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The effect of workpiece cooling on the machining of biomedical grade polymers

Barry Aldwell[a]*, Jimmy O'Mahony[b], Garret E. O'Donnell[a]

[a] Department of Mechanical and Manufacturing Engineering, Trinity College Dublin, College Green, Dublin 2, Ireland
[b] DePuy Ireland, Loughbeg, Ringaskiddy, Co. Cork, Ireland

* Corresponding author. Tel.: +353 1 896 1134; *E-mail address:* aldwellb@tcd.ie

Abstract

Biomedical grade polymers are commonly used in applications where surface finish and dimensional accuracy are key, such as in total joint replacement and intraocular lenses, yet relatively little research has been conducted into the machining of these materials. It has been established that workpiece temperature has a large effect on machinability in soft polymers, with alterations to the chip formation mechanism possible when workpiece temperature is adequately controlled. This is due to the change in material behaviour at the glass transition temperature, which varies with the composition and crystallinity of the polymer. In polymers which have low glass transition temperatures, liquid nitrogen cooling is used, in some cases with a control system used to regulate the workpiece temperature during machining. This work concentrates on the machining of Ultra High Molecular Weight Polyethylene (UHMWPE) workpieces which have been pre-cooled before machining. Past work has concentrated on the development of a measurement chain for the monitoring of polymer machining, and characterising the machining of UHMWPE at ambient temperature, while varying tool and process parameters. Little work has been done on the cryogenic machining of UHMWPE, though it is known that the high crystallinity of UHMWPE alters thermomechanical behaviour when compared to conventional blends of polyethylene, and the glass transition temperature is in the region of -120°C. The aim of this work is to provide insight into the effect of workpiece temperature on machinability and surface quality in UHMWPE.

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Keywords: Polymer; Machining; Cryogenic

1. Introduction

The in-service performance of biomedical grade polymers in orthopaedic applications is strongly influenced by the surface finish of the bearing surface. These components are typically machined as a finishing operation due to the requirement for a complex freeform geometry, with high dimensional accuracy and fine surface finish. Achieving these requires careful choice of machining and tooling parameters. This paper details an investigation into the effect of workpiece cooling to cryogenic temperatures (<150 K) on the machining of biomedical grade polymers.

Nomenclature

CNC	Computer Numerical Control
DOC	Depth of cut
K	Degree Kelvin
P	Probability of an observation being a result of chance variation only
r	Edge radius of cutting tool
R^2	Coefficient of determination
Ra	A measure of surface roughness, defined as the arithmetic average of absolute values of deviations from the mean profile
T_g	Glass transition temperature
UHMWPE	Ultra High Molecular Weight Polyethylene

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1.1. Machining of polymers

The machining of polymers was first investigated by Kobayashi [1], Rao [2] and Kazanskii [3], with subsequent work acknowledging that polymers are difficult to cut well [4], often due to workpiece deformation [5, 6], and that care is required to achieve a good surface finish [7].

1.2. Viscoelastic nature of polymers

Polymers typically display viscoelastic behaviour, where a response to an applied force will have a combined viscous-elastic response, which is dependent upon the temperature of the material, the time over which the load is applied (i.e. the strain rate), the strain history of the material, and the crystallinity of the material [8]. There is a step change in this behaviour at the glass transition temperature (T_g) of a material, below which it behaves as a glassy solid and above which it behaves in a more viscous manner. Machining at or around the glass transition temperature can greatly improve surface quality in the machining of polymers [9-11], in some cases enabling machining to be carried out on materials which are not machinable at room temperature [12].

1.3. Chip formation mechanisms in polymer machining

The types of chips formed during the machining of polymers are shown in Table 1. The fundamental work in this field was carried out by Kobayashi [1], with subsequent work by Rubenstein and Storie [5] establishing that chip formation mechanisms vary with rake angle, depth of cut and material. Later work by Wyeth and Atkins [13] broke down polymer chip formation mechanisms into brittle and ductile modes.

