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# Influence of Drilling Parameters on Temperature and Hole Roundness in PTFE Machining

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## ABSTRACT

*This study examines the influence of drilling parameters and techniques on the machining performance of polytetrafluoroethylene (PTFE), a polymer known for its low friction, high chemical resistance, and thermal sensitivity. PTFE's low thermal conductivity and high deformability often lead to dimensional inaccuracy, burr formation, and heat-induced defects during drilling. To address these challenges, the effects of spindle speed, feed rate, and drilling methods (straight, peck, and dwell) were investigated using an 8 mm HSS drill bit under controlled dry-machining conditions. Temperature distribution along the drilling path was monitored using dual K-type thermocouples positioned at entry and exit points, while an optical microscope was used to evaluate hole roundness. This study presents an analysis and strategic optimization of drilling parameters for PTFE to resolve conflicting performance objectives between geometric accuracy and thermal stability. Using Signal-to-Noise ratio analysis, the most critical quality characteristic, hole roundness, was found to demand a high spindle speed to ensure stable cutting conditions. This requirement imposes a significant thermal penalty, as high spindle speed is simultaneously the least optimal setting for minimizing both Entry and Exit temperatures. The final process configuration addresses this trade-off by selecting parameters that maximize thermal mitigation: a high feed rate is chosen to reduce the time-in-cut and dissipate heat efficiently, and the Dwell technique is implemented. The Dwell technique is identified as the optimal thermal moderator, as it provides robust hole roundness while simultaneously maximizing the SN ratio to minimize the critical Exit Temperature. This strategic compromise effectively achieves the primary objective of superior geometric tolerance while preventing catastrophic material failure caused by thermal degradation at the hole exit.*

**Keywords:** Drilling Parameter Optimization, PTFE Machining Challenges, Hole Roundness Accuracy, Temperature Sensitivity in Polymers.

## 1. INTRODUCTION

Polytetrafluoroethylene (PTFE) has exceptional properties, such as low friction, chemical resistance, and thermal stability, which make it a vital material in industries like medical devices, electronics, and aerospace, where precision is critical [1]. Drilling PTFE presents unique challenges due to its low thermal conductivity, soft texture, and slippery nature [2]. These characteristics often result in issues like burr formation and dimensional instability, particularly under dry machining conditions [3][4].

In particular, the spindle speed affects the perpendicular forces acting on the workpiece during drilling, whereas the feed rate influences the torque. Higher spindle speeds combined with lower feed rates have been found to produce better results and reduce the cutting forces [4].

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Furthermore, due to its inherent material properties, effective thermal management remains a challenge and must be incorporated into PTFE drilling. As PTFE is easily deformable compared to most metals and has a low melting point, heat control during the drilling process must be carefully managed. Additionally, studies on drilling PTFE highlight the importance of cutting parameters like spindle speed and feed rate in influencing thrust and torque, with higher spindle speeds and lower feed rates proving beneficial for drilling performance and quality [4]. A critical process during PTFE drilling is temperature management. One of the vital techniques is conditioning the production board, which must be cooled to below 40 degrees Celsius for 30 to 40 minutes before drilling. This cooling process has been observed to have a significant impact on the drill bit's functionality, as it optimizes cutting. By making the PTFE substrate cooler, it becomes more dimensionally stable and less prone to melting during drilling, which is problematic with PTFE due to it low melting point. The drilling of PTFE is sensitive to cutting parameters, particularly spindle speed and feed rate. This research has shown that high spindle speeds, coupled with low feed rates, are effective in producing enhanced drilling results and improved hole roundness. In the context of drilling polymers, hole roundness is a geometric tolerance defined as the radial difference between the maximum inscribed circle and the minimum circumscribed circle that can be fitted within the hole's boundary. This parameter quantifies the deviation of the drilled hole’s cross-sectional profile from a perfect circle, where a smaller value indicates greater circularity and dimensional accuracy [5].

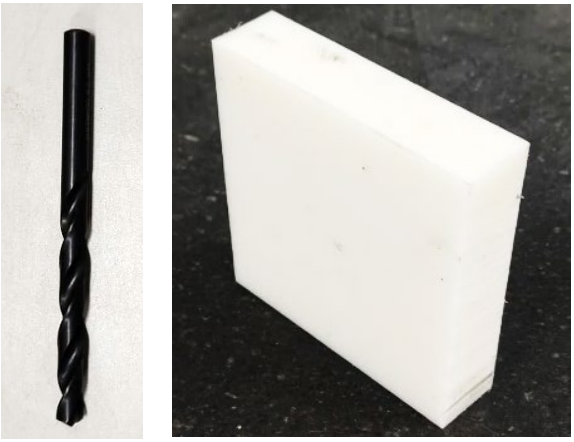
Hole roundness is an important feature in machining operations, as it influences component performance, functionality, and quality. Achieving great precision in hole roundness is especially crucial in areas like aerospace, automotive, and precision manufacturing, where tight tolerances and dependability are required. The research focuses on investigating significant drilling parameters and techniques for hole roundness and hole temperature to improve hole roundness, minimize heat generation, and enhance efficiency in PTFE machining. Key factors, such as spindle speed, feed rate, and drilling methods (straight, dwell, and peck), are analyzed through systematic experiments. Thermal behavior and geometric precision are evaluated to identify their influence on machining performance. PTFE's low thermal conductivity and unique properties make heat buildup and dimensional accuracy significant challenges. By addressing these issues, the study aims to refine drilling processes to ensure high-quality, precise, and reliable PTFE components. These improvements are particularly valuable for industries such as medical devices, electronics, and aerospace, where PTFE’s exceptional properties are critical for performance and safety. The findings provide practical insights into drilling PTFE, contributing to better efficiency, accuracy, and component reliability across various applications.

## 2. MATERIAL AND METHODS

### 2.1 Experimental setup

Drilling experiments were conducted on polytetrafluoroethylene (PTFE) workpieces measuring 60 mm × 65 mm × 25 mm. The drilling operations were performed using an 8 mm-diameter High-Speed Steel (HSS) twist drill, as shown in Figure 1. All machining tests were carried out on a 3 Axis YORNEW CNC machine to ensure consistent cutting parameters and precise feed control. Prior to drilling, the PTFE specimens were securely clamped on the machine table to minimize vibration and movement during operation. The drilling process was performed under dry conditions at room temperature, and all machining parameters were carefully controlled to evaluate the drilling performance of the HSS tool on PTFE. Dimensional accuracy and surface quality of the drilled holes were subsequently examined to assess the influence of drilling conditions.

An 8mm High-Speed Steel (HSS) drill bit, as shown in Figure 1, is used. HSS is known for maintaining cutting performance at high temperatures and is suitable for general-purpose machining of materials like steel, aluminum, and plastics.



(a) (b)

**Figure 1**: (a) 8 mm HSS drill bit (b) PTFE block.

In this study, a K-type thermocouple was used to measure the temperature at the drill–workpiece interface during drilling. The thermocouple, known for its wide temperature range, accuracy, and fast response time, was strategically positioned to capture the thermal behavior throughout the drilling operation. As illustrated in Figure 2, thermocouples were embedded at both the entry (t1) and exit (t2) points of the drilled hole. The thermocouple at the entry side measured the initial temperature rise as the drill engaged with the workpiece surface, while the one at the exit side recorded the temperature as the drill broke through the material, where friction and heat accumulation often peak. The entry temperature represents the immediate area of contact between the revolving drill bit and the PTFE substance. This dual placement allowed for a comprehensive assessment of temperature distribution along the drilling path and provided insight into thermal gradients that may influence tool wear and workpiece quality. Additionally, an Xoptron X80 Series optical microscope was used to examine the drilled holes and evaluate their roundness. High-resolution images of the hole profiles were captured and analyzed to assess deviations from circularity, enabling precise evaluation of dimensional accuracy and surface integrity of the machined holes.

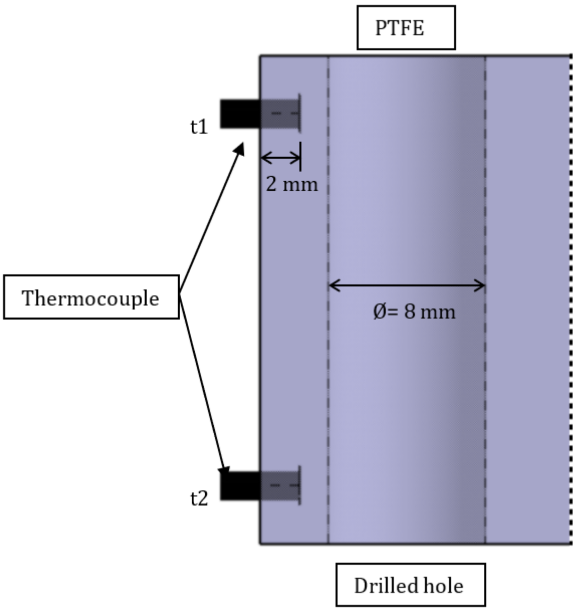


**Figure 2**: Temperature measurement configuration.

## 2.4 Cutting Parameter

This study examines process factors such as feed rate, spindle speed, and drilling techniques, specifically for the drilling experiment. The spindle speed ranges from 1500 to 2500 rpm, and feed rates range from 50 to 250 mm/min, with drilling methods including straight, peck, and dwell. The Taguchi method, utilizing orthogonal arrays, is employed to analyze the effects of these parameters. In this study, a smaller-is-better signal-to-noise (S/N) ratio is applied to temperature to minimize heat generation during drilling, while a larger-is-better S/N ratio is used for hole roundness to achieve improved dimensional accuracy. The experimental design was prepared using Minitab statistical software. Table 1 presents Taguchi's L9 orthogonal array, outlining the three cutting parameters (feed rate, spindle speed, and drilling technique) at three levels each.

**Table 1**: Cutting parameters and drilling techniques.

| No | Spindle Speed (rpm) | Feed Rate (mm/min) | Drilling Technique |
|---|---|---|---|
| 1 | 1500 | 50 | Straight |
| 2 | 1500 | 100 | Peck |
| 3 | 1500 | 150 | Dwell |
| 4 | 2000 | 50 | Peck |
| 5 | 2000 | 100 | Dwell |
| 6 | 2000 | 150 | Straight |
| 7 | 2500 | 50 | Dwell |
| 8 | 2500 | 100 | Straight |
| 9 | 2500 | 150 | Peck |

## 3. RESULTS AND DISCUSSION

The study on drilling PTFE aims to investigate temperature and hole roundness in machining operations, aiming to gauge the cutting interface and assess drilled holes. These parameters are crucial for defining machining characteristics and their use in high-precision applications. The analysis provides insight into changes in PTFE behavior due to drilling parameters, thermal and geometrical trends.

### 3.1 Temperature Result

Table 2 below displays the results of employing several drilling techniques, such as straight, dwell, and peck, as well as spindle speed and feed rate as parameters. As can be seen, the temperature at the entry point (t1) is always higher than the exit temperature (t2) for all cutting trials, regardless of the technique and cutting parameters. It is attributed to the position of t1, which is located closer to the tool shank than t2, leading to a more pronounced accumulation of chips at t1. This chip accumulation impedes the dissipation of cutting heat, thereby elevating the cutting temperature in the t1 region [4]. Furthermore, the increased chip buildup expands the contact area between the chip and the hole wall, enhancing frictional interactions and consequently generating additional frictional heat. As a result, the drilling temperature at t1 consistently exceeds that at t2, irrespective of the applied drilling parameters.

The drilling process in PTFE, as shown in Figure 3, involves two stages: S1 (entry phase) and S2 (exit phase). The entrance temperature rises during the S1 phase due to the drill bit's initial contact with the material, leading to friction and localized heating. The temperature production is mild and concentrated at the entry site. As drilling progresses, the drill bit becomes fully engaged with the PTFE, and temperature diffuses down the drill's length. The exit temperature rise is not as high as the entry temperature as the drill tip approaches the PTFE's exit side. In the S2 (exit phase), the drill tip completely leaves the PTFE material, leading to a dramatic drop in exit temperature and reducing the temperature rise.

**Table 2**: Temperature Result.

| No | Technique | Spindle Speed (rpm) | Feed rate (mm/min) | t1 Temperature (°C) | t2 Temperature (°C) |
|---|---|---|---|---|---|
| 1 | Straight Drill | 1500 | 50 | 71.20 | 42.12 |
| 2 | Peck Drill | 1500 | 100 | 48.72 | 43.02 |
| 3 | Dwell Drill | 1500 | 150 | 43.12 | 37.91 |
| 4 | Peck Drill | 2000 | 50 | 54.04 | 47.49 |
| 5 | Dwell Drill | 2000 | 100 | 46.29 | 34.32 |
| 6 | Straight Drill | 2000 | 150 | 47.12 | 43.02 |
| 7 | Dwell Drill | 2500 | 50 | 62.02 | 56.36 |
| 8 | Straight Drill | 2500 | 100 | 56.78 | 46.57 |
| 9 | Peck Drill | 2500 | 150 | 45.40 | 41.96 |

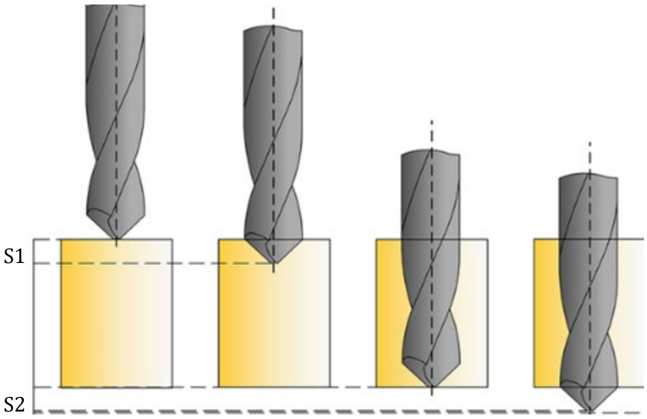


**Figure 3:** Drilling stage process.

Based on Table 2, the straight drilling technique at 1500 rpm and 50 mm/min feed rate recorded the highest entry temperature of 71.2°C. This technique involves the drill bit moving continuously through the material, generating heat from friction at the drill tip and causing the entry temperature to rise dramatically. The entry temperature is significantly higher than that of the other drilling technique. This discrepancy is due to localized heat generation at the drill-material interface and PTFE's insulating properties, which inhibit rapid heat dissipation to the surrounding material. In contrast, the exit temperature peaks at a lower amount because the heat created at the entry site takes time to move outside via the PTFE material. PTFE's poor thermal conductivity delays heat transfer, and when heat spreads, it dissipates across a wider volume, resulting in a smaller localized temperature increase.

The dwell drilling technique, with a spindle speed of 2500 rpm and a feed rate of 50 mm/min, achieves the highest exit temperature of 56.36°C among to techniques. This is due to PTFE's low thermal conductivity, which inhibits heat transfer from the drill tip to the surrounding material. The exit temperature rises gradually and eventually peaks at 56.36°C, influenced by residual heat transfer and the lack of quick-cooling methods at the entry. The material near the exit retains heat for a longer period due to the lack of quick-cooling methods at the entry. The dwell drilling technique adds localized heating at the drill-material interface, initially raising the entry temperature and eventually spreading outward, resulting in a progressive increase in the exit temperature. Despite heat transfer, the exit temperature peaks lower than the entry temperature due to heat loss during transport and heat distribution over a larger volume of material. These characteristics represent PTFE's insulating capabilities, which prevent rapid heat loss. The exit temperature behavior reveals the interactions among heat generation, transport, and retention in the material, providing valuable insights into the thermal dynamics of the dwell drilling process.

The main effects plot for S/N ratios in Figure 4 illustrates the influence of spindle speed, feed rate, and drill technique on the entry temperature during the drilling of PTFE. Based on a Taguchi experimental analysis with entry temperature during drilling as the response variable, the optimal parameters for minimizing and stabilizing heat generation during PTFE drilling are clearly identified. The spindle speed of 2000 rpm provides the ideal balance, reducing frictional heating more effectively than either lower or higher speeds. A higher feed rate of 150 mm/min significantly lowers entry temperature by minimizing rubbing and reducing the tool's contact time with the soft polymer. This trend agrees with results reported by [2], who observed that higher feed rates shorten tool–workpiece contact time, thereby minimizing heat generation and temperature rise in polymeric materials. Most critically, employing a peck drilling technique substantially enhances thermal control by allowing intermittent cooling and preventing continuous heat accumulation. Together, this combination of moderate spindle speed, high feed rate, and peck drilling ensures robust, low-temperature drilling essential for maintaining PTFE's structural integrity and achieving high-quality, dimensionally accurate holes. This behavior aligns with prior findings that PTFE’s low thermal conductivity restricts heat dissipation during drilling, and higher spindle speed promotes chip removal while reducing frictional heating at the cutting zone [6][2]. Regarding drill technique, the peck drilling method produces the lowest S/N ratio, followed closely by the dwell technique, while straight drilling yields the highest entry temperatures. The intermittent retraction of the tool in peck drilling enhances chip evacuation and allows partial cooling between drilling cycles, effectively reducing localized heat accumulation [7][8]. Overall, the combination of spindle speed = 2000 rpm, feed rate = 150 mm/min, and drill technique = Peck represents the optimal condition for minimizing entry temperature in PTFE drilling. These results are consistent with previous observations that efficient chip removal, reduced frictional heat, and proper thermal control are critical for achieving stable and low-temperature machining of PTFE [9].

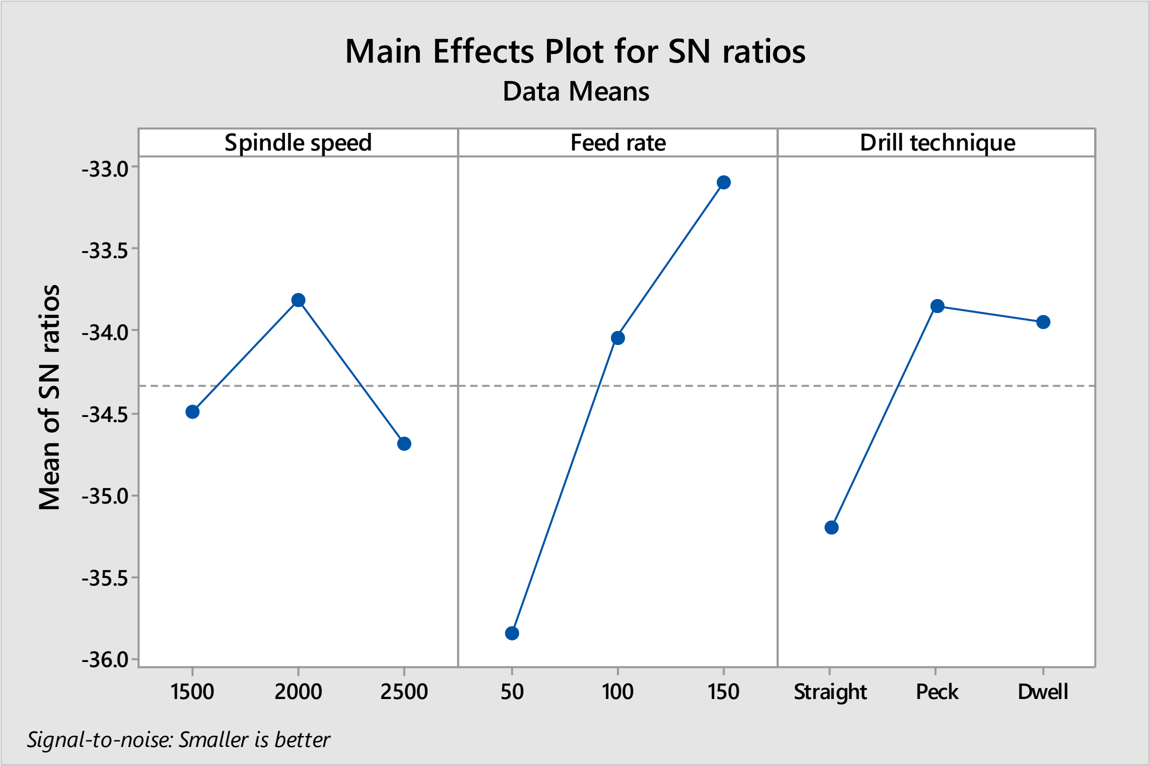


**Figure 4**: Main Effect of SN ratios for entry temperature.

The main effects plot for S/N ratios in Figure 5 depicts how spindle speed, feed rate, and drill technique affect the exit temperature during drilling of PTFE. Since the experiment follows the “smaller-the-better” criterion, a higher S/N ratio indicates a lower, more consistent exit temperature, which is desirable for improving thermal stability and dimensional accuracy. For spindle speed, the S/N ratio decreases sharply from 2000 rpm to 2500 rpm, indicating that higher spindle speeds lead to increased exit temperatures. This trend can be attributed to the greater frictional heat generated at elevated cutting speeds, which is insufficiently dissipated due to PTFE's extremely low thermal conductivity (≈ 0.25 W/m·K) [6]. At moderate speeds (1500–2000 rpm), the exit temperature remains lower and more stable, as the heat generation rate and conduction capacity are better balanced [2].

A clear trend is also observed in feed rate, where the S/N ratio rises markedly from 50 mm/min to 100 mm/min, then stabilizes at 150 mm/min. The lowest S/N ratio (i.e., the highest exit temperature) occurs at 50 mm/min, suggesting that low feed rates result in greater heat accumulation due to longer tool–material contact and frictional rubbing [8]. In contrast, higher feed rates (100–150 mm/min) minimize the cutting edge's residence time in contact with the polymer, reducing local thermal softening and enabling better chip removal. Regarding drill technique, the Dwell method yields the highest S/N ratio, followed by the Straight and Peck methods. This indicates that the Dwell approach generates the least exit temperature, likely due to the brief pause that allows partial heat dissipation before complete tool breakthrough. The Peck technique, while effective for chip evacuation, involves repeated tool retraction and re-engagement, which may increase friction and cause secondary heating at the exit region.

Overall, the analysis reveals that the optimal combination for minimizing exit temperature during PTFE drilling is spindle speed = 1500 rpm, feed rate = 100 mm/min, and drill technique = Dwell. These conditions promote balanced heat generation, efficient chip removal, and improved cooling near the tool exit, consistent with findings from prior polymer-machining studies.

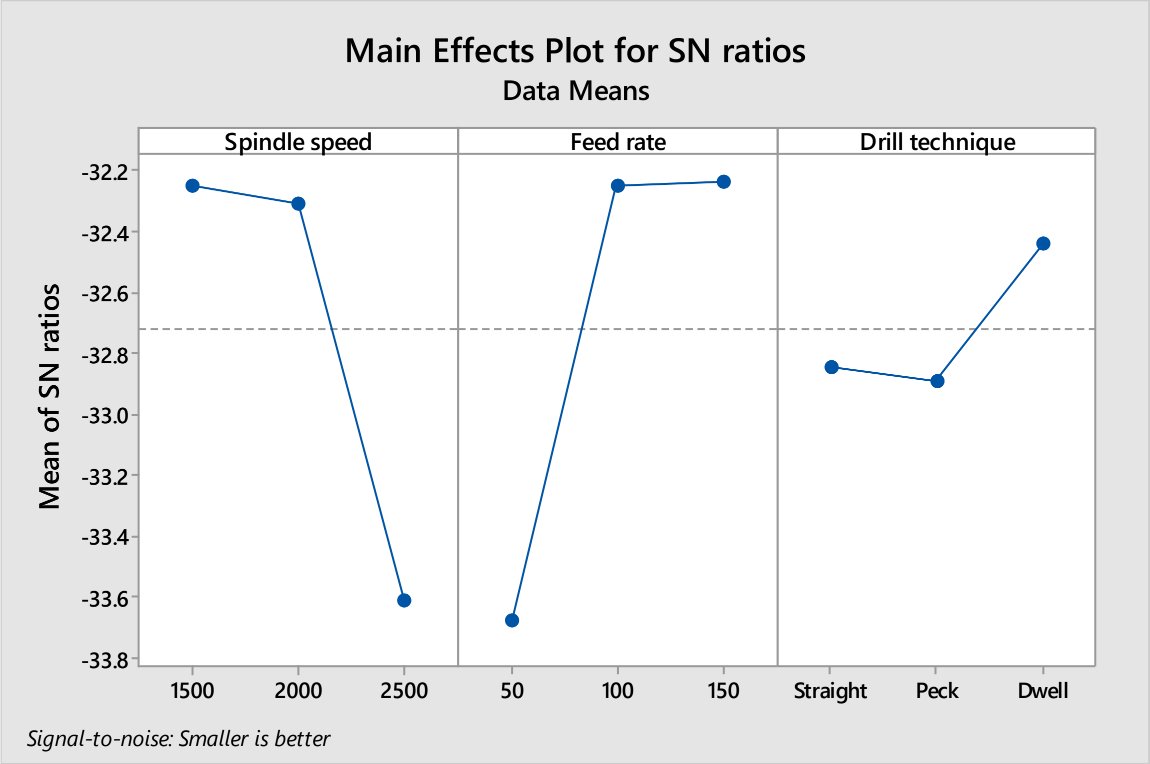


**Figure 5**: Main Effect of SN ratios for exit temperature.

### 3.2 Hole Roundness Analysis

An optical microscope was used to examine the hole's roundness and dimensions, which were supposed to be 8mm in diameter. The actual diameter diverged from the predicted value due to the creation of burrs during the drilling operation. Drilling technique, spindle speeds, and feed rates significantly impact burr development and drilled hole roundness as shown in Figure 6. The hole dimensions are shown in Table 3, which shows the quality of every combination of drilling parameters.

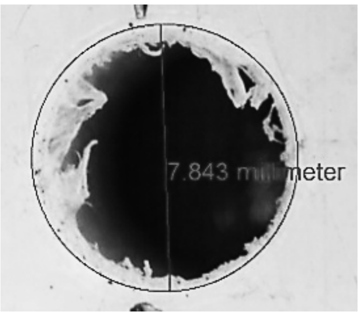


**Figure 6**: Burr formation at the drilled hole.

Straight drilling at 2500 rpm and 100 mm/min produces the best results, with a roundness value of 7.979 mm. This indicates a well-balanced spindle speed and feed rate, resulting in little material deformation and consistent cutting performance. Dwell drilling, which involves maintaining the drill stationary at the bottom of the hole, often yields superior hole roundness results [10, 11]. However, higher spindle speeds or slower feed rates can marginally reduce hole roundness. Straight drilling produces consistent results and works best with greater spindle speeds and moderate feed rates [12, 13]. The hole roundness value of 7.979 mm at 2500 rpm and 100 mm/min demonstrates the ability to achieve high precision under ideal conditions. Peck drilling typically reduces burr formation and ensures good hole roundness, although one result at 2000 rpm and 50 mm/min (7.389 mm) should be discarded due to a human error during clamping. Under other circumstances, peck drilling produces hole roundness values of 7.813 mm and 7.805 mm, respectively, which are close to the optimum diameter of 8 mm. In conclusion, the best hole roundness (7.979 mm) is achieved with straight drilling at 2500 rpm and 100 mm/min, underscoring the need for balanced machining settings.

**Table 3**: Hole Roundness Result.

| No | Technique | Spindle Speed (rpm) | Feed Rate (mm/min) | Result (mm) |
|---|---|---|---|---|
| 1 | Straight | 1500 | 50 | 7.806 |
| 2 | Peck | 1500 | 100 | 7.813 |
| 3 | Dwell | 1500 | 150 | 7.909 |
| 4 | Peck | 2000 | 50 | 7.389 |
| 5 | Dwell | 2000 | 100 | 7.840 |
| 6 | Straight | 2000 | 150 | 7.840 |
| 7 | Dwell | 2500 | 50 | 7.843 |
| 8 | Straight | 2500 | 100 | 7.979 |
| 9 | Peck | 2500 | 150 | 7.805 |

The main effects plot for S/N ratios (larger-is-better) in Figure 7 shows how spindle speed, feed rate, and drilling technique influence hole roundness during PTFE machining. Because PTFE is a soft, highly elastic polymer, excessive heat or tool deflection can cause deformation and lead to out-of-round holes [6]. The spindle speed trend indicates that hole roundness quality drops significantly at 2000 rpm, while both 1500 rpm and 2500 rpm provide higher S/N ratios. This suggests that mid-range speeds generate more heat and elastic recovery. In contrast, higher speeds promote cleaner shearing with less deformation, consistent with findings by Ni et al.[6]. The feed rate results show the lowest S/N ratio at 50 mm/min, meaning slower feeds worsen hole roundness due to longer tool–material contact and greater thermal softening. Improved hole roundness at 100 and 150 mm/min occurs because faster material removal reduces heat accumulation, an effect also reported in PTFE machining studies [2]. In drilling techniques, Peck drilling produces the poorest hole roundness, likely due to repeated re-entry of the tool, which causes vibration and instability. Straight and Dwell drilling yield higher S/N ratios, with Dwell drilling performing best by allowing heat dissipation and better chip clearance at breakthrough, aligning with observations in polymer drilling research [9]. In summary, the S/N ratio indicates that a 2500 rpm spindle speed, a 100 mm/min feed rate, and Dwell drilling technique provide the most stable and accurate hole roundness when drilling PTFE, as they minimize thermal distortion and tool deflection.

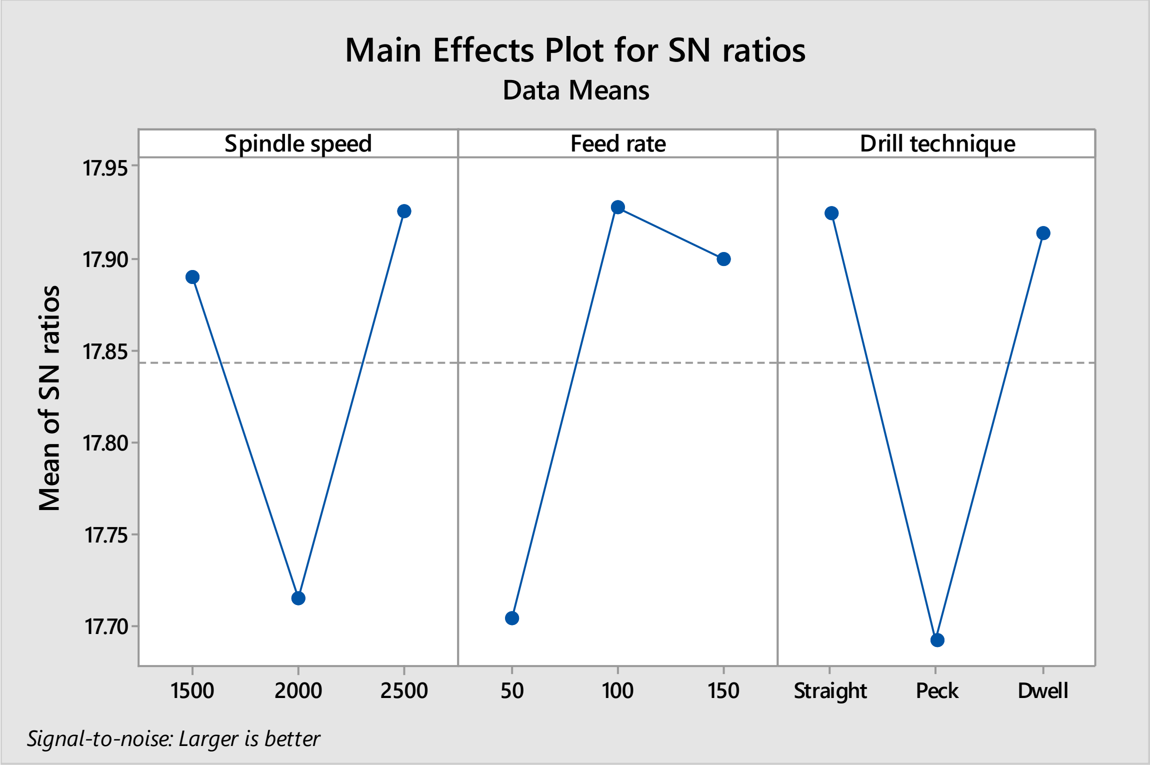


**Figure 7**: Main Effect for hole roundness.

The multi-objective optimization of the PTFE drilling process reveals a critical conflict governed by the material's thermo-mechanical properties and low thermal conductivity. Given that hole roundness is the designated critical quality characteristic, the parameter selection is driven by its corresponding optimal setting. To achieve the highest geometric fidelity and most robust performance (maximum Signal-to-Noise ratio for hole roundness), a high Spindle Speed of 2500 rpm is required, as this condition promotes stable cutting and minimizes tool-workpiece interaction time necessary for precise material removal.

However, this optimal hole-roundness setting creates an unavoidable trade-off with thermal performance: 2500 rpm is simultaneously the least optimal condition for minimizing both Entry Temperature and Exit Temperature. Running at this high speed dramatically increases frictional heat generation, resulting in a substantially elevated thermal load on the workpiece. Selecting 2500 rpm thus necessitates accepting thermal sub-optimality to achieve superior geometric accuracy. This trade-off is justified only under the strict condition that the resulting, higher Entry and Exit temperatures remain below the critical thermal degradation threshold of PTFE, thereby mitigating the risk of matrix softening, thermal expansion, and the subsequent loss of the very hole roundness that was prioritized.

## 4. CONCLUSION

In conclusion, this investigation demonstrates that PTFE machining is governed by a critical trade-off between achieving dimensional accuracy and managing thermal loading. Achieving the required geometric precision, particularly in hole roundness, requires a high spindle speed, which inherently generates frictional heat and elevates workpiece temperature. To mitigate this unavoidable thermal penalty, selecting an elevated feed rate and a specific drilling technique proved essential. These parameters act as thermal moderators by reducing the tool-workpiece contact time and facilitating heat dissipation. The resulting optimized process configuration effectively reconciles the competing objectives, ensuring superior hole quality without exceeding the polymer's thermal degradation threshold. This strategic parameter compromise offers a valuable framework for the precision machining of PTFE and other thermally sensitive, low-conductivity materials.

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**Author contributions statement:** Conceptualization, Syahmi Aiman Zaini and Muhammad Syamil Zakaria; Methodology, Syahmi Aiman Zaini and Mohd Uzair Mohd Rosli; Coding, Syahmi Aiman Zaini and Muhammad Syamil Zakaria; Validation, Syahmi Aiman Zaini; Machining Process, Syahmi Aiman Zaini; Investigation, Syahmi Aiman Zaini; Resources, Masniezam Ahmad; Data Curation, Syahmi Aiman Zaini, Mohd Hazwan Mohd Hanid and Muhamad Nur Misbah; Writing – Original Draft Preparation, Syahmi Aiman Zaini; Writing – Review & Editing, Syahmi Aiman Zaini and Muhammad Syamil Zakaria; Visualization, Syahmi Aiman Zaini; Supervision, Muhammad Syamil Zakaria; Project Administration, Syahmi Aiman Zaini.