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The Role of Tool Texture Design on the Chip Formation in PEEK Machining

Anna Bottin[1,a*], Rachele Bertolini[1,b], Haizea Gonzalez[2,c], Eneko Ukar[2,d] and Stefania Bruschi[1,e]

[1]Department of Industrial Engineering, University of Padova, via Venezia 1, 35131, Padova, Italy

[2]Department of Mechanical Engineering - CFAA, University of the Basque Country UPV/EHU, Pl. Torres Quevedo 1, 48013 Bilbao, Spain

[a]anna.bottin.1@phd.unipd.it, [b]rachele.bertolini@unipd.it, [c]haizea.gonzalez@ehu.eus, [d]eneko.ukar@ehu.eus, [e]stefania.bruschi@unipd.it

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Abstract. Biocompatible, chemical-resistant, and low-wear-rate materials are essential in biomedical applications to produce durable components that can withstand the conditions of the human body. PEEK is increasingly used due to its mechanical properties that are similar to those of human bones, making it a common material in orthopaedic prostheses. However, its low thermal conductivity, coupled with limited ductility, makes it difficult to machine. One of the main issues is the formation of continuous chips, which can reduce productivity and compromise final product quality. Innovative approaches, such as cryogenic machining and textured tools, have been recently studied to overcome this issue. Cryogenic machining can actively change the chip morphology from continuous, obtained in dry machining, to fragmented. On the other hand, textured tools can alter the chip flow, acting as chip breakers. This work examines how variations in texture design, specifically the distance of the texture from the cutting edge and the groove depth, may affect chip formation. To do that, turning trials were conducted under both dry and cryogenic cooling conditions using different textured tools. The results were assessed based on chip-tool contact length, chip dimensions, and morphology. Forces and temperatures were also acquired during the turning trials. The findings are that textured tools modify chip morphology in both dry and cryogenic conditions by altering chip flow on the insert. Deeper textures placed close to the cutting edge enhance chip breakability during cryogenic cooling and modify chip morphology in both machining environments.

Introduction

Prosthetic materials must exhibit biocompatibility, high chemical stability, and wear resistance to ensure safety in contact with human tissues, and sufficient mechanical strength to guarantee durability. In addition, their mechanical properties must be compatible with those of bones to avoid stress shielding and ensure proper load transfer [1]. Within the class of polymers that are potential candidates for biomedical use, polyetheretherketone (PEEK) has emerged as one of the most promising materials due to its resistance to degradation, biocompatibility, and human bone-like elastic modulus [2]. These characteristics make PEEK particularly suitable for dental implants and load-bearing implants such as orthopedic and spinal prostheses.

The machining of PEEK can provide high dimensional accuracy and customization for small batches or patient-specific parts, offering an alternative to injection molding. However, PEEK's low thermal conductivity and very ductile behavior make its machining challenging [3]. The accumulation of heat in the cutting zone can lead to thermal degradation, while its ductility promotes the formation of long, continuous chips that may entangle around the tool and damage the machined surface. Moreover, the use of conventional cutting fluids is not suitable for biomedical manufacturing because of contamination risks associated with flood coolants, which require time-consuming and costly cleaning steps to remove residues prior to sterilization.

To overcome these limitations, cryogenic cooling has been investigated as a sustainable strategy to improve polymer machinability [4]. The use of liquid nitrogen (LN_2) has been shown to reduce cutting temperature and suppress thermal softening, inducing a brittle response in PEEK [5]. Due to the different behavior of the material under cryogenic temperatures, the main effect of the LN2 was to obtain the chip breakage, transitioning from continuous to discontinuous chip formation.
Meanwhile, the use of innovative cutting tools has shown promising results in metal machining, where surface textures on the tool rake face can alter tool-chip contact, reduce friction, and improve chip flow. Surface texturing is a promising new technique for reducing or eliminating the need for cutting fluids [6]. As reported in [7], tool surface texturing can also affect chip formation mechanisms, promoting smoother chip flow and modifying chip morphology. In particular, grooves on the rake face have been shown to alter chip segmentation, leading to thinner, more regularly shaped chips than with conventional tools.
Similar benefits can be achieved in polymer machining, as reported in previous work by the authors [8]. It was demonstrated that texturing the rake face of the cutting tool improved chip fragmentation in cryogenic machining of PEEK, while also influencing chip formation and chip flow direction in dry machining. This can be seen as an improvement in polymer machining, and investigating the influence of texture design can enhance the effectiveness of the tool texture. However, the specific influence of texture design parameters on chip segmentation and flow under both dry and cryogenic conditions has not been systematically assessed. In fact, the efficacy of textured cutting tools depends on the texture design. Parameters such as texture width, spacing, depth, shape, orientation, and distance from the cutting edge must be optimized to achieve the intended benefits, such as reducing chip-tool contact, improving chip control, and enhancing heat dissipation [9].
In this framework, the present study aims to investigate further the influence of texture configuration on chip formation in PEEK machining, focusing specifically on the distance of the texture from the cutting edge and the groove depth. Turning trials were conducted under both dry and cryogenic conditions to identify the most effective design for promoting chip breakage.