Table 1: Types of chips formed in polymer machining. Adapted from Kobayashi [1]

Type of chip	Cause
Continuous – flow	High elastic deformation
Continuous – shear	Shear plane generated upwards from the point of the tool, similar to metal cutting. Continuous due to small shear intervals
Discontinuous – simple shear	As per continuous-shear, but with larger shear intervals
Discontinuous – complex	Combination of large compressive stress and shear stress
Discontinuous – crack	Chip formed by brittle fracture, with cracking around the point of the tool
Discontinuous – complex (shear with crack)	Combination of shear plane generated upwards and crack propagating downwards from the tool tip

1.4. The size effect

In order to quantify the effect of increasing the tool edge radius *r*, it must be considered in terms of the nominal depth of cut, as shown in Equation 1. The influence of this factor is referred to as the size effect, which has been well studied in metal cutting [14, 15]

$$\frac{r}{DOC_{\text{Nominal}}} \tag{1}$$

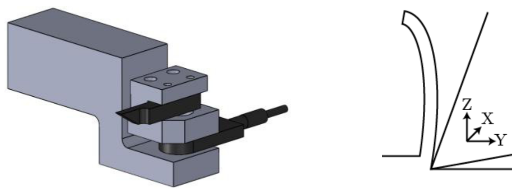
In the case of a perfectly sharp tool this ratio is at or approaching zero, and as a tool wears or blunts this ratio increases. The nominal depth of cut is used as in polymer machining the workpiece may deform noticeably, both ahead of the tool [1] and on the machined surface [16]. Past work [17] has identified that when this ratio exceeds 1 the surface finish of the machined part becomes extremely poor.

2. Experimental setup

The experimental setup used was substantially similar to that used in past work [17, 18]. In order to effectively characterise the machining operations carried out, a process monitoring system was required [19]. Two stages of process monitoring were used:

1. In process
2. Post process

In process measurements consisted of measuring cutting forces using a Kistler 9602 force sensor integrated into the tool holder, as shown in Figure 1. Post process measurements consisted of analysing the chip formed during each cutting operation, and inspecting the machined surface, using a profilometer to measure surface roughness and profile, and an optical microscope for visual inspection.



a) b)

Figure 1: Cutting force measurement, showing a) Custom toolholder, and b) Cutting force directions

Machining was carried out in an Okuma LT-15M CNC lathe, using workpieces which had been sectioned into 2.2mm width discs, with a slot cut in each disc to prevent chip buildup from corrupting force data.

a) b)

Figure 2: Experimental setup, showing a) Okuma LT-15M, and b) Workpiece design

2.1. Design of experiments

A full factorial experimental design was used, with no replication. The factors and levels used are detailed in Table 2. Minitab 16 statistical software was used to perform statistical analysis on the data collected.

Table 2: Experimental design

Factor	Number of levels	Levels
Rake angle	4	-20°, 0°, 20°, 40°
Sharpness	3	Sharp, worn, highly worn
Initial workpiece temperature	2	Cold (100 – 150 K), Room (295 – 300 K)
Cutting speed	2	155, 300 m/min
Depth of cut	2	0.06, 0.19 mm/rev

To achieve the "cold" level of initial workpiece temperature, samples were submerged in liquid nitrogen (T = 96 K) for a minimum of 24 hours to ensure that they were below the glass transition temperature of UHMWPE, which is below 150 K [20]. Samples were removed from the liquid nitrogen immediately before machining, to ensure that a low material temperature was maintained.

2.2. Data acquisition

Data acquisition for in process measurement was carried out using a National Instruments CompactDAQ 9178 chassis, using NI LabVIEW SignalExpress software for data logging.

2.3. Data processing

Data processing was carried out using Matlab. A 10 Hz lowpass filter was used for all force data to remove the interruptions caused by the slot in the workpiece, after which an average of 500 data points was used to establish steady state cutting force levels for each axis. Z axis force data was used for cutting force, while the resultant of the X and Y axes was used for thrust force. These axes are shown in Figure 1.

3. Results

3.1. Cutting force and thrust force

The main effects for cutting force are shown in Figure 3, while the main effects for thrust force are shown in Figure 4.

