Machinability of hydrophobic acrylic polymer for customized intraocular lenses

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Intraocular lenses (IOLs) are critical optical devices surgically implanted to replace the natural crystalline lens in cataract patients, restoring vision and preventing blindness. The precision and surface quality of these lenses are paramount, as they directly influence the visual outcome and patient satisfaction. This work investigates the diamond turning of hydrophobic polymer SHi49 (Contamac Ltd. Saffron Walden, United Kingdom) and Polymethylmethacrylate (PMMA), two materials commonly used in intraocular lens (IOL) manufacturing, focusing on the effects of varying turning speeds, feed rates, and temperatures. The study analyzes cutting forces (F_c), thrust forces (F_p), and surface roughness (Sa) to optimize the machining process. Results show that pre-cooling significantly reduces forces and surface roughness, particularly at higher speeds and moderate feed rates. Cooling is essential for maintaining material stability and achieving superior surface quality in hydrophobic polymer. This research provides valuable insights for the machinability of IOL hydrophobic polymer, enlightening the optimizing direction of IOL production parameters, which is crucial for the success of cataract surgeries and the restoration of patients' vision.

NOMENCLATURE

a_p = Cutting depth	F_c = Cutting force
F_f = Feed force	F_p = Thrust force
FTS = Fast-Tool-Servo	IOL = Intraocular lens
n = Turning speed	PMMA = Polymethylmethacrylate
v_f = Feed Speed	T_g = Glass transition temperature

1. Introduction

Polymers, particularly thermoplastics, are valued for their lightweight and the ability to be processed into complex shapes. The precision machining of polymers has become a critical area of research, driven by the demand for high-performance components in industry such as biomedical devices, optics, and aerospace. One of the most important application is the machining of customized intraocular lenses (IOL) or rigid gas-permeable contact lenses [1].

In Germany, about 800,000 cataract surgeries are conducted annually [2]. Nowadays, standard foldable IOLs are made of hydrophilic or hydrophobic acrylic polymer. In contrast to the IOLs made of hydrophilic polymer, hydrophobic ones are advantageous for preventing the after-cataract—an excessive growth reaction of remaining epithelial cells of the natural lens after surgery. And because they allow thinner lenses due to their high refractive index, they are often provided in so called pre-loaded injection devices being extremely convenient for the surgeon [3]. However, the machinability of available hydrophobic polymers, especially in ultra-precision processes like diamond turning, presents unique challenges due to their viscoelasticity, low thermal conductivity, and sensitivity to temperature variations [4, 5], particularly for the ones with lower glass transition temperature (T_g).

The machining behavior of polymers is significantly influenced by cutting parameters and their mechanical and thermal properties, which can vary widely between different types of polymers. Kobayashi and Saito [6] created an early cutting model in polymer processing. Xiao and Zhang [7] evaluated the machinability of typical thermoplastic and thermosetting polymers and gave hints to understand the effect of their viscous properties on surface integrity, chip formation and machining forces, where the importance of glass transition temperature, fracture toughness and molecular mobility is atoned for the optimal machining conditions. Ghosh et al. [8] performed a case study of cryogenic machining for IOLs, found the machined hydrophobic samples have a better surface quality in RMS roughness over the industry standard at -40 °C. They posited that mechanical processing in either the rubber or glass state would lead to an inferior surface finish. In the rubber state, the machined surface is characterized by tearing and corrugation, whereas in the glass state, it is marked by the formation of cutting chips and surface fractures on the workpiece. This matches the conclusions of Carr and Feger [9], indicating that the machinability and surface finish of many polymers can be optimized within the temperature range around the glass transition temperature.