Materials and Methods

Workpiece material**.** The material investigated in this study is a biomedical-grade PEEK, supplied by Ensinger Plastics with the commercial name of TECAPEEK™. Cylindrical bars of 42 mm diameter and 1000 mm length were provided in the annealed state, obtained by heat treatment at 221 °C for four hours to ensure thermal stability and minimize residual stresses. The thermal properties of PEEK were characterized using a DSC™ 200 system, with a controlled heating rate of 10 °C/min from 40 °C to 360 °C. The main thermal properties obtained were a glass transition temperature of 154 °C and a melting temperature of 344 °C. The degree of crystallinity was 24 %.
Tool texturing. Tungaloy™ VNMA 160402–330.5 TH10 uncoated turning inserts with a 0° rake angle were used for the turning trials. Laser texturing of the rake face was performed with a Trumpf™ TruMark 5050 nanosecond-pulsed laser system, using consistent parameters: mean power of 50 W, a scanning speed of 100 mm/s, a frequency of 6250 Hz, and a pulse duration of 250 ns. Based on previous results from the authors [8], which showed better performance for textures oriented perpendicular to the cutting edge, a constant 90° orientation with respect to the cutting edge was adopted. The main investigated parameter (see Fig. 1) was the distance of the texture from the cutting edge (D), which was varied to 70 µm, 100 µm, and 130 µm. Furthermore, two texture depths were investigated: 10 µm and 40 µm, obtained respectively with two (2p) and eight (8p) laser passes using a single track strategy. The selected groove depths provided two controlled levels of rake-face modification to compare their effects on chip formation without weakening the cutting edge. While a constant groove pitch (P) of 100 µm and a nominal groove width (G_w) and depth (G_d) of 40 µm were maintained. All the texture parameters are reported in Table 1.

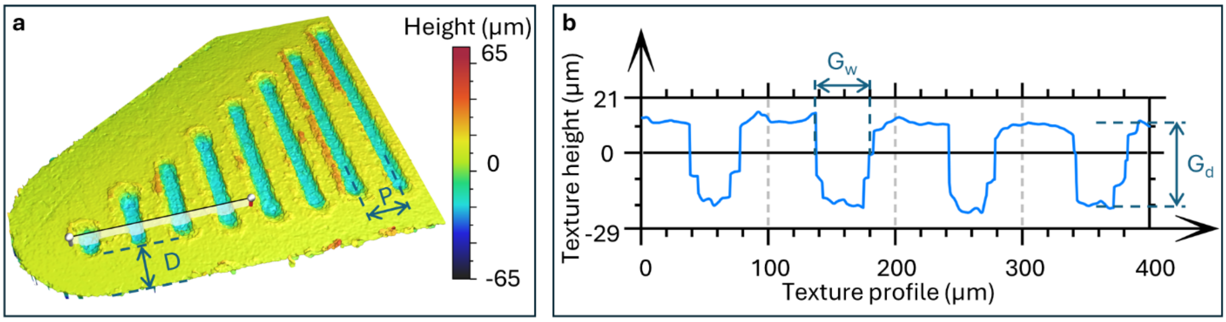

Fig.1. Textured tools. (a) 3D surface topographies of a tool showing the distance of the texture from the cutting edge and the pitch between grooves. (b) Texture profile (along the line in Fig. 1a) highlighting the groove width and depth.

Table 1. Tools nomenclature.

