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Investigation of surface finish and chip morphology in cryogenic machining biomedical grade polyetheretherketone

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Abstract. Polyetheretherketone (PEEK) is attracting the attention of the biomedical field, thanks to its high biocompatibility and wear resistance. Nevertheless, the attainment of good quality surfaces when machining PEEK is still challenging. In this framework, the aim of the paper is to investigate the viabilityof using cryogenic machining to enhance the surface finish of PEEK compared to the outcomes of dry cutting. To do that, turning trails were executed at varying cooling strategy and depth of cut, and the resultant surface finish and chip morphology were evaluated. The obtained results indicated that cryogenic machining carried out at the highest depth of cut greatly enhanced the PEEK machinability.

Introduction

Polyetheretherketone (PEEK) is a thermoplastic semi-crystalline polymer characterized by an elasticmodulus close to that of human bones, high biocompatibility, stable chemical resistance, and good wearresistance [1]. Thanks to these characteristics, PEEK has been used as a biomaterial in the biomedical area for orthopedic implants since 1987 [2] and is still assessed as one of the most promising polymers for biomedical applications. The conventional route to manufacture PEEK parts comprises machining steps carried out without any cutting fluid to avoid oil residues on the machined surface. Davim and Mata [3] performed dry turning trials on PEEK bars and studied the effect of PCD tool inserts at varying cuttingspeed and feed. They found that the cutting speed increase and feed decrease contributed to reduce the surface roughness. Abdullah et al. [4] dry-turned the biomedical grade PEEK using carbide tools and optimized the machining parameters, namely cutting speed, feed, and depth of cut to minimize the surfaceroughness. However, dry machining of PEEK is still challenging as the increase in temperature at the cutting zone usually prompts a drastic reduction of the surface quality. A reduced surface finish increasesfriction and accelerates polymer wear rate during the lifespan of the implant: an example is given by acetabular cups, which must be characterized by smooth surfaces when coupled with femoral heads to increase the hip implant performances [5].

To this extent, cryogenic machining can be seen as a possible alternative to dry cutting, which can effectively remove the cutting-generated heat, whilst still preserving the cleanliness of the machined surfaces.

Bertolini et al. [6] investigated the machinability of the polyamide 6 under cryogenic cooling conditions and showed smoother and harder surfaces compared to the ones obtained using a conventionalcutting fluid. Aldwell et al. [7] submerged ultra-high molecular weight polyethylene (UHMWPE) in liquid nitrogen for nearly 24 hours before machining: this process chain was found to lead to a stiffer surface compared to dry conditions. Dhokia et al. [8] froze ethylene-vinyl acetate using liquid nitrogen showing the polymer surface hardening, which, in turn, allowed a 1% dimensional error after machining.Putz et al. [9] studied the influence of cryogenic cooling on cutting forces and surface integrity of the nitrile-butadiene-rubber elastomer. It was found that, by using the cryogenic coolant, the cutting forceswere increased, but the surface deformation was reduced, promoting a better surface quality compared to that obtained under dry cutting conditions.

According to the literature survey, cryogenic machining of PEEK has been scarcely researched, in particular as regards the impact of the depth of cut on the polymer machinability. In this context, the paper investigates the effect of cryogenic cooling on the PEEK surface finish and the onset of surface defects in comparison with the outcomes from dry cutting. Further, the chip morphology was analyzed and correlated to the machined surface characteristics.

Experimental - Material

The polymer material under investigation was the TECAPEEK^{TM} supplied by Ensinger Plastics. Thisis a biomedical grade used specifically to fix spinal traumas, cruciate ligaments, and meniscal tears. Thematerial was purchased in form of a bar of 42 mm diameter. The PEEK mechanical and thermal properties in the as-received state are listed in Table 1.

Table 1. PEEK mechanical and thermal properties in the as-received state [10].

