Advanced and Sustainable Technologies
ASET
E-ISSN 2976-2294

Volume 4, No 1, June 2025 [124-133]

Investigation of Machinability in Milling of PTFE under Dry and Wet Conditions

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Received 26 February 2025, Revised 17 March 2025, Accepted 26 March 2025

ABSTRACT

This study investigates the effect of the endmill flute number and cutting conditions on the milling of PTFE (polytetrafluoroethylene). High-speed steel (HSS) tools with 2 flutes and 4 flutes were evaluated by varying spindle speeds, feed rates, and cutting conditions (dry and wet). Surface roughness and chip formation were the major criteria used to assess the performance of different cutting conditions. The study found that the 2-flute end mill decreased PTFE milling surface roughness better than the 4-flute tool. Due to PTFE's self-lubrication, dry cutting produces smoother surfaces than wet cutting. The self-lubricating feature of PTFE caused short, discontinuous chips during dry cutting and tangled, needle-like chips in wet conditions owing to coolant interference. These findings contribute to improving the machining of PTFE, bringing insights into selecting the correct cutting tools and cutting conditions.

Keywords: Polytetrafluoroethylene, Milling, Dry and wet conditions, Endmill flute number.

1. INTRODUCTION

Machining is an important manufacturing process through which a workpiece is created through cutting, shaping and refining operations with tools to achieve the workpiece of the right size, shape and finish. Although associated with metals, machining is also used in polymers, ceramics and composites, showing its versatility in many kinds of materials. Polytetrafluoroethylene (PTFE), a synthetic fluoropolymer of tetrafluoroethylene, is regarded as the pinnacle of material science and is known for its remarkable characteristics and numerous applications. Because its molecules consist of a carbon backbone and fluorine atoms surrounding it, PTFE exhibits high chemical stability [1]. This makes it very resistant to corrosion and chemical reactions. PTFE, also known by the brand name Teflon, is a versatile fluoropolymer with distinctive features such as minimal friction, great chemical resistance, and high-temperature stability [2]. PTFE's qualities make it widely employed in a variety of industries, including automotive, aerospace, electronics, and medical devices. PTFE materials are commonly employed in ultra-clean flow control systems. With remarkable high-temperature resistance, ranging from -200°C to 260°C, PTFE remains structurally stable even under extreme heat conditions, making it ideal for gaskets, seals, and electrical insulation in high-temperature environments [3]. However, their mechanical processing characteristics differ significantly from those of metals and other non-metallic materials. Numerous studies have explored the machining of PTFE. Natarajan et al. used a Taguchi L27 (34) orthogonal array design of experiments to identify the optimal solution for a multi-objective machining issue using PTFE, ultimately deriving a minimization function for surface

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roughness and a maximization function for material removal rate utilizing Response Surface Methodology (RSM) [4]. Ying et al. studied the effect of cutting parameters and conditions in turning PTFE by using the Taguchi method [5]. The vital findings are that an increase in the length of PTFE corresponded with a decrease in cutting stability, and employing a higher feed rate improved the cutting stability. Ni et al. conducted a machinability study to evaluate the MRR and cutting energy of PTFE [6]. This study implemented the Taguchi method to evaluate cutting force, chip temperature, and surface roughness. The results showed that the depth of cut and feed rate had a significant influence on the cutting force and chip temperature. Ni et al. conducted a study in which they evaluated torque, force, surface roughness, and temperature while drilling the PTFE [7]. Based on the result, spindle speed was the most important factor in thrust, and the feed rate had a significant effect on torque. The combination of higher spindle speeds with lower feed rates is the best parameter for achieving the drilling performance of PTFE. Cui et al. conducted an investigation and found that cutting speed significantly influences the surface roughness of PTFE during the turning process [8]. A study by Catalin and Felicia reported different findings whereby the surface roughness was highly influenced by the feed rate [9]. Unfortunately, there is a scarcity of thorough experimental results that cover a broader variety of tool materials and cutting conditions. Furthermore, surface quality and chip formation have not been fully investigated. This study aimed to investigate the influence of milling flute number and cutting condition on the surface quality and chip formation of PTFE in the milling process.