Tool design	Untextured	40-130	40-100	40-70	10-130	10-100	10-70
D (µm)	-	130	100	70	130	100	70
P (µm)	-	100	100	100	100	100	100
G_w (µm)	-	40	40	40	40	40	40
G_d (µm)	-	40	40	40	10	10	10

Turning experiments and post-machining analysis. The turning trials were conducted on a Mori Seiki™ NL 1500 CNC lathe using the textured inserts. Two machining environments were investigated: dry, the standard practice in machining polymers in biomedical applications, and cryogenic cooling, a sustainable alternative that enhances surface integrity while maintaining a contaminant-free surface. During cryogenic machining, liquid nitrogen (LN_2) was supplied from a 15 bar pressurized dewar and delivered to the cutting zone through two custom-designed copper nozzles, directed toward the tool rake and flank faces (see Fig. 2a and 2b).

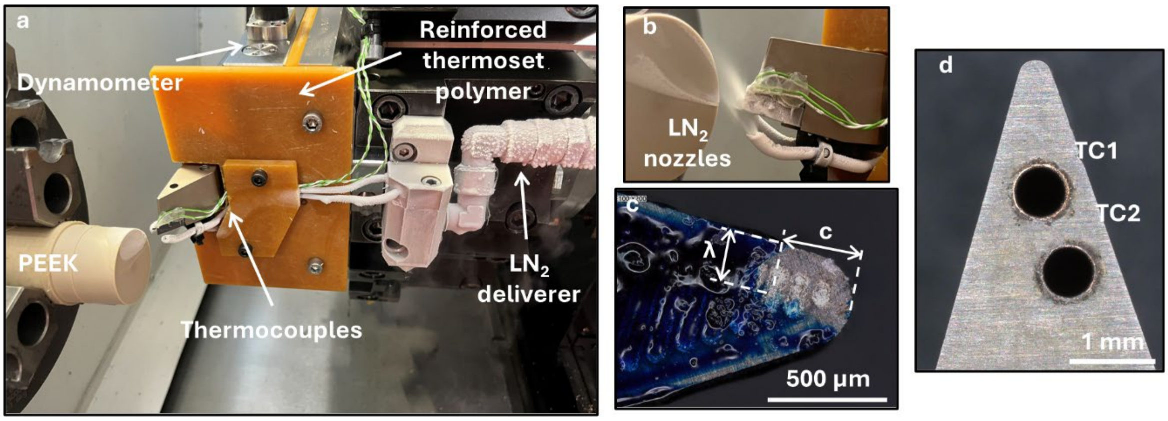

Fig. 2. (a) Set-up for the cryogenic cooling turning trials. (b) Customised nozzles for cryogenic delivery. (c) Tool-chip contact length and width measurements. (d) Thermocouple housing holes in the back of the insert.

The machining parameters shown in Table 2 were selected based on a previous study by the authors [10] to ensure a sufficiently high surface finish.

Table 2 . Machining parameters.

Cutting speed (m/min)	200
Depth of cut (mm)	0.5
Feed (mm/rev)	0.1
Sample length (mm)	5

To evaluate the tool-chip contact area, additional cutting tests were carried out under dry conditions, using the machining parameters listed in Table 2, but with a reduced cutting length of 0.5 mm. Before machining, each insert was pre-coated with a blue oil-based paint. The cutting action caused the coating to be removed in the contact area between the chip and the tool rake face, enabling measurements of the tool-chip contact length (λ) and width (c) imprints using a Keyence™ VHX-S770E/S750E optical microscope (see Fig. 2c).

After each trial, the produced chips were collected and analyzed using the optical microscope and a scanning electron microscope (SEM) FEI™ QUANTA 450. The analysis focused on overall morphology, specifically chip fragmentation and chip dimensions as width (W) and length (L), where applicable.

The cutting force, defined as the main tangential force component measured along the cutting speed direction, was measured using a Kistler™ type 9129AA three-component piezoelectric dynamometer and recorded with Dynoware™ software at a sampling rate of 2500 Hz. The signals were processed using a 12 Hz low-pass filter to obtain mean force values and standard deviations. To prevent cooling damage, a glass fibre reinforced thermoset polymer panel was used as an insulating layer between the tool holder and the dynamometer. To monitor temperature during machining, two K-type thermocouples, each 0.4 mm in diameter, were embedded in blind EDM-drilled holes near the cutting edge. The holes were spaced 0.75 mm apart and positioned 0.4 mm from the cutting edge, reaching approximately 0.2 mm from the rake face to ensure proximity to the cutting zone (see Fig. 2d). Temperature signals were acquired using a National Instruments™ NI 9211 module connected to a Compact-RIO 9035 controller and monitored in real time through the LabVIEW™ software at a sampling interval of 0.05 s.