Property	PEEK
Modulus of elasticity (MPa)	4200
Tensile strength at yield (MPa)	116
Hardness ASTM D2240 (Shore D)	85
Glass transition temperature, T_g (°C)	150
Melting temperature, T_m (°C)	341
Density (g/cm^3)	1.31
Thermal conductivity (W/(k·m))	0.27
Specific heat (J/(g·K))	1.1

Machining Trials

The Mori Seiki^{TM} NL 1500 CNC lathe with the experimental apparatus shown in Fig. 1 (a) was usedto carry out the turning tests. A left-hand tool insert, namely the VCEX 11 03 01L-F 1125 purchased from Sandvik Coromant^{TM}, was used, see Table 2 for its nomenclature. The cutting speed (*Vc*) and feed (*f*) were selected on the basis of the tool manufacturer's guidelines and kept fixed for all the turning trials.On the contrary, it was chosen to vary the depth of cut (*ap*) to evaluate its impact on the PEEK machinability.

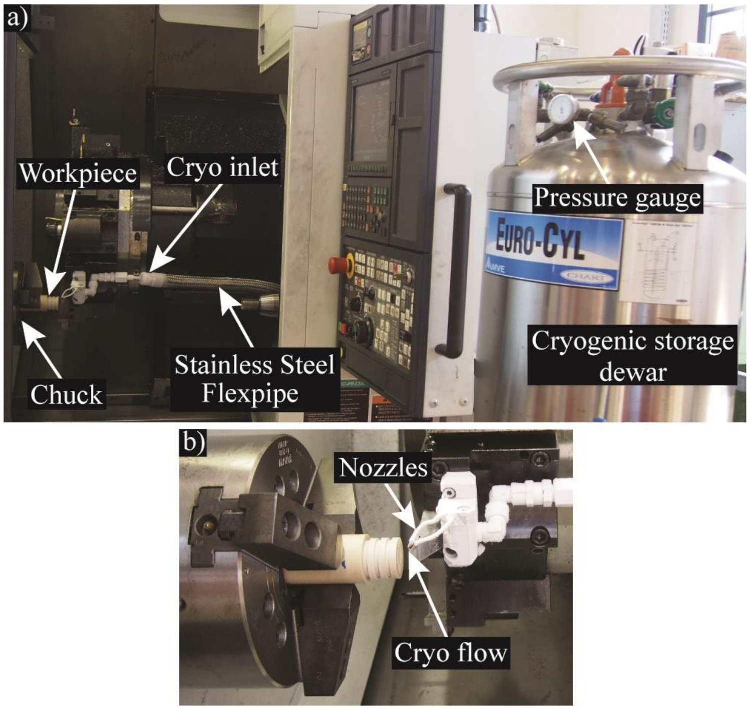

Fig. 1. (a) Machining setup; (b) Closer view of the cutting zone when applying cryogenic cooling.

Table 2. Cutting tool nomenclature and specifications.

ISO code	VCEX 11 03 01L-F 1125
Cutting edge effective length (mm)	10.971
Corner radius (mm)	0.1
Major cutting edge angle (°)	93
Insert thickness (mm)	3.175
Rake angle (°)	5.5
Clearance angle major (°)	7

At first, the external layer of the as-received PEEK bar was removed to eliminate any defect and dimensional error. On this basis, a turning step was performed to achieve a 40 mm diameter by using a cutting speed of 100 m/min, feed of 0.1 mm/rev, and depth of cut of 1 mm.

The turning tests were conducted under both dry and cryogenic cooling conditions with three repetitions for each experimental condition. The liquid nitrogen was stored in a Dewar tank at 15 bars. Two copper nozzles of 0.9 mm diameter were used to spray the liquid nitrogen to the tool flank and rakefaces simultaneously (see Fig. 1 (b)). In each experimental run, the approximate lead time for liquid nitrogen to stabilize was 30 seconds. Table 3 reports the experimental plan of the machining trails.

Table 3. Cutting parameters.

Cutting speed (m/min)	200
Feed (mm/rev)	0.1
Depth of cut (mm)	0.15, 0.25, 0.5
Cooling condition	Dry, Cryogenic
Liquid nitrogen mass flow rate (Kg/s)	0.0058
Length of cut (mm)	5

Surface Quality and Chip Morphology Characterization

The Sensofar PLu Neox^{TM} optical profiler with a 20x magnification Nikon^{TM} confocal objective wasused to analyze the machined surface finish. The scanned surfaces were then assessed using the SensoView^{TM} software.