2. MATERIAL AND METHODS

In this study, a CNC milling machine (Yornew VMC300) is utilized to investigate surface roughness and chip formation in PTFE milling, as shown in Figure 1. This experiment employs various cutting speed and feed rate settings, maintaining a constant depth of cut at 0.15 mm. Table 1 displays the cutting parameters and conditions for a total of 24 milling runs on PTFE. The tool used in this experiment is high-speed steel (HSS) with a diameter of 8 mm. Different flute numbers, which are 2 and 4, are used as study parameters. The parameters of this experiment are spindle speed and feed rate. A device called the Mitutoyo SJ-410 tester instrument determines the average surface roughness (Ra). The workpiece size in this experiment is a block of Teflon with a dimension of 100 mm length × 60 mm width × 25 mm height.

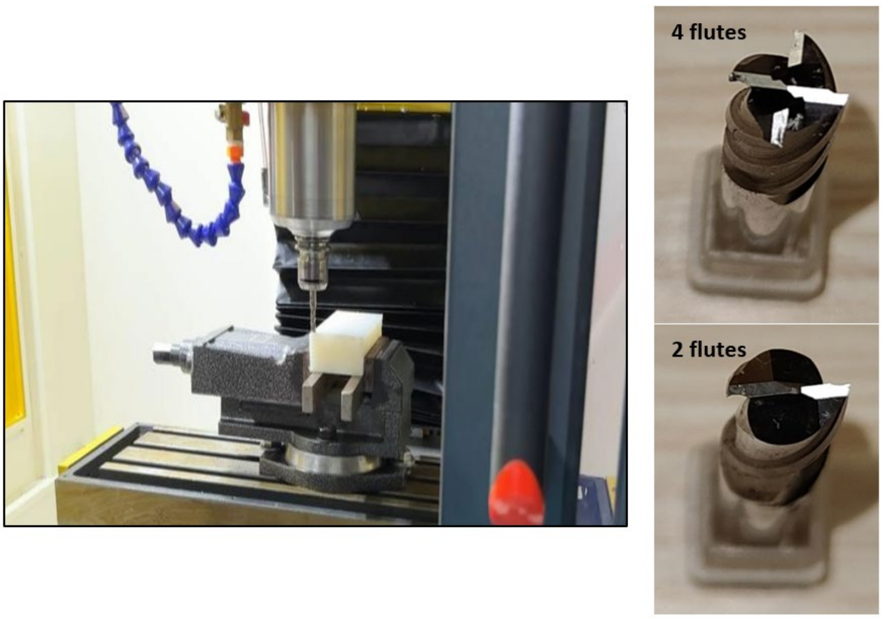

Figure 1: Experimental setup and end mill flutes.

Table 1: Cutting parameters.

Study parameter	
Spindle speed (m/min)	80,100,120
Feed rate (mm/min)	200,400
No of flutes	2,4
Condition	Dry, Wet

3. RESULTS AND DISCUSSION

The experimental findings of surface roughness are shown in Table 2. When milling PTFE, several variables, such as cutting parameters, tool geometry, and material properties, affect surface roughness. Since PTFE has low heat conductivity and is soft and ductile, it can be difficult to machine while maintaining a high level of surface finish. In this section, it presents the effect of the cutting condition on surface roughness and chip formation.