Experimental Results

Chip morphology. The morphology of the produced chips depended on both the cooling strategy and the tool texture design. Two main chip types were identified: long, continuous chips, which tended to wrap around the workpiece or the tool, and short, discontinuous chips obtained under cryogenic conditions, regardless of the texture design. These results are consistent with previous findings and are due to low temperatures and high deformation rates, which suppress PEEK's viscoelastic response, promoting a stiffer and more brittle material behavior that facilitates chip breakage [11]. Although cryogenic cooling was the primary factor determining chip breakage, the introduction of surface textures also influenced chip formation in both machining environments, altering chip morphology and contributing to measurable changes in chip geometry.

The SEM images in Fig. 3 confirmed these differences. Under dry cutting, the chips exhibited a smooth, continuous surface with no visible signs of fracture. On the contrary, cryogenic chips, especially those produced with textured tools, exhibited more irregular surfaces. Even if the microscopic appearance of chips produced with the different textured tools was similar, specific features associated with the texture were visible. Texture marks (TM), which are imprints corresponding to the tool grooves, were visible on the back surface of chips produced in both cutting conditions, becoming more evident for deeper grooves and texture closer to the cutting edge. Serrations (S), which are fractures on the chip, appear on the free surfaces of cryogenic chips only when using a textured tool, indicating a local interaction between the chip and the groove that facilitated fragmentation.

The quantitative analysis of the chip length (L, in Fig. 3, available only for cryogenic chips) confirmed that tool texture reduced chip length compared to the untextured geometry. For the deepest texture, chip length decreased by 68%, 74%, and 85% for texture distances of 130 μm, 100 μm, and 70 μm from the cutting edge, respectively. The shallowest texture showed a similar trend, although with less pronounced reductions of 63%, 67%, and 71%.