According to the ISO 25178-2:2012 standard, the surface texture was evaluated in terms of surface roughness, namely the arithmetical mean height (*Sa*), reduced peak height (*Spk*), and reduced valley depth (*Svk*). These surface texture parameters were selected as indicative of the machining quality. According to [11], *Spk* can be related to the wear properties of a surface, while *Svk* to characteristics such as fluid retention properties. The *Spk*/*Svk* ratio was also evaluated to assess the distribution of valleys and peaks on the machined surface.

Scanning electron microscope (SEM) analysis was carried out using a FEI^{TM} QUANTA 450 to evaluate the possible presence of defects on the machined surfaces. To do such analysis, the samples were gold-sputtered with 25 mA for 3 minutes using the Denton Vacuum^{TM} Desk V machine.

After each turning trial, the chips were collected and analyzed using light optical microscope (LOM)and SEM with the aim of evaluating their morphology at varying cutting parameters. In addition, the cutting ratio (*r*) was calculated on the basis of Eq. 1:

$$r = \frac{t_0}{t_c} \tag{1}$$

where t_0 is the uncut chip thickness, equal to the feed, and t_c the chip thickness measured using LOM.

Results and Discussion

Surface texture of the machined samples.

Fig. 2 reports the average values of *Sa* along with their standard deviation bars as a function of the depth of cut and cooling strategy.

In the case of dry cutting, a clear trend cannot be identified since the surface roughness was improvedby varying *ap* from = 0.15 mm to = 0.25 mm, and later it was increased at *ap*=0.5 mm, On the contrary,when using the cryogenic cooling strategy, a strong reduction of the surface roughness was observed at increasing depth of cut. 25% and 36% decreases were found for *ap*=0.25 mm and *ap*=0.5 mm with respectto the lowest depth of cut, respectively. At the highest depth of cut, the section of the chip was increasedas well as its brittleness when deformed at lower temperatures. This made its breakage easier, as it will be later documented.

Regardless of the depth of cut, cryogenic cooling was effective in reducing the surface roughness compared to dry cutting. This is due to the fact that the cryogenic fluid cools down the polymer materialvery rapidly, reducing its elongation at rupture and, therefore, overall ductility.

On the contrary, in case of dry cutting, the much higher ductility induced by the higher cutting temperatures results in uneven surfaces, as the material is too easily deformed.

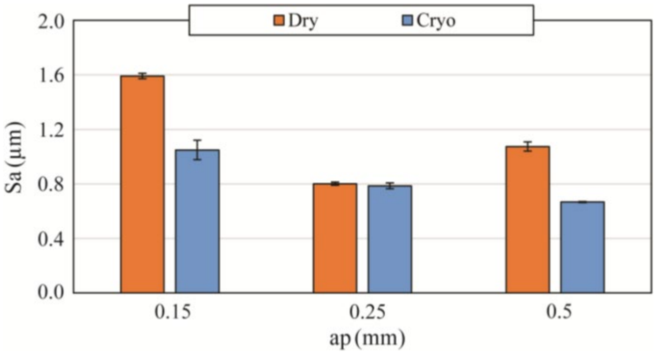

Fig. 2. Sa under dry and cryogenic cooling conditions as a function of the depth of cut.

Further, *Svk* and *Spk* values were analyzed and the results are reported in Fig. 3. For both the coolingstrategies, except at the highest depth of cut that induced both peaks and valleys almost characterized bythe same height, wider valleys and shallow peaks were produced compared to the lowest depth of cut. Both the height of the valleys and depths of the peaks were reduced at increasing depth of cut, regardlessof the cooling strategy. Specifically, the cryogenic strategy assured the heights of the peaks increased by37% and 6% for *ap*=0.15 mm and *ap*=0.25 mm compared to *ap*=0.5 mm, respectively. Similarly, the depths of the valleys increased by 271% and 124% for *ap*=0.15 mm and *ap*=0.25 mm compared to *ap*=0.5mm, respectively.