The recommended cutting parameters for hydrophobic materials are: for rough turning, n=9000 1/min, v_f=18 mm/min and a_p =0.13 mm; for fine turning, n=9000 1/min, v_f =10 mm/min and a_p=0.07 mm [10]. In off-axis fast-tool-servo (FTS) diamond turning of IOLs [11], these parameters are yet constrained by FTS dynamics, data point density, processing speed, and other factors, resulting in a much lower possible turning speed. This work analyzes the machinability of commercially available hydrophobic IOL polymer at relatively low turning speed. The diamond turning experiment is conducted to show the machinability of hydrophobic polymers at different turning speed, feed speed and temperatures, compared to PMMA. The machinability is analyzed using two indicators: machined surface roughness (*Sa*) and forces (cutting force (F_c) and thrust force (F_p)) measured during the machining process. This work provides valuable insights for the machinability of IOL hydrophobic polymer, contributing to optimizing process parameters for ultra-precision diamond turning of polymers.

2. Materials and Methods

2.1 Materials

The commercially available PMMA and SHi49 blanks used are cylindrical discs; with a diameter of 16 mm and a height of 2 mm. Detailed parameters are provided in Table 1. Both materials are divided into two groups: one pre-cooled in a refrigerator to around 0°C and the other kept at room temperature (approximately 20°C). All blanks are pre-turned before the experiment. It takes about 5 minutes from withdrawal from the refrigerator to the start of the cutting experiment.

Table 1. Properties of polymers used in this work

Material	PMMA	SHi49
Supplier	Röhm	Contamac
Glass transition temp. (T_g)	105 – 138°C	> 7°C
Dispersion (Abbe-number)	53	50
Refractive Index (546 nm)	1.49	1.49

2.2 Design of experiments

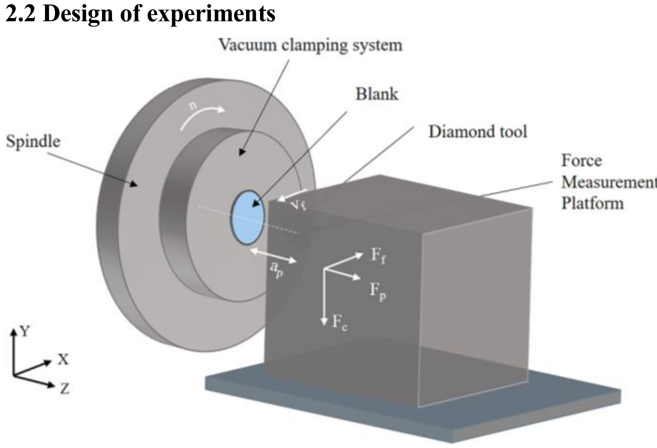

Fig. 1 Principal kinematics and machine setup of turning system

An ultra-precision on-axis diamond turning system is established, with the principal kinematics and setup shown in Fig. 1 and the experimental setup depicted in Fig. 2. In this system, the blanks are face-turned with the spindle rotating clockwise while the diamond tool moves from the outer edge toward the center.

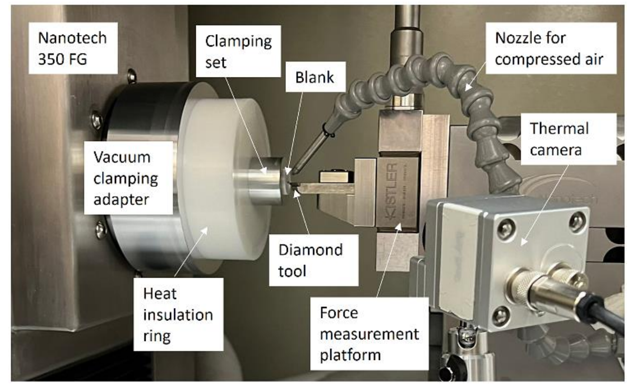

Fig. 2 Experimental setup for the machinability test

The machine tool applied is a 350 FG (Moore Nanotechnology Systems LLC, Swanzey, United States), and features a custom vacuum clamping system with an adapter, heat insulation ring, and clamping set. An ultra-precision diamond tool (DCGW 070202; Matzdorf, Nuremberg, Germany) with a 0.2 mm corner radius is mounted on a force measurement platform (MiniDyn Type 9119AA1; Kistler Instrumente AG, Wintherthur, Switzerland). A nozzle for compressed air is positioned beside the blank to remove chips during cutting, and the process is recorded using an infrared camera (PI200; Optris GmbH, Berlin, Germany). The parameters for machinability experiments are given in Table 2.