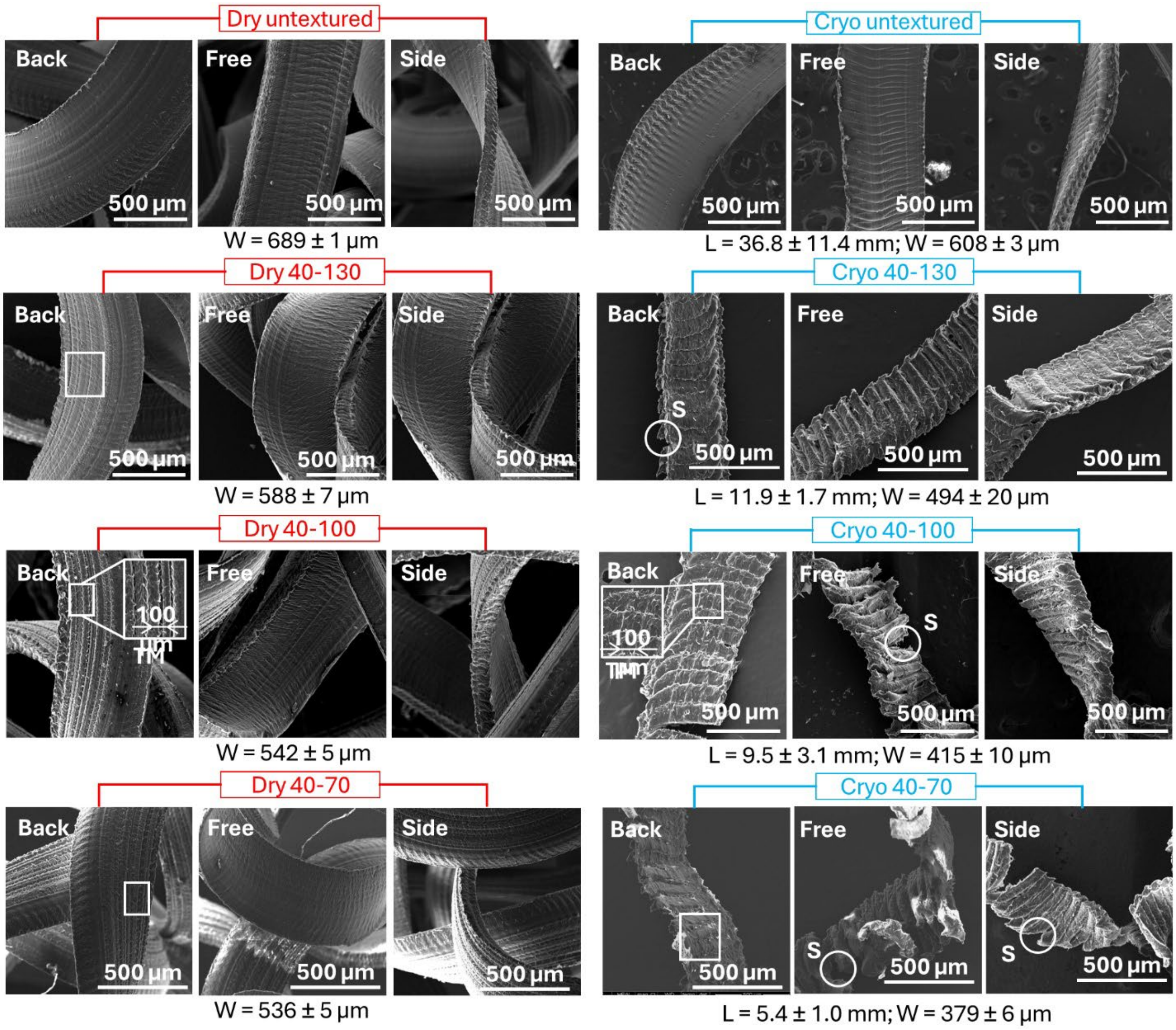

Fig. 3. Chip morphology under different cooling conditions using untextured and the deepest textured tools. Chip width (W) and chip length (L) are reported when applicable.

Another parameter showing a similar trend is the chip width (W, in Fig. 3). In both machining environments, the introduction of textures on the tool reduced the chip width compared to the untextured geometry. In dry machining, the deepest texture reduced the chip width by 15%, 21% and 24% decreasing the distance of the texture from the cutting edge. The shallowest followed the same trend, but with small reductions of 16%, 18%, and 19%. Under cryogenic cooling, this effect was amplified, reaching 19%, 32%, and 38% for the deepest texture compared to the untextured tool. The same also for the shallower textures, which reached 17%, 28%, and 29%.

Overall, these results show that the combination of deeper grooves and shorter distances from the cutting edge promotes effective chip control. Deeper grooves enhance chip-tool interaction and favor fragmentation, particularly when located closer to the cutting edge. This aligns with previous findings [12], which reported that when the textured zone is positioned nearer the cutting edge, the chip engages the micro-grooves earlier in its formation, promoting smoother chip flow. Moreover, as discussed in [13], deeper textures can promote the formation of micro air gaps between the chip and the tool surface, decreasing adhesion and altering the chip flow, whereas shallower textures maintain more continuous contact and have a reduced influence on chip segmentation. At the same time, the reduction in chip width can be associated with increased chip curvature, which, under cryogenic conditions, contributes to chip fragmentation. Although the chips produced in dry cutting remained continuous, the decrease in width suggests that the textured surface still influenced chip flow, even if insufficiently to promote complete fracture.

Chip-tool contact analysis. The results of the tool-chip contact area tests are summarized in Table 3, reporting the measured contact length and width under dry cutting conditions. In general, tool textures reduced the overall contact area compared to the untextured geometry. For the deepest texture, the contact length decreased progressively with decreasing the distance from the cutting edge, resulting in a reduction of about 26% for the texture closest to the cutting edge compared to the untextured insert. A similar trend was observed for the contact width, which decreased by 24% when using the tool texture with the lowest distance from the cutting edge. The shallowest texture produced smaller variations, with average reductions of about 18% and 10% in contact length and width, respectively, compared to the untextured tool.

Table 3. Chip-tool contact length and width.

Tool design	Contact length (µm)	Contact width (µm)
Untextured	276 ± 19	660 ± 24
40-130	261 ± 5	657 ± 12
40-100	225 ± 12	551 ± 15
40-70	205 ± 6	502 ± 10
10-130	228 ± 8	632 ± 6
10-100	226 ± 14	599 ± 17
10-70	224 ± 5	596 ± 12

This reduction in contact length when using textured tools is consistent with the shorter chip lengths and narrower widths observed, suggesting that an optimized texture geometry can effectively control tool-chip contact. Deeper textures positioned closer to the cutting edge reduce the effective contact area, likely because chips engage the micro-grooves earlier. This behavior is in line with previous findings [14], where a shorter chip-tool contact length was shown to reduce plastic deformation to a narrower region, leading to thinner and more easily segmented chips, thus improving chip breakability.