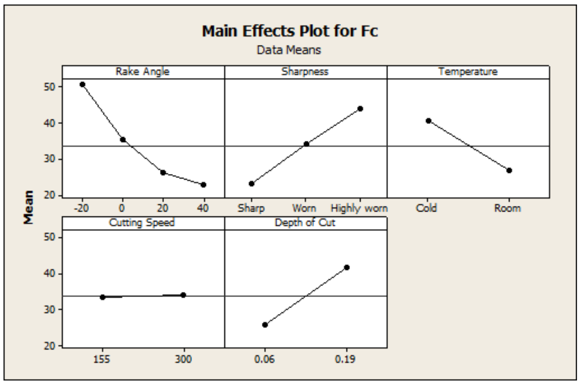


Figure 3: Main effects plot for cutting force

The effect of workpiece temperature is clear, with cold workpieces having higher values for both cutting and thrust force. Cutting speed is not a statistically significant factor for cutting force (P = 0.378, with model R^2 = 99.74%) or thrust force (P = 0.522, with model R^2 = 99.93%), while depth of cut is not statistically significant for thrust force (P = 0.064). Past work at room temperature [17] has shown both cutting speed and depth of cut to be statistically significant, albeit marginally in the case of cutting speed.

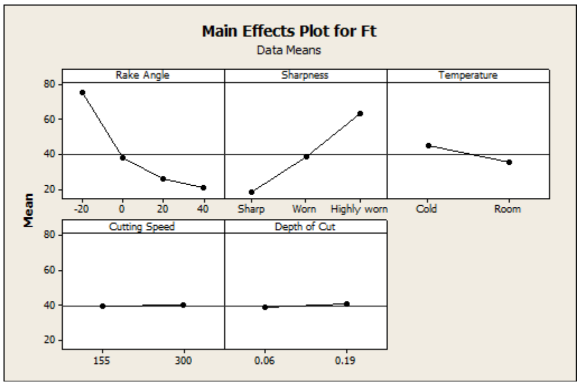


Figure 4: Main effects plot for thrust force

3.2. Surface roughness

A main effects plot for surface roughness is shown in Figure 5. All five main effects appear significant (model R^2 = 79.58). It is clear that the lower workpiece temperature and a sharper tool delivers an improved surface finish, while the relationship between rake angle and surface roughness shows a spike at a rake angle of 20°, which may be a feature of the critical rake angle [7, 17], or indicative of unexplained variation in the analysis.

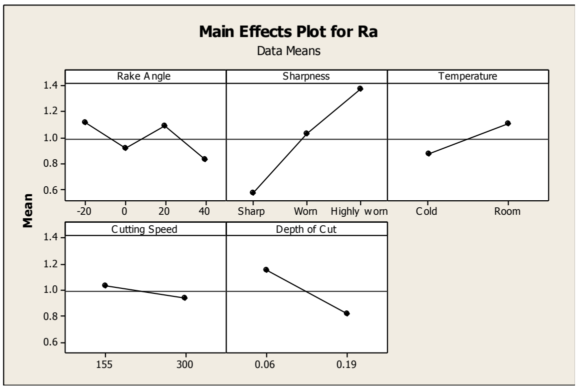


Figure 5: Main effects plot for surface roughness

3.3. Chip thickness

The main effects for chip thickness are shown in Figure 6. This data represents the difference between the cut chip thickness and the nominal depth of cut for the test. Neither cutting speed (P = 0.058, with model R^2 = 99.82) nor depth of cut (P = 0.139) are statistically significant. This analysis could only be carried out for the sharp level, as not all cuts at the worn and highly worn levels produced a chip.

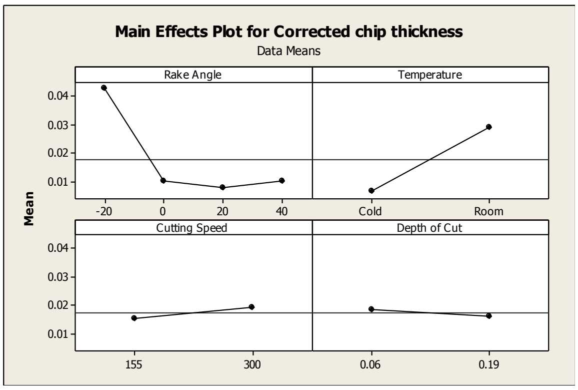


Figure 6: Main effects plot for difference between cut and uncut chip thickness

An interaction plot between rake angle and temperature is shown in Figure 7. It is clear that at -20° rake angle there is a large change in the difference between cut and uncut chip thicknesses, which signifies a change in chip formation mechanism when machining at cold temperatures with a -20° rake angle tool. This change is supported by the statistical significance of the rake angle/temperature interaction (P = 0.001).