Table 2. Experimental process parameters

Parameters	Values
Materials	PMMA, SHi49
Starting temperature T [°C]	0, 20
Turning speed n [1/min]	100, 500, 1000
Feed speed v_f [mm/min]	2, 10
Cutting depth a_p [µm]	10

3. Results and Discussions

3.1 Surface roughness

Surface roughness is measured using a white light interferometer (WLI; TalySurf CCI HD, Taylor Hobson, Leicester, United Kingdom), with a 50x magnification (measured area 325 µm*325 µm). The data is analyzed using MountainsLab Expert 10 software, with a roughness filter of 80 µm applied. Topography measurements are taken at the three positions shown in Fig. 3 for each workpiece and then averaged.

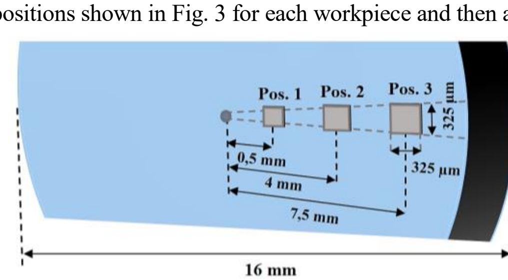

Fig. 3 Measured positions for topography evaluation by WLI

It is important to note that no obvious correlation between cutting speed (v_c)—i.e. represented here by the turning radius (r) in Fig. 3—and surface roughness Sa was observed. This finding aligns with the previous research [12], where no obvious correlation between roughness and cutting speed during diamond turning of OFHC copper and electroless nickel was found.

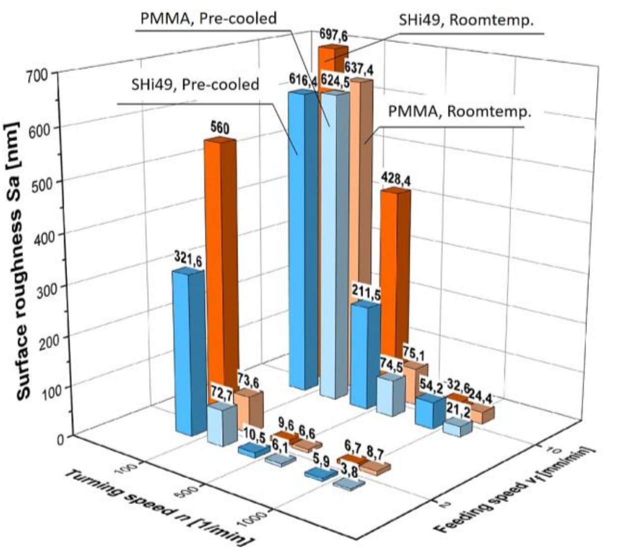

Fig. 4 Surface Roughness *Sa* of SHi49 and PMMA under different machining conditions

The surface roughness in Fig. 4 shows that both materials are highly sensitive to machining parameters. Lower initial temperatures, reduced feed speeds, and higher turning speeds generally result in lower surface roughness. With a lower glass transition temperature, SHi49 is more ductile than PMMA, leading to higher surface roughness, especially without cooling. This is evident from Fig. 5, where PMMA's cutting path is clear, while SHi49's is nearly indistinguishable; no matter pre-cooled or at room temperature, while other conditions are identical (a_p =10 µm, v_f =2 mm/min and n =100 1/min). Cooling significantly improves the surface quality by reducing roughness, particularly when *Sa* is high without pre-cooling. Despite SHi49 consistently having higher *Sa* values than PMMA, an optical quality with an *Sa* of 5.9 nm is achieved in the best case. These results suggest that while SHi49 can meet the surface quality standards for IOLs, it requires careful control of machining parameters, especially cooling and cutting settings.