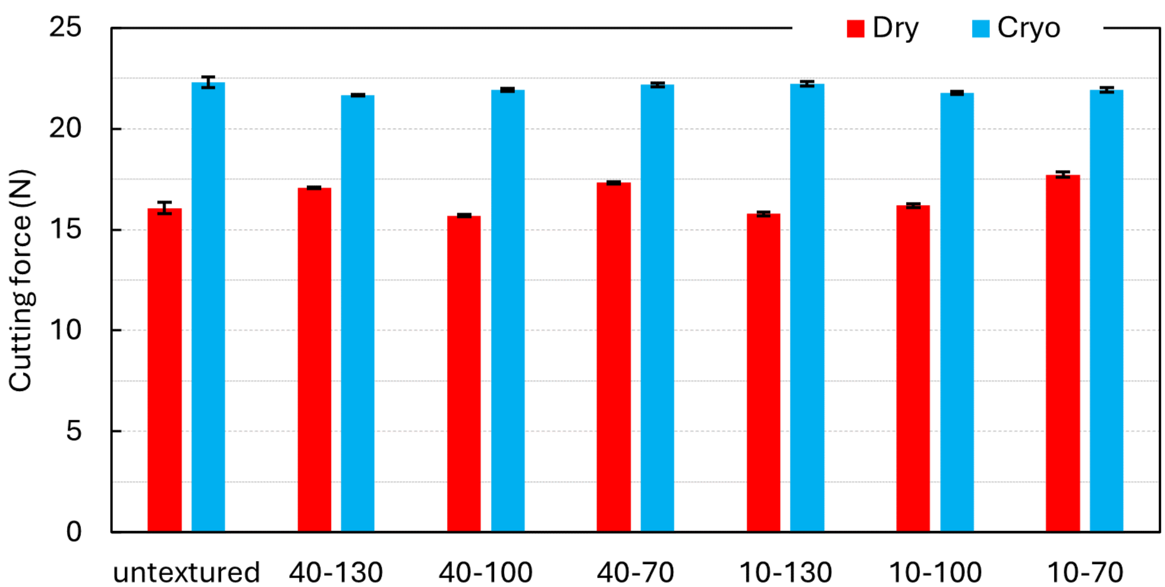

Fig. 4. Mean cutting force and relative standard deviation under dry and cryogenic machining with the various tool designs.

Force and temperature results. Fig. 4 presents the mean and standard deviation of the cutting force measured under dry and cryogenic machining with the various tool designs. As expected, the cryogenic condition resulted in higher cutting forces compared to dry cutting, with an average increase of approximately 35%. This increase aligns with the literature [15], which reports that PEEK becomes stiffer and more resistant to plastic deformation at cryogenic temperatures, requiring the tool to apply greater force to shear the material and, consequently, increasing the cutting force.

The influence of texture design on the cutting force was relatively limited. Compared to the untextured tool, the maximum variation across all textures remained within 10%. No clear correlation with either the texture depth or the distance from the cutting edge was observed. This limited variation is because the adhesive tool-chip contact zone, where the highest mechanical stresses develop, occupies approximately half of the total contact length [16]. Even when the texture is positioned close to the cutting edge, a significant portion of chip formation still occurs within this adhesive region, whereas the grooves primarily interact with the sliding portion of the contact, where forces are lower [17]. Despite the minimal changes in force magnitude, the use of textured tools generally reduced the variability of the cutting force signals, indicating a more stable cutting process. This trend is consistent with previous findings [18], which showed that textures interrupt continuous tool-chip contact, reducing the effective contact area and thus the friction coefficient and promoting chip segmentation, thereby producing a more stable cutting.

Fig. 5 presents the evolution and the average temperatures recorded by the two thermocouples (TC1, nearer to the cutting edge, and TC2, farther away) embedded in the insert. In dry machining, both sensors registered a temperature rise after the tool engagement, followed by a steady plateau (see Fig. 5a). As expected, TC1 measured higher values than TC2, confirming the presence of a thermal gradient across the insert.