Cryogenic machining helped in reducing the height of the peaks and especially in increasing the depthof the valleys. The latter was increased by 35%, 12% and 7% at *ap*=0.15 mm, *ap*=0.25 mm, and *ap*=0.5mm compared to the dry cases, respectively.

Having a surface characterized by shallow peaks and deep valleys may help to increase the surface wear resistance as this kind of surface can assure both fluid accessibility and accumulation of the wear debris. In general, deep valleys function as fluid reservoirs to decrease friction and wear by reserving and supplying fluid to the bearing surfaces. Additionally, wear debris can accumulate within deep valleyfeatures. Consequently, abrasive wear produced by third-body wear particles can be reduced [12].

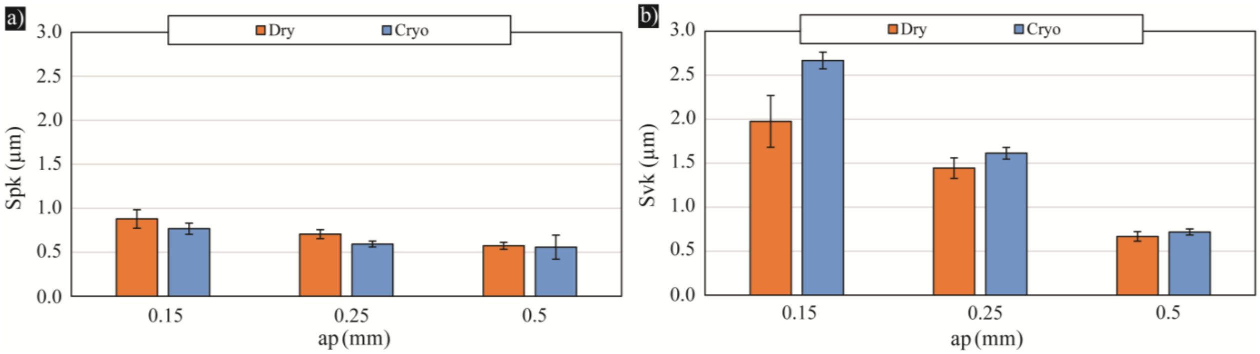

Fig. 3. Spk and Svk under dry and cryogenic cooling conditions as a function of the depth of cut.

The *Spk*/*Svk* ratio was calculated to understand the peculiar nature of the surface texture. In particularthis ratio refers to the average distributed ratio of the peaks and valleys on the machined surfaces. In all the investigated cases, the lowest depth of cut and the use of cryogenic cooling led to the *Spk*/*Svk* reduction, meaning that the surface is dominated by valleys, see Fig. 4.

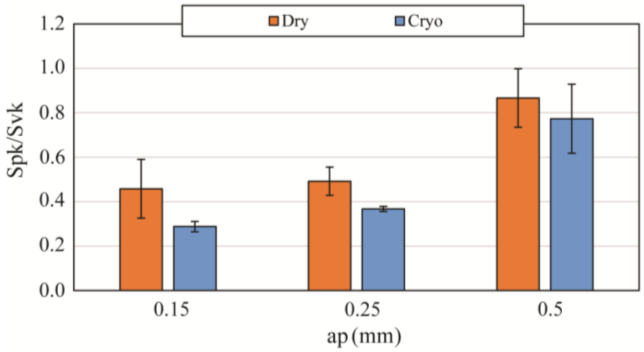

Fig. 4. Spk/Svk under dry and cryogenic cooling conditions as a function of the depth of cut.

The SEM images of the machined surfaces at varying depth of cut are given in Fig. 5. Regardless of the depth of cut, grooves adjacent to feed marks, flakes, and tearing caused by micro-peeling were observed in dry conditions. The highest density of defects was found at the lowest depth of cut, whereasthe lowest density of defects was at the intermediate depth of cut.