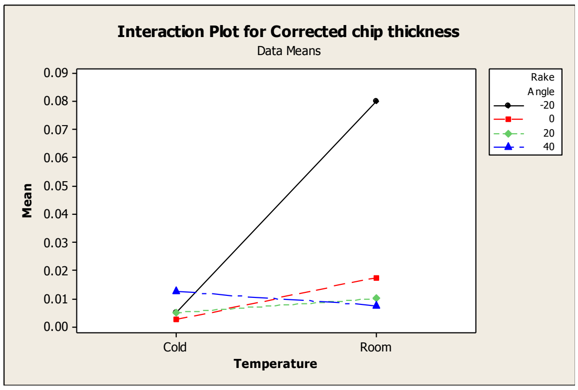


Figure 7: Interaction plot between temperature and rake angle for chip thickness

3.4. Chip formation mechanisms

In addition to measuring the chip thickness, the form of the chip was classified into one of three categories:

1. Continuous
2. Discontinuous
3. Dust

It was found that at the high level of depth of cut a continuous chip was formed in all cuts other than that at room temperature, using a highly worn tool with -20° rake angle, where a discontinuous chip was formed. The results for the low level of depth of cut are shown in Table 3.

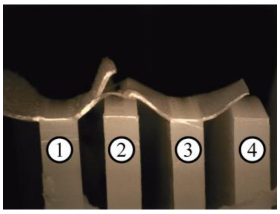
Table 3: Chip types formed for low depths of cut. Continuous chip types are marked C, discontinuous chip types are marked D, and levels for which only dust was produced are marked Du. Underlined entries displayed workpiece deformation during cutting

	Rake	-20		0		20		40	
	Cutting speed	L	H	L	H	L	H	L	H
Sharp	Cold	C	C	C	C	C	C	C	C
	Room	C	C	C	C	C	C	C	C
Worn	Cold	Du	Du	C	C	C	C	C	C
	Room	Du	D	Du	C	C	C	C	C
Highly worn	Cold	Du	Du	Du	D	D	D	D	D
	Room	Du	Du	Du	Du	Du	Du	D	D

It can be seen that in some worn and highly worn tool states the workpiece temperature has an effect on the chip formed, with the case of a worn tool with 0° rake angle having a different chip formation mechanism at low cutting speed for the two levels of workpiece temperature.

3.5. Machined surface analysis

It was found that in many cases where a discontinuous chip was formed that the material had also flowed axially, to either side of the tool, forming "wings" on either side of the machined surface. As the tool width exceeded the width of the discs being machined (3.6mm and 2.2mm respectively) this must be the result of large thrust forces compressing the workpiece during the cut. Figure 8 shows a sectioned view of a workpiece where this occurred. The operations in which this was observed are marked by underlined entries in Table 3



	Cutting speed	Depth of cut
1	Low	Low
2	Low	High
3	High	Low
4	Low	High

Figure 8: Sectioned view of workpiece, showing material flow at low depths of cut due to rubbing. Tests performed with a cooled workpiece, 0° rake angle, worn tool. Each disc is of width 2.2 mm, with the remaining material on 1 being approximately 0.45mm thickness, and on 3 being approximately 0.25 mm thickness

Inspection of the surface using an optical microscope showed a frosted surface on these "wings", and an irregular surface on the face of the disc. An example of this is shown in Figure 9.

a) b)

Figure 9: Machined surface for 20° rake angle, highly worn tool, low depth of cut, a) low cutting speed, b) high cutting speed. Cuts performed from right to left

The lines apparent on the machined surface have smaller spacing for the higher depth of cut. This spacing was measured using direct output from the profilometer over an approximately 18.5° arc in the direction of the cut, which was then compared to a best fit circle for that arc, and the difference between the measured data and the best fit arc were plotted. Examples of this data for low and high cutting speeds are shown in Figure 10 and Figure 11