Table 2: Experimental results for surface roughness

Trial	Number of flutes	Condition	Cutting speed (m/min)	Feed Rate (mm/min)	Surface Roughness (μm)
1	2	DRY	80	200	0.368
2	2	DRY	80	400	1.591
3	2	DRY	100	200	0.442
4	2	DRY	100	400	1.21
5	2	DRY	120	200	0.441
6	2	DRY	120	400	1.038
7	2	WET	80	200	0.648
8	2	WET	80	400	2.598
9	2	WET	100	200	0.984
10	2	WET	100	400	0.933
11	2	WET	120	200	0.927
12	2	WET	120	400	0.941
13	4	DRY	80	200	1.112
14	4	DRY	80	400	1.523
15	4	DRY	100	200	1.19
16	4	DRY	100	400	0.915
17	4	DRY	120	200	0.583
18	4	DRY	120	400	1.103
19	4	WET	80	200	1.753
20	4	WET	80	400	2.283
21	4	WET	100	200	0.665
22	4	WET	100	400	2.64
23	4	WET	120	200	0.769
24	4	WET	120	400	2.443

3.1 Surface roughness

Figure 2 and Figure 3 show the variation in Ra values of the PTFE milling samples cut in different conditions (dry and wet), respectively. For a 2-flute milling tool, the graph in Figure 2 illustrates the relationship between surface roughness, feed rates, and cutting conditions (dry and wet) at 80, 100, and 120 m/min. In general, dry conditions demonstrate better surface roughness than wet conditions for all cutting speeds and feed rates. The highest surface roughness, measured in dry and wet conditions with a feed rate of 400 mm/min and a cutting speed of 80 m/min, is roughly 1.5 and 2.6 μm, respectively. When comparing wet and dry circumstances, surface roughness is often lower in the dry condition for all cutting speeds and feed rates. Cutting in wet conditions causes the coolant to interfere with the chip formation process, resulting in irregularities in the surface finish. Increasing the cutting speed from 80 to 120 m/min at a feed rate of 200 mm/min results in a minor improvement in surface quality in both dry and wet circumstances. In dry conditions, surface roughness stays reasonably constant with a feed rate of 200 mm/min at all cutting speeds, staying near 0.5 μm. This suggests that, under dry conditions, cutting speed has little effect on surface roughness at lower feed rates. On the other hand, surface roughness is reduced by increasing cutting speed at a feed rate of 400 mm/min. The surface roughness is around 1.6 μm at cutting speeds of 80 m/min and progressively decreases to about 1.0 μm at cutting speeds of 120 m/min.

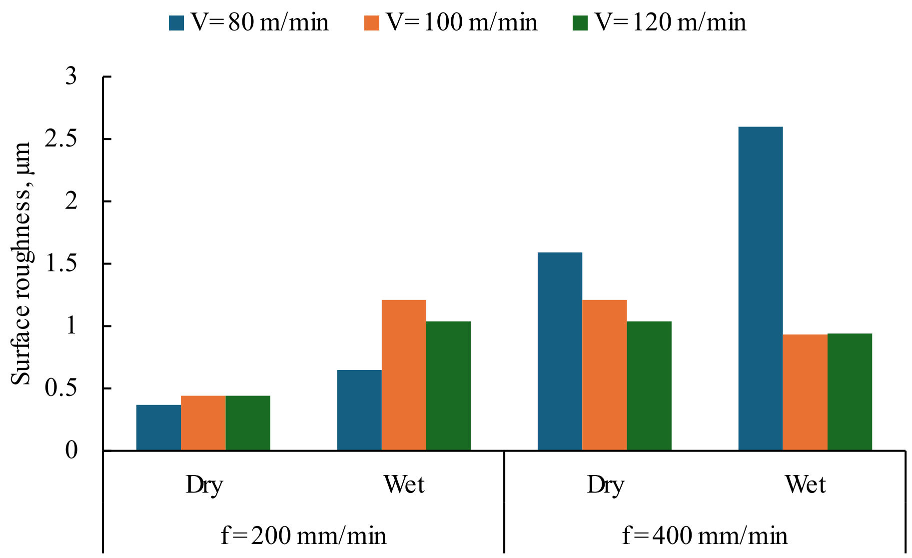

Figure 2: Surface roughness for 2 flutes.