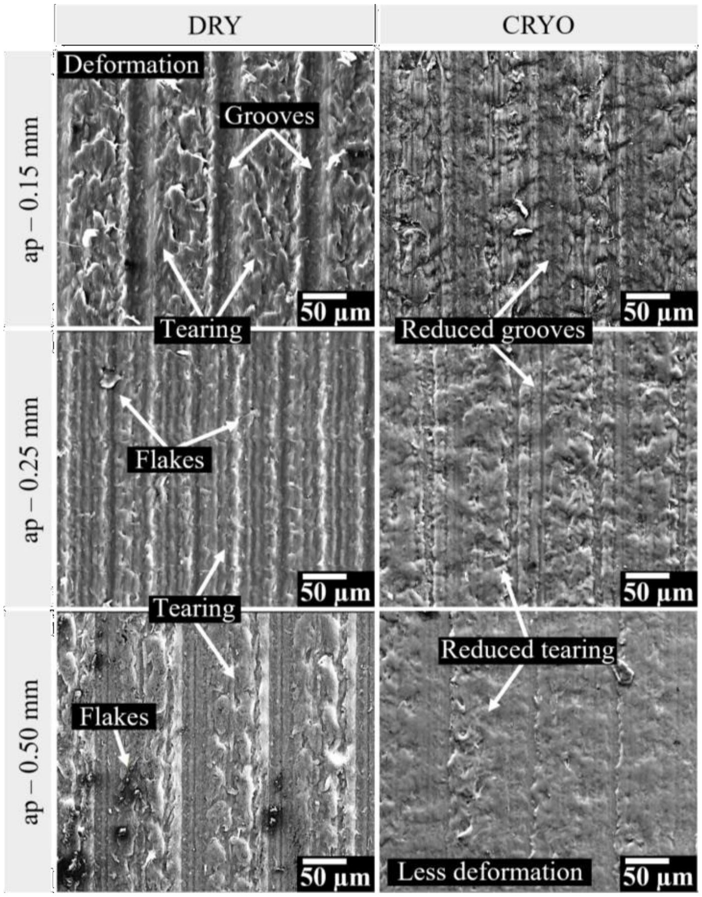

Fig. 5. Dry and cryogenic machined surfaces appearance as a function of the depth of cut.

When applying cryogenic cooling, defects were significantly reduced: the grooves disappeared as wellas the tearings. On the other hand, the cryogenic machined surfaces were characterized by bump-shapedfeatures. A nearly defects-free surface was obtained at the highest depth of cut. These findings on the surface appearance well match the surface roughness data shown in Fig. 2.

The attainment of surfaces with a lower amount of defects in the case of cryogenic machining can beascribed to the cutting temperature. In fact, dry machining can drastically increase the polymer temperature in the cutting zone, which induces a significant increase in its ductility, leading to the material tearing instead of a proper cutting [13].

The chip morphology was assessed as well to be correlated with the surface finish. Fig. 6 and Fig. 7 show the chips at different magnifications as a function of the cutting conditions. The chip morphology was determined according to the ISO 3685-1977 (E) standard [14]. In dry machining, the increase in thedepth of cut led to a change of the chip morphology from continuous tubular snarled to continuous ribbonsnarled chips. This can be ascribed to the increase of ductility given by the temperature increases when adopting more severe process parameters. This is confirmed by the higher magnification images reportedin Fig. 7, which show the presence of a higher amount of shear marks that are indicative of attainment ofhigh strain in the chip.