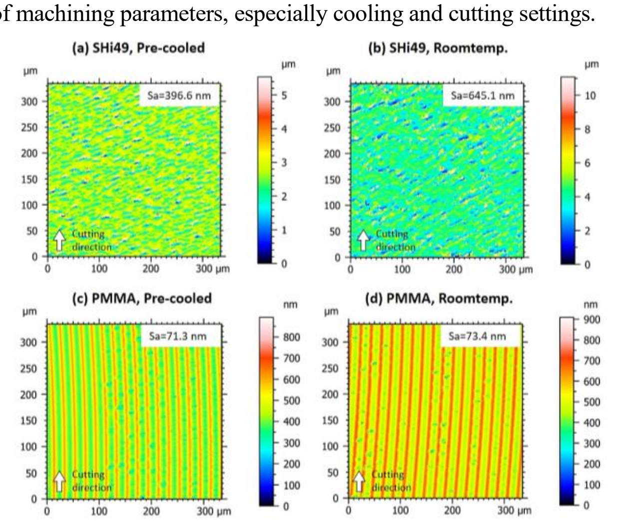

Fig. 5 Surface texture of the machined surfaces at Pos. 2 in Fig. 3

3.2 Cutting force and Thrust force

Feed force, cutting force, and thrust force are recorded by the MiniDyn force measurement platform during the first half of the cutting process at a frequency of 10 kHz, due to data storage limitations. The data is then processed and analyzed using an in-house software (MesUSoft 3). The feed force is disregarded as it is typically too small, providing no significant information. The average force measured during the first half cutting process is used for the analysis.

A selected example of cutting and thrust force is given in Fig. 6, with a reduced frequency of 1250 Hz for the first 10 s, where the pre-cooled SHi49 is machined at a_p=10 µm, v_f = 10 mm/min and different turning speeds. As n increases from 100 1/min to 500 and 1000 1/min, the cutting force magnitude decreases considerably, averaging from around 250 mN to around 50 mN and 30 mN, respectively, with much lower fluctuations; the thrust force has also the same trend. This trend indicates that higher turning speeds stabilize the cutting process and reduce the forces required, likely due to improved material removal efficiency and reduced tool-material interaction time.

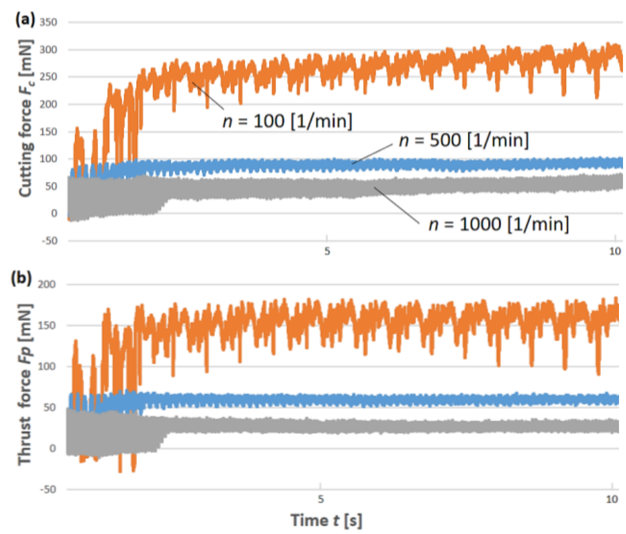

Fig. 6 Measured (a) cutting and (b) thrust forces of pre-cooled SHi49 at different turning speed.

For both materials, the cutting force significantly decreases with increasing turning speed, as demonstrated in Fig. 7. Initially, at the lowest speed (100 1/mm), the cutting force reaches up to 275 mN for pre-cooled conditions with a feed rate of 10 mm/min. This value substantially drops to 47 mN at the highest speed (1000 1/mm), demonstrating the effectiveness of higher turning speeds in reducing cutting forces. Pre-cooling appears to have a notable impact at lower speeds but becomes less significant as the turning speed increases, where the forces converge regardless of cooling.

