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Off-Axis Fast-tool-servo diamond turning of customized intraocular lenses from hydrophobic acrylic polymer

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Abstract

Intraocular lenses (IOLs) are small optical devices for implantation into the human eye to substitute the opacified natural crystalline lens (cataract). The requirement for such cataract surgery arises when the opacification significantly impedes vision in order to prevent blindness. To date, apart from moulding, the prevailing method for manufacturing IOLs is single-piece on-axis diamond turning especially for small batch production and product variability as in toric lenses. In the scope of this project, an exploration of alternative techniques, i.e. off-axis diamond turning with fast-tool-servo (FTS), will be undertaken to increase the productivity and to manufacture highly customized lenses; a vacuum clamping device aiming to enable the simultaneous processing of multiple pieces will be developed. Specifically, hydrophobic acrylic polymer where cooling is required, rather than hydrophilic materials, will be used as raw materials, in order to meet the increasing market demand for hydrophobic IOLs.
The primary objective is to improve production efficiency by realizing faster, more resource-efficient, and ultimately more cost-effective manufacturing processes. In this contribution, principal process designs for FTS machining including vacuum clamping of hydrophobic blanks are discussed and particular solutions are demonstrated; the collected manufacturing data using FTS off-axis diamond turning are analysed.

Manufacturing (CAM); Material; Turning; Ultra-Precision

1. Introduction

In progressed age, the transparency of the natural lens gradually decreases, i.e. cataract, and vision deteriorates, which can even lead to blindness without treatment. The only known effective treatment for cataract is to surgically substitute the cloudy lens with an intraocular lens (IOL) [1]. In Germany, about 800,000 cataract surgeries are conducted annually [2]. The productivity of customized IOLs is yet limited to maximal 4,000 pieces per machine per year, which is much lower than the need. A potential solution to increase the productivity is parallelized processing with FTS, whose application in optical surface manufacturing has been proved [3].

Standard foldable IOLs are made of hydrophilic or hydrophobic acrylic polymer. Compared 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 [1]. However, since the glass transition temperature T_g of available hydrophobic acrylic polymer is distinctly lower than room temperature, it can only be continuously manufactured with in-process cooling.

In this paper, we discuss the principal process designs of alternative techniques for customized hydrophobic IOL production, i.e. off-axis diamond turning with FTS, including vacuum clamping device and embedded in-process cooling function. This process design aims at increasing the production efficiency of IOLs by parallelized processing.

2. Principle process designs for FTS off-axis turning

The simultaneous diamond turning of multiple free-form surfaces is only possible with the additional degree of freedom offered by FTS.

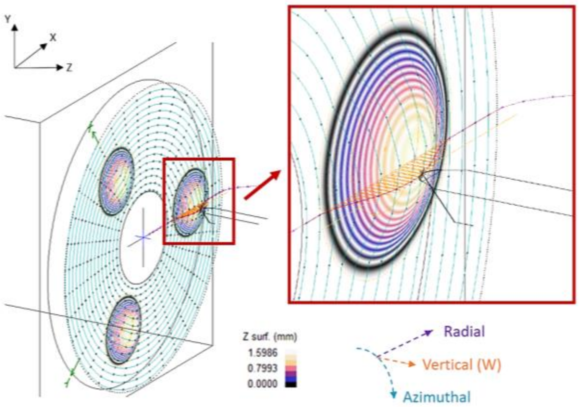

Figure 1. CAM simulated tool path in azimuthal, radial and W directions; Sample IOLs with cutting path area (D = 50 *mm*, blue) and lens geometry (d = 6 *mm*, coloured)

Figure 1 shows the simulated diamond tool path in the CAM software Precitech/Ametek Diffsys, where the point cloud above the three IOLs (coloured) and the entire clamping device represents the information for the computer numerical control (CNC). In contrast to conventional on-axis turning, for off-axis turning with FTS, the diamond tool exhibits not only radial motion but also expeditious perpendicular movement concerning the clamping device in vertical direction, while the clamping device rotates in azimuthal direction.

Two prerequisites must be satisfied to transition from simulation to processing: clamping device that can concurrently secure three IOLs while facilitating in-process cooling, and assessing the feasibility of using FTS for polymer processing.

3. Clamping device and embedded in-process cooling

The three vacuum fixing positions align with the relative positions of the sample IOLs in figure 1, forming a rotational symmetric distribution on the clamping device with an included angle of 120°. The upper side of figure 2 depicts air evacuation from the backside through vacuum channels, ensuring uniform pressure dispersion across the polymer blank's surface via a porous vacuum insert to prevent localized pressure damage. To maintain blank temperature below the T_g, continuous cooling is applied through a ribbed structure, with cold air injected at the rear and exiting at the front (lower side of figure 2).

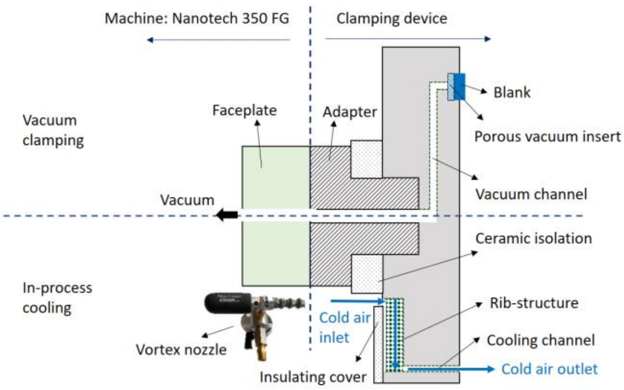

Figure 2. Design of vacuum clamping device (upper) and embedded in-process cooling function (lower)

A simplified vacuum clamping device (figure 3) was used for testing the cooling effects statically. A vortex nozzle, at 8 *bar* pressure, 200 *l/min* flow, and 20*°C* starting temperature, was employed. This includes porous vacuum inserts of three materials (aluminum with pore diameters of 15 μm and 400 μm, poroplastic with a pore diameter of 10 μm) paired with blanks of two materials (polymethylmethacrylate (PMMA) and steel).

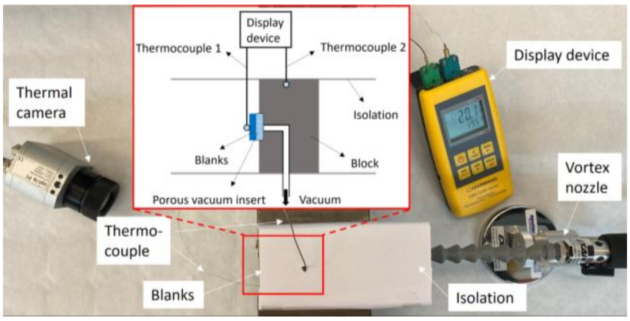

Figure