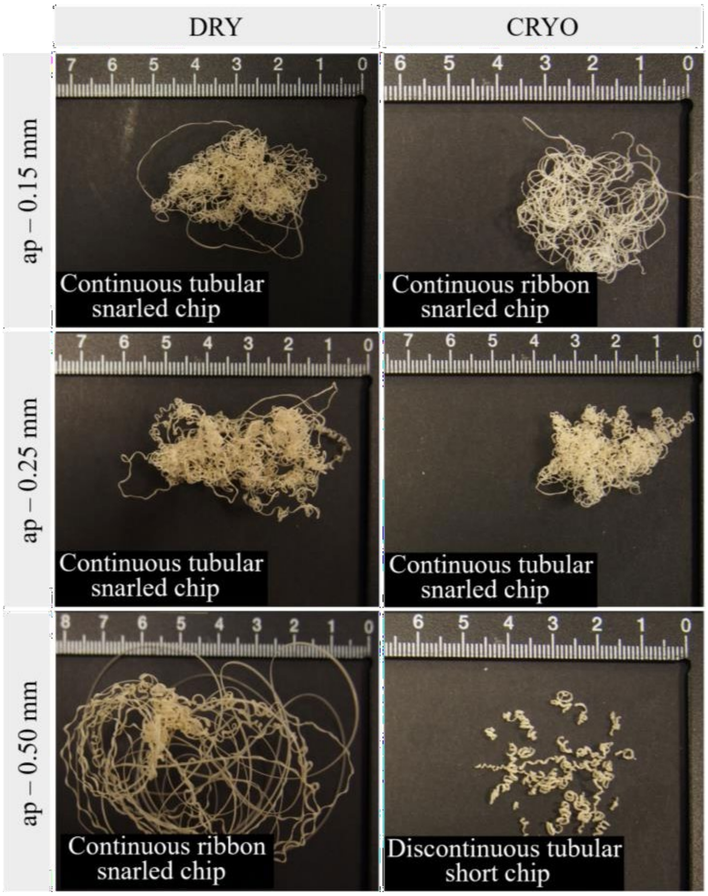

Fig. 6. Morphology of the chips obtained under dry and cryogenic cooling conditions as a function of the depth of cut.

In the case of cryogenic machining, continuous ribbon snarled chips, continuous tubular snarled chips,and discontinuous tubular short chips were formed at *ap*=0.15 mm, *ap*=0.15 mm, and *ap*=0.5 mm, respectively. The breakage of the chip at the highest depth of cut can be ascribed to the synergistic presence of low temperatures and high stresses due to the highest material removal rate. Discontinuous chips can indeed be produced when high compressive stresses are involved or when a brittle material is machined [15].

Actually, Fig. 7 evidences that the shear marks are more emphasized and more frequently observed in the case of the highest depth of cut as a result of the brittleness of the material as a consequence of thelow temperature during cryogenic machining. A fracture can be more likely to nucleate from these shearbands, and then propagate leading to the macroscopic rupture of the chip.

Similar, even if not equal, evidences were found at the lowest and intermediate depths of cut: even though cryogenic machining did not induce a change in the chip morphology, it reduced the bulkiness and lengths of the formed chips with the respect to the dry case.

The presence of discontinuous chips assures the formation of a surface characterized by a lower amount of defects as shown in Fig. 5. If the cutting temperature is kept well below the polymer rubberyregion, the polymer is subjected to a lower deformation, which reduces defects like tearings.

It is worth underlining that discontinuous chips are usually desired in turning operations because theyare less likely to entangle on the machine surfaces and machine tools [5].