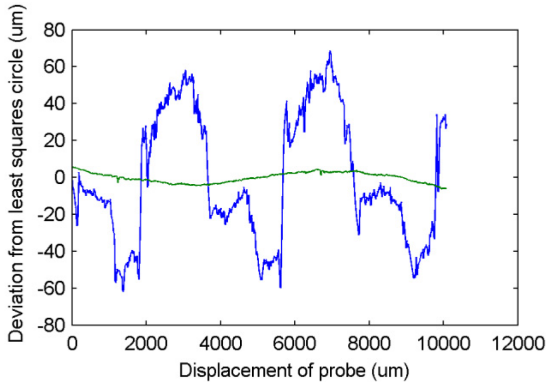


Figure 10: Profilometer output for cold workpiece, 20° rake, highly worn tool, low cutting speed, low depth of cut. Green shows profilometer output from a machined sample with a smooth surface, for comparison. The direction of the cut was left to right

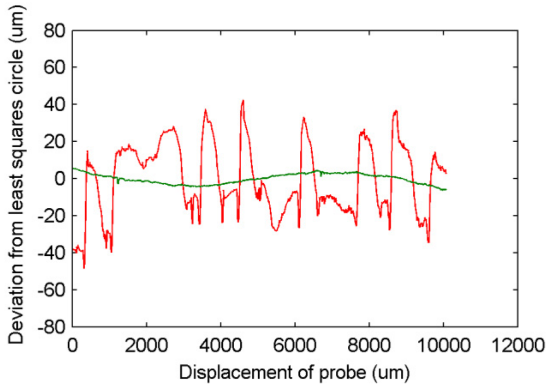


Figure 11: Profilometer output for cold workpiece, 20° rake, highly worn tool, high cutting speed, low depth of cut. Green shows profilometer output from a machined sample with low surface roughness, for comparison. The direction of the cut was left to right

The reduced gap between peaks at the higher cutting speed is evident, with an accompanying reduction in the depth of the grooves. The slope away from the cutting point indicates crack growth downwards from the edge of the tool.

4. Discussion

4.1. Effect of material cooling

It is clear from the cutting and thrust force data that material which has been pre-cooled to cryogenic temperatures (100 – 150 K) is stiffer when compared to the same material at room temperature (300 K), but that the effect is not so large that other factors such as rake angle and tool sharpness can be ignored. The surface roughness data compliments this by showing reduced values of Ra at the cold workpiece temperature, but again this reduction is not of a scale which renders all other factors insignificant.

4.2. Chip formation mechanisms

A change in chip formation mechanism has been identified for sharp tools with a -20° rake angle, with the chip thickness results in Figure 7 showing a continuous-shear type chip at room temperature (300 K) and a continuous-flow* type chip at the cold temperature (100 – 150 K). In addition, it was shown that where discontinuous chips were produced that there was a well defined pattern to the surface, displaying evidence of crack growth downwards from the point of the tool, indicating the discontinuous-complex (shear with crack) type of chip formation was occurring.

4.3. Influence of the size effect in polymer machining

The surface roughness results demonstrate that sharp tools with a larger depth of cut provide superior cutting, both for low and room temperature level workpieces. This is a clear demonstration of the significance of having a small ratio of edge radius to depth of cut in polymer machining, and the effect which it has on surface quality. In cases where this ratio is larger the chip formation mechanism changes and the surface profile becomes visibly patterned due to crack formation.

5. Conclusions

An investigation into the effect of workpiece pre-cooling on cutting forces, chip formation and surface quality in the machining of UHMWPE was carried out. From the work carried out the following conclusions can be drawn:

- That workpiece pre-cooling to cryogenic temperatures (100 – 150 K) increases workpiece stiffness and improves surface quality in the machining of UHMWPE.
- The improvements in surface quality were not of a magnitude which exceeds that of the other factors studied.
- Thus, the choice of rake angle, tool edge radius and cutting parameters remain important factors if a transition is made from machining at room temperature (300 K) to cryogenic temperatures (100 – 150 K)
- The discontinuous chip formation mechanism for UHMWPE where the edge radius approaches or exceeds the depth of cut has been identified as the discontinuous – complex (shear with crack) type, as per the nomenclature of Kobayashi [1].
- A link between the size effect and the chip formation mechanism has been identified, which warrants further investigation to identify the point at which transitions in chip formation mechanism occur.

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