This implies that in dry situations, greater cutting speeds enhance surface roughness at higher feed rates. In wet conditions, the surface roughness depicted a similar pattern as in dry conditions. The highest surface roughness (2.6 μm) is recorded at the higher feed rate (400 mm/min) when the cutting speed is 80 m/min and then drastically reduces to 0.9 μm at the speed of 120 m/min. To sum up, PTFE's natural ability to lubricate along with its thermal and chemical properties, make dry cutting better for getting a rougher surface than wet cutting.

A similar graph in Figure 3 shows how surface roughness and cutting circumstances relate to one another when utilizing a 4-flute cutting tool. In dry conditions, the maximum surface roughness of roughly 1.5 μm is achieved at a feed rate of 400 mm/min and a cutting speed of 80 m/min. In contrast, wet conditions with a feed rate of 400 mm/min and a cutting speed of 100 m/min result in the highest surface roughness, which is approximately 2.6 μm. Dry conditions consistently produce a smoother surface than wet ones at all cutting speeds at a feed rate of 200 mm/min, demonstrating inherent lubricating properties that reduce the need for external cooling or lubrication. Although the difference is less noticeable, dry conditions also result in smoother surfaces than wet conditions at a higher feed rate of 400 mm/min. In dry conditions, surface roughness generally diminishes as cutting speeds increase, especially at 120 m/min. On the other hand, under wet conditions, surface roughness significantly increases with increasing feed rates, particularly at an intermediate cutting speed of 100 m/min. When the cutting speed increases from 80 m/min to 100 m/min, surface roughness steadily declines at the higher feed rate of 400 mm/min. However, after 100 m/min, it stabilizes, suggesting that surface finish improvements fade at higher speeds. At a lower feed rate of 200 mm/min, surface roughness drops dramatically from 80 m/min to 100 m/min before stabilizing with little change as cutting speed rises. It seems that surface smoothness gets better as cutting speeds go up for both feed rates, but the improvements are most noticeable at slower speeds. The fact that surface roughness stays lower at all cutting speeds for the 200 mm/min feed rate compared to the 400 mm/min feed rate shows that the surface finish is better. The two finish states' differences in surface roughness are greatest at 80 m/min and get smaller as the cutting speed rises, indicating that cutting speed has a bigger impact on surface finish at higher feed rates.

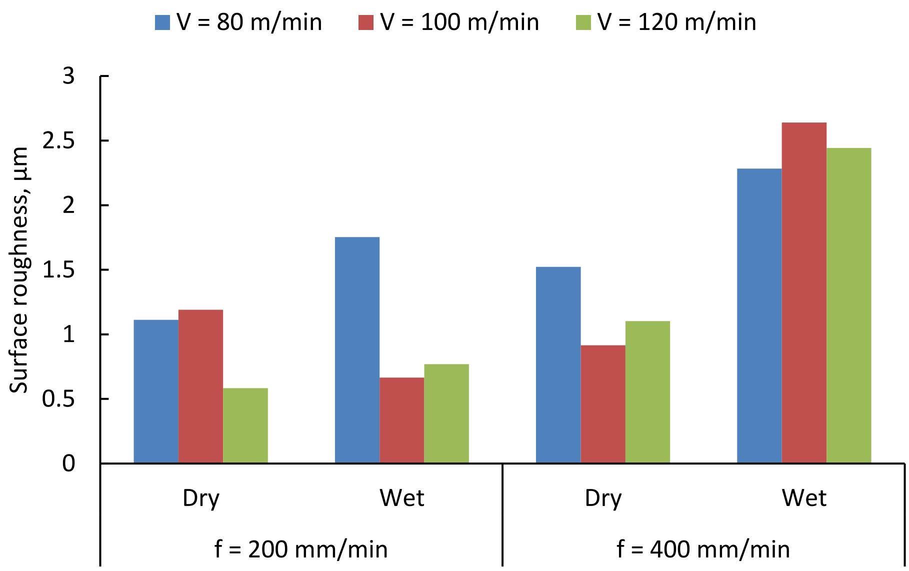

Figure 3: Surface roughness for 4 flutes.

In general, cutting at low speed (80 m/min) produces higher surface roughness because of less softening effect during material deformation and possible tool vibrations. Surface imperfections are reduced when the cutting speed rises to 100 m/min and then to 120 m/min because faster speeds result in smoother material shearing and shorter tool-workpiece contact times. Feed rate also significantly impacts surface quality. A lower feed rate of 200 mm/min gradually removes the material, resulting in a smoother finish due to fewer tool marks. On the other hand, a greater feed rate of 400 mm/min results in more noticeable tool marks and possible vibrations, which raises surface roughness.

Figure 4 analyzes the surface roughness performance between 2 and 4 flutes. At a low feed rate (200 mm/min), 2 flutes demonstrated superior surface roughness for all cutting speeds. Low flute number provides a larger flute space for efficient chip evacuation, especially when cutting soft materials like PTFE. This reduces the chance of chips being recut or compressed against the workpiece, which can damage the surface. High flute numbers with smaller flute spaces cause less effectiveness at evacuating the long, continuous chips produced by PTFE. Poor chip removal can lead to chip clogging, rubbing, or material smearing, increasing surface roughness. In a 2-flute end mill, each flute handles a higher chip load at a given feed rate, which is suitable for soft materials like PTFE. This promotes effective cutting and reduces rubbing. In contrast, a 4-flute end mill at the same feed rate would distribute the chip load across more cutting edges, potentially leading to rubbing rather than cutting, which deteriorates the surface quality. However, at a high feed rate (400 mm/min), the 2-flute end mill depicted higher surface roughness as compared to the 4-flute end mill. This is because having only two cutting edges results in a higher chip load per tooth at a given feed rate. This can cause larger chip formation, more aggressive cutting, and possibly the tearing of PTFE, resulting in a rougher surface. The lower number of cutting edges means fewer interactions with the workpiece per revolution. At high feed rates, this can create larger uncut material between passes, leading to a less smooth surface. The higher chip load at high feed rates can cause the PTFE to smear rather than be cleanly cut, especially if the tool is unable to evacuate the chips efficiently.

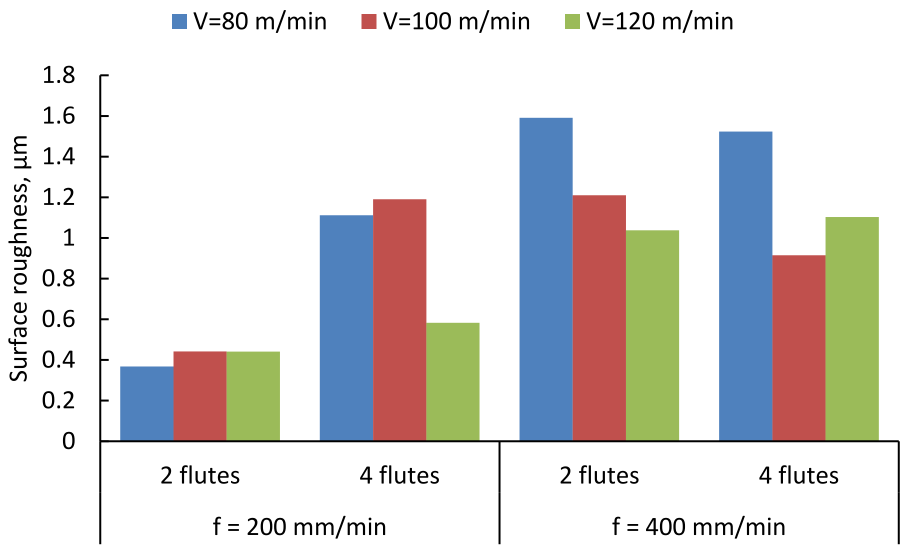

Figure 4: Surface roughness for dry condition at different flute numbers.

3.2 Chip morphology

PTFE has special properties when it comes to chip formation in milling because of its ductility, low melting point, and non-adhesive surface. The chip morphology after dry and wet milling PTFE for different cutting speeds and feed rates is shown in Figures 5 and 6. All chip shapes in dry conditions have the same characteristics, whether they are 2-flutes or 4-flutes, which are short and discontinuous. This can be explained by PTFE's low-friction and self-lubricating properties [10]. Thus, it reduces the tendency of chips to adhere to each other or the tool. This natural property enhances the likelihood of chip separation in dry conditions. The smearing effect is avoided in dry cutting as it happens in wet conditions when chips remain intact due to lubrication. Without the coolant, chips are more likely to detach cleanly from the workpiece, resulting in shorter chips. In addition, PTFE has poor thermal conductivity [6], so the heat generated during dry cutting is concentrated near the cutting zone. This localized heat weakens the material close to the cutting edge, causing chips to break into smaller pieces. However, only at a cutting speed of 100 m/min during dry milling with 4 flutes produced continuous and long chips at the feed rates of 200 mm/min, as shown in Figure 5. Cutting in wet condition produced needle chips both for 2-flutes and 4-flutes. The observed chip morphology in 2 and 4-flute wet conditions is characterized by tiny, irregular, and curled, which reflects the interaction between the tool geometry, cutting parameters, and coolant application. The chips tend to tangle each other due to a viscous environment, slowing down the chip movement and causing overlapping or bunching of chips. In wet conditions, the coolant can act as a cushion, thus preventing chips from curling and breaking. Given that PTFE is a thermoplastic polymer characterized by its high toughness, the chips produced tend to resist breaking, leading to an accumulation of chips [7].

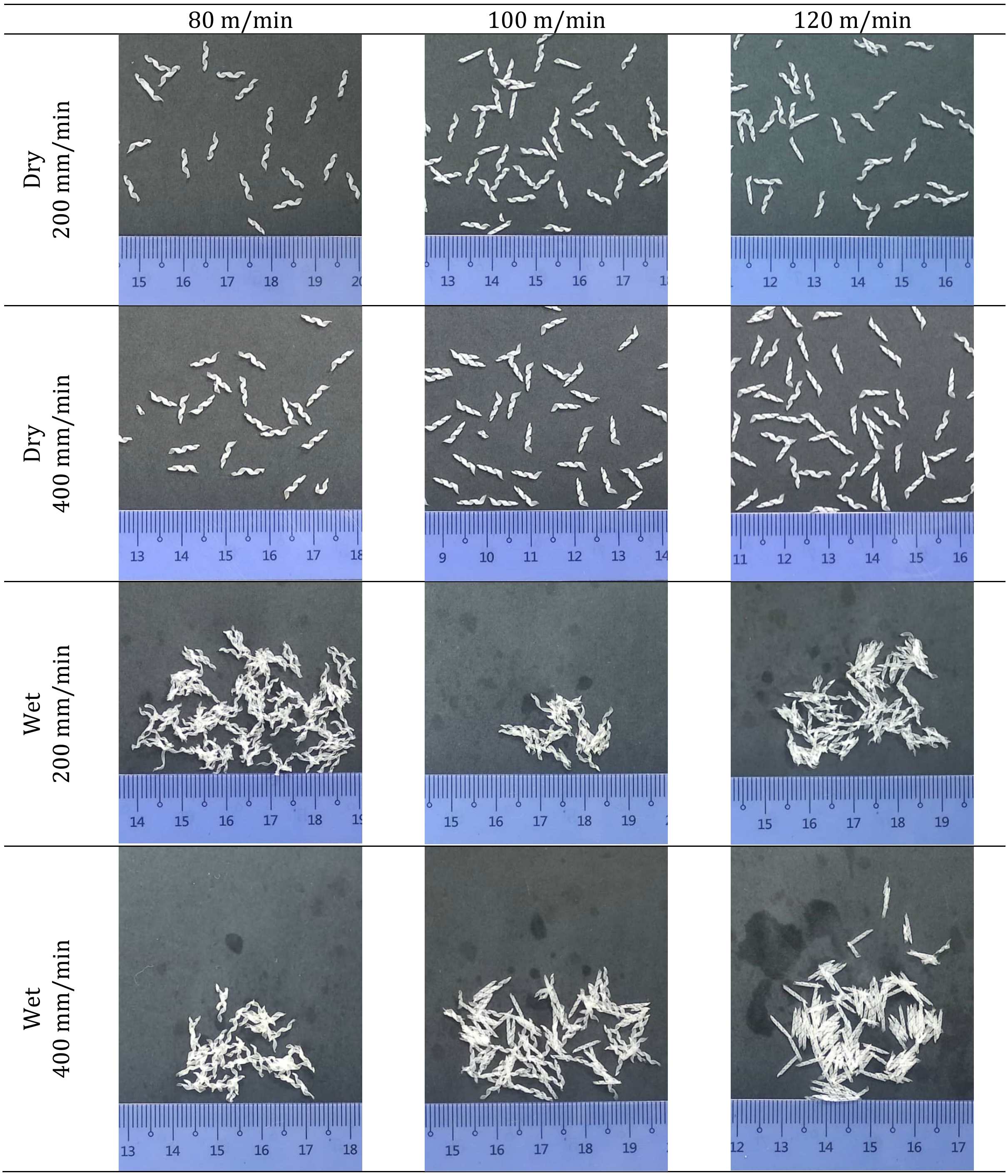

Figure 4: Chip formation for 2 flutes.

The accumulation of chips leads to an increase in cutting heat within the workpiece. In comparison to tools with more flutes, the 2-flute tool usually offers less cutting-edge engagement in each revolution, which might result in less heat generation and efficient chip evacuation in wet conditions. The significantly straighter chip morphology may be explained by the enhanced thermal effects and plastic deformation caused by the greater cutting speed of 120 m/min as opposed to the earlier scenario of 100 m/min. Chip segmentation results from the high cutting pressures caused by the high feed rate (400 mm/min).

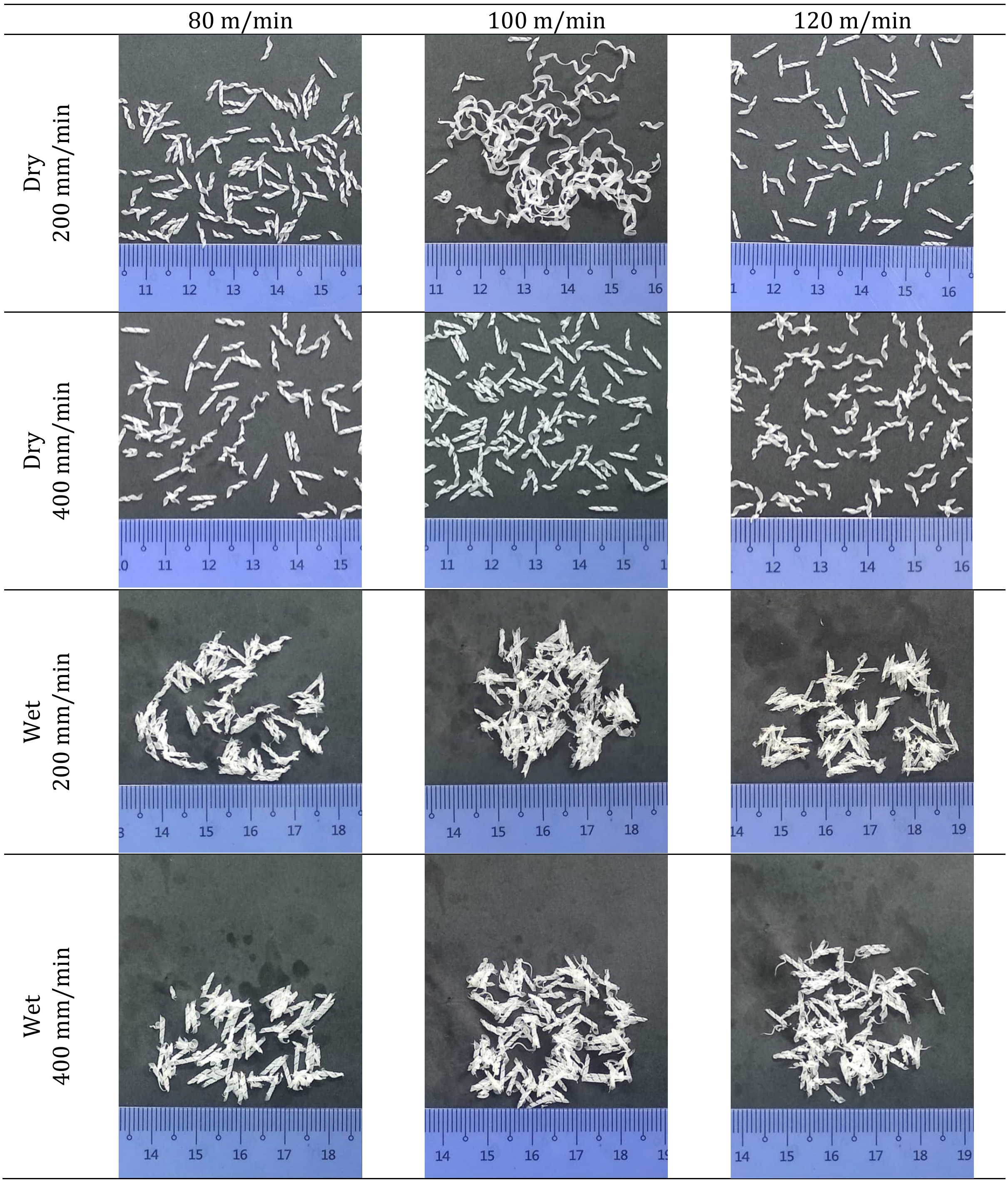

Figure 5: Chip formation for 4 flutes.

4. CONCLUSION

The milling experiment of PTFE was conducted in both dry and wet conditions in this study. The study concludes that the 2-flute end mill consistently outperformed the 4-flute tool in attaining reduced surface roughness during PTFE milling. Dry cutting conditions generally produce smoother surfaces compared to wet conditions due to PTFE's self-lubricating properties. Higher cutting velocities and lower feed rates resulted in superior surface finishes by reducing tool marks and facilitating finer material shearing. Conversely, higher feed rates increased surface roughness because of more pronounced tool marks and potential vibrations. PTFE's self-lubricating nature also influenced chip morphology, resulting in short, discontinuous chips during dry cutting and tangled, needle-like chips in wet conditions due to coolant interference. These findings emphasize the importance of selecting appropriate cutting tools and parameters to optimize surface quality and chip management in PTFE machining.

ACKNOWLEDGEMENTS

The authors would like to express sincere gratitude for the assistance provided by colleagues and technical experts and the support from the Faculty of Mechanical Engineering & Technology, Universiti Malaysia Perlis (UniMAP).

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Conflict of interest statement: The authors declare no conflict of interest.

Author contributions statement: Conceptualization & data collection, Mohamad Akmal Alif Bin Ismail**;** Supervision, Writing – Review & Editing, Muhammad Syamil Zakaria; Methodology design, Mohd Uzair Mohd Rosli and Masniezam Ahmad.