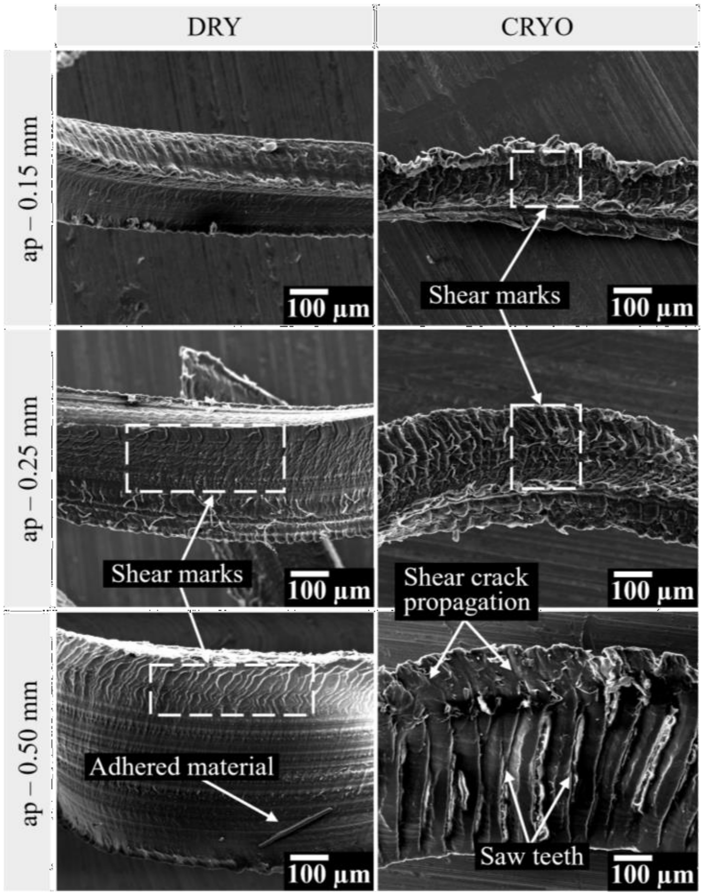

Fig. 7. SEM images of free surfaces of the chips obtained under dry and cryogenic cooling conditions as a function of the depth of cut.

The cutting ratio (*r*) can be considered a machinability index, being influenced by the nature of the chip-tool interaction, chip contact length, and morphology.

Fig. 8 reports the cutting ratio as a function of the process parameters. Regardless of the depth of cut,the cutting ratio is higher under cryogenic cooling conditions compared to dry ones. To a higher cuttingratio corresponds a higher shear angle and a lower shear plane area that leads to a decrease in the shear force needed to form the chip. This can be attributed to a reduction in the friction angle thanks to the application of cryogenic cooling. This in accordance with [16], where it was stated that the lower the friction coefficient the higher the shear angle.

Only in the case of dry cutting, a slight cutting ratio increase was observed at increasing depth of cut. This confirms the predominance of the temperature effects over the mechanical ones in a dry environment.

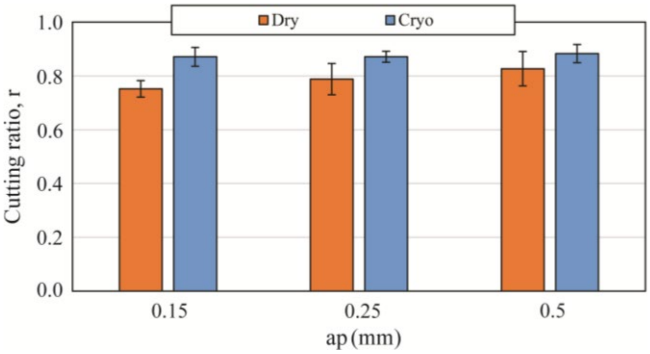

Fig. 8. Cutting ratio under dry and cryogenic cooling conditions as a function of the depth of cut.

Summary

The paper investigated the influence of the depth of cut and coolant strategy on the surface finish andchip morphology in machining biomedical grade PEEK.

The following results can be drawn:

- At increasing depth of cut, smoother surfaces were obtained in cryogenic machining, whereas noclear effect was found in dry machining.
- Cryogenic machining led to a decrease in the height of the peaks, resulting in a surface finish improvement, compared to dry machining. On the other hand, at increasing depth of cut, the height of the peaks was reduced, with consequent improvement of surface finish, regardless of the cooling condition.
- Under cryogenic cooling condition and at the lowest depth of cut, a reduction in the *Spk*/*Svk* ratiowas observed.
- Cryogenic machining lowered the amount of surface defects compared to dry machining. An increase in the depth of cut under cryogenic cooling condition contributed to improve the machined surface quality.
- The chip breakage was obtained solely when the highest depth of cut and cryogenic cooling condition were applied. For the other depths of cut considered, cryogenic machining reduced the bulkiness and lengths of the formed chips with the respect to the dry case.
- The cutting ratio values under cryogenic cooling condition were higher than those obtained underdry conditions at all the depths of cuts.
- A slight increase in the cutting ratio was observed at increasing depth of cut, solely in the case ofdry cutting.

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