The analysis of F_p of SHi49 and PMMA in Fig. 8 shows distinct trends compared to F_c, where the thrust force tends to decrease when the blanks are pre-cooled. The cooling effect is mostly pronounced at lower speeds and diminishes as speed increases, mirroring the behavior of cutting forces. Importantly, the thrust force is consistently lower than the cutting force for SHi49 across all conditions. This suggests that the material reacts differently in the cutting and thrust directions, with higher resistance to cutting and lower resistance to thrust, possibly due to friction.

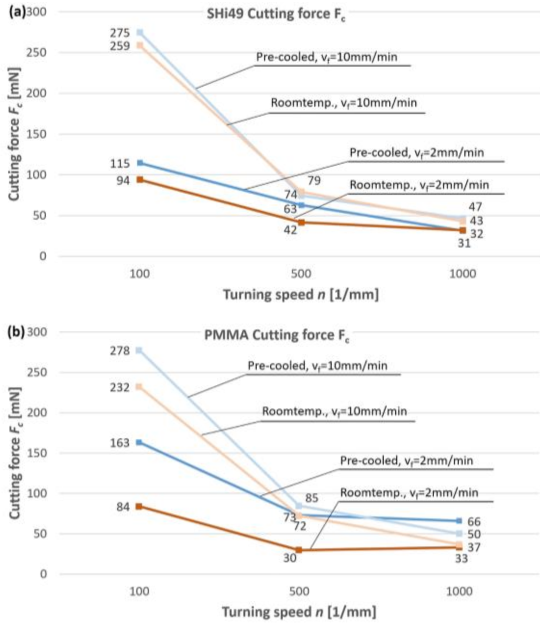

Fig. 7 Cutting force F_c of (a) SHi49 and (b) PMMA under different machining conditions

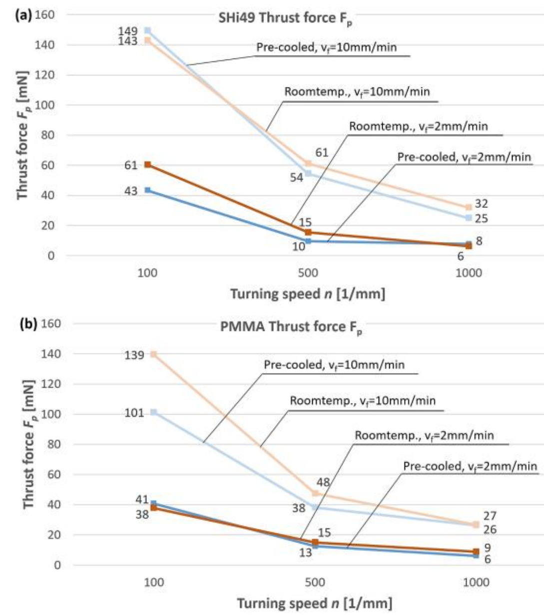

Fig. 8 Thrust force F_p of (a) SHi49 and (b) PMMA under different machining conditions

4. Summary

This work analyzes the machinability of hydrophobic polymers in comparison to PMMA, in terms of surface roughness, cutting and thrust force under different machining conditions. The results provide valuable insights into the machining of hydrophobic IOL, guiding the directions of IOL production optimization.

- Increasing turning speed reduces both cutting and thrust force for SHi49 and PMMA, with SHi49 showing higher force values, indicating greater resistance. Higher turning speed enhances surface quality and stabilizes force behavior, which is essential for consistent machining; while no obvious correlation between cutting speed and surface roughness Sa was observed, which aligns with the results from diamond turning of other materials.
- Pre-cooling is effective at lower speeds, reducing thrust force and surface roughness in SHi49. SHi49 responds yet differently to cooling in cutting and thrust directions: thrust force decreases at lower temperatures, while cutting force tends to increase; the thrust force is also consistently lower than the cutting force.
- With pre-cooling, an optical surface quality of *Sa* 5.9 nm is achieved for the hydrophobic material SHi49 at a relatively low turning speed of 1000 1/min compared to the recommended speed.

Overall, the quantitative analysis reinforces the earlier analysis, showing that hydrophobic material SHi49 can meet the surface quality standards for IOLs with careful control of machining parameters, which is crucial for hydrophobic IOL production.

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