Under dry conditions, for the untextured tool, the maximum temperatures measured by TC1 and TC2 were 53.0 ± 1.3 °C and 46.1 ± 2.6 °C, respectively (see Fig. 2b). The introduction of surface textures slightly lowered these values and reduced the temperature difference between the two thermocouples, suggesting a more uniform heat distribution along the rake face. This effect was most pronounced for the deepest texture positioned 70 µm from the cutting edge, where the temperature gradient between TC1 and TC2 decreased from about 7 °C to 1 °C. The shallowest textures produced smaller variations. Similar findings were reported in [19], where textured tools were shown to enhance heat transfer from the cutting zone by creating cavities on the rake face, promoting more efficient heat removal at the interface.

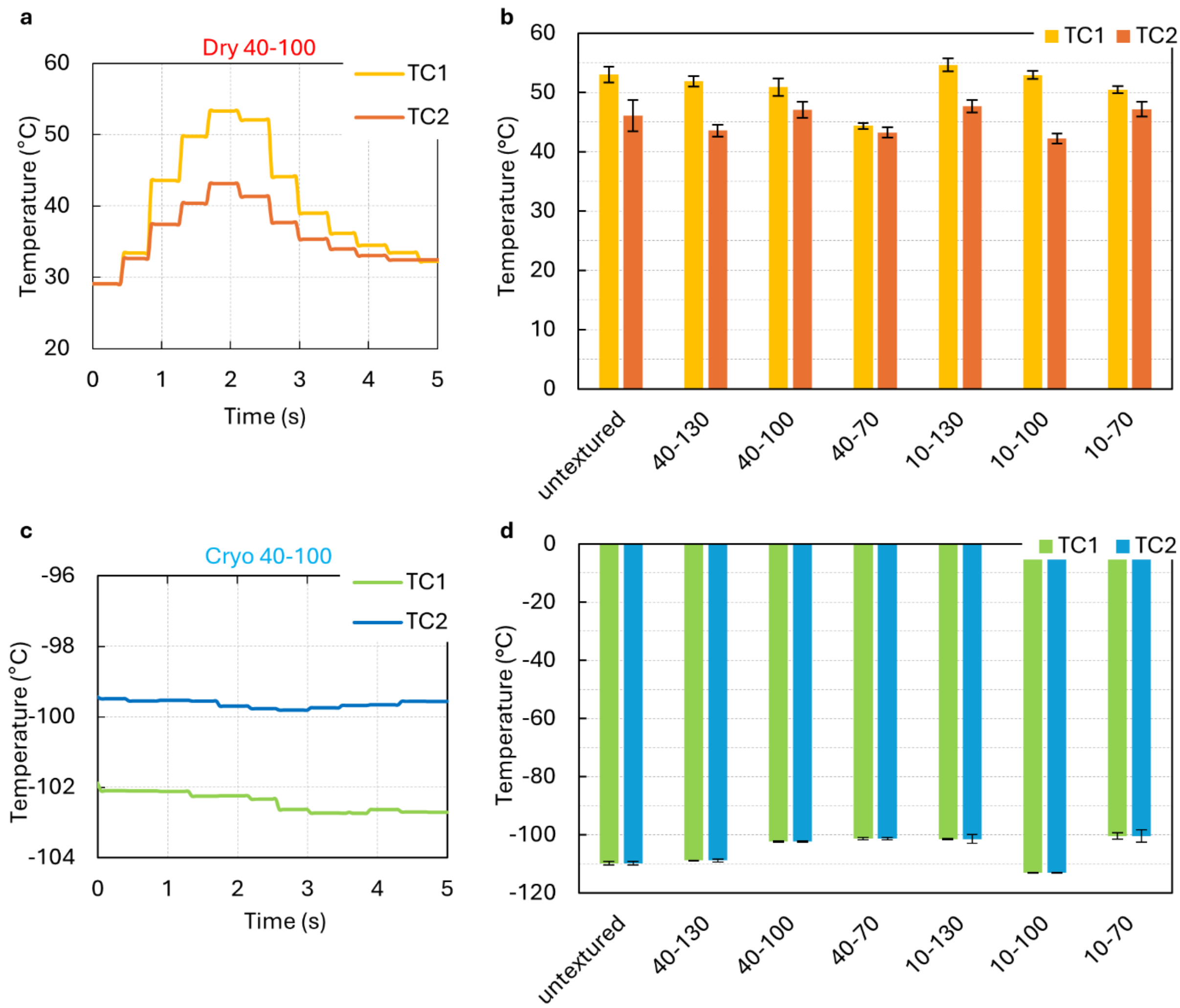

Fig. 5. Temperature evolution during cutting in (a) dry and (c) cryogenic machining for the insert 40-100. Mean temperatures and relative standard deviations under (b) dry and (d) cryogenic machining with the various tool designs.

