speeds: (a) 4500 RPM – scratches, (b) 9000 RPM – micro-scratches, (c) 13500 RPM – grooves, (d) 18000 RPM – fine scratches

The results reveal that the surface roughness of PTFE decreases progressively as spindle speed increases, with the smoothest finish achieved at 18,000 RPM (extreme point). This can be attributed to the optimised cutting conditions, where higher spindle speed reduces tool-material friction, improves chip formation, and minimises surface defects. The findings align with Ni [6], who observed improved surface finish with higher spindle speeds during PTFE machining. However, the result surpasses previous studies by demonstrating finer and more consistent tool marks, highlighting the competitiveness of robotic milling in achieving superior surface quality. This agrees with classical machining theory, where increased cutting speed enhances surface accuracy by reducing cutting forces and thermal effects. Overall, these results highlight the advantage of robotic milling for PTFE, providing a competitive edge in industries requiring precision and high surface quality.

5. CONCLUSION

This study investigated the influence of spindle speed on the surface roughness of PTFE using robotic milling technology. The results demonstrate that increasing spindle speed significantly improves surface quality, with the smoothest surface achieved at 18,000 RPM. Higher spindle speeds reduce cutting resistance, enhance chip formation, and minimize surface defects such as scratches and grooves, confirming that optimised machining parameters lead to better surface finishes. The findings align with existing literature on polymer machining but provide new insights into the effectiveness of robotic milling systems in achieving superior surface textures. Compared to traditional machining techniques, robotic milling offers

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enhanced flexibility, precision, and consistency, making it competitive for applications requiring smooth and defect-free surfaces. This research also highlights the critical role of input parameters, such as spindle speed, in determining output performance (Ra, Rq, Rz), which is essential for the precision machining of temperature-sensitive materials like PTFE.

Furthermore, the results contribute to machining theory by demonstrating that higher spindle speeds improve tool-material interaction and minimise thermal distortion. In conclusion, this study validates the advantage of robotic milling for PTFE. It also offers valuable guidance for aerospace, medical, and electronics industries, where achieving high surface quality is paramount for functional performance and product reliability.

6. ACKNOWLEDGEMENTS

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7. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted without any self-benefits or commercial or financial conflicts and declare the absence of conflicting interests with the funders.

8. AUTHOR'S CONTRIBUTIONS

Wan Nor Shela Ezwane Wan Jusoh: Conceptualization, methodology, formal analysis, investigation and writing-original draft; **Shukri Zakaria, Mahamad Hisyam Mahamad Basri**: Conceptualization, methodology, and formal analysis; **Mohamad Irwan Yahaya**: Conceptualisation, formal analysis, and validation; **Md Razak Daud, Noor Iswadi Ismail**: Conceptualization, writing- review and editing, and validation.

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