As visible in Fig. 5c under cryogenic conditions, both thermocouples recorded nearly constant temperatures during cutting, with average values around -105 °C, confirming the dominant cooling effect. Variations under texture configurations remained below 10%, indicating that the influence of tool geometry on thermal behavior is negligible under liquid nitrogen cooling (see Fig. 5d).

Correlation between chip formation and contact conditions. The relationship between chip length and chip-tool contact length is shown in Fig. 6, which compares these parameters across the various tool designs. A general decreasing trend is observed as the texture is positioned closer to the cutting edge in both chip length and contact length, indicating that a shorter contact promotes earlier chip detachment and fragmentation.

With the deepest texture, reducing the distance from the cutting edge from 130 μm to 70 μm decreased the contact length by 20% and accordingly the chip length by 43%. The shallowest texture followed the same trend, though less pronounced, with average decreases of about 4% and 16%, respectively. Despite being obtained under different cutting conditions (dry for contact length and cryogenic for chip length), the two values show a consistent trend, with a correlation coefficient of R = 0.82.

These results can be supported by previous studies [20], which reported that both dry and cryogenic turning exhibited systematic variation in the tool-chip contact length with cutting parameters, with cryogenic cooling producing overall shorter contact lengths while maintaining the same trend. A similar behavior is expected when varying the texture geometry; although the absolute values differ, the same relationship between chip-tool contact reduction is observed.

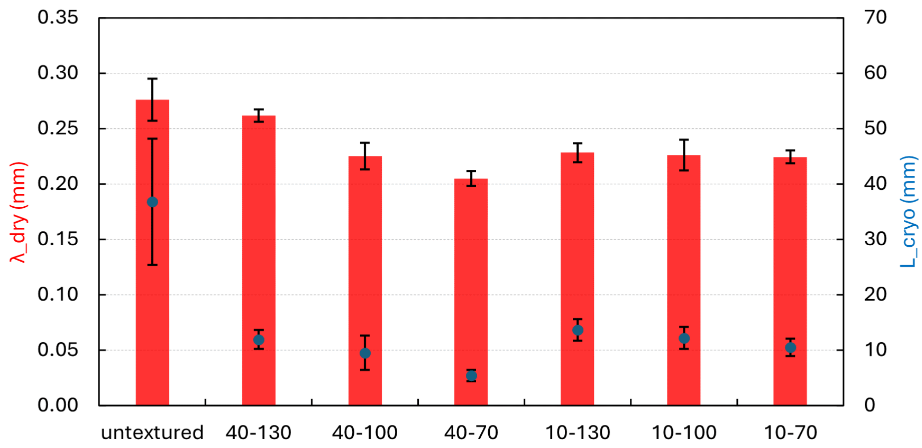

Fig. 6. Correlation between chip-tool contact length measured under dry cutting and chip length measured under cryogenic cutting.

Conclusions

This work investigated the influence of tool texture design on chip formation mechanisms, contact conditions, and thermal and mechanical responses during PEEK turning in dry and cryogenic conditions. Textured tools with different groove depths and distances from the cutting edge were compared. Based on the experimental analysis, the following main conclusions can be drawn:
Textured tools modified the chip morphology under both dry and cryogenic conditions. Furthermore, in cryogenic cooling, when the texture was positioned closer to the cutting edge, shorter chips were produced.

- The chip-tool contact length and width decreased with increasing texture depth and decreasing distance from the cutting edge, confirming the influence of texture geometry on chip formation.
- Cutting forces were not significantly affected by the texture design, although textured tools exhibited lower force variability, indicating a more stable cutting process.
- Tool textures reduced the temperature gradient within the insert under dry cutting, while no significant differences were observed under cryogenic cooling.

Overall, deeper textures positioned closer to the cutting edge were the most effective configuration. In dry machining, improving chip flow, while in cryogenic machining, promoting chip breakage while keeping the cutting forces unchanged. This confirms that an optimized texture geometry can enhance chip control in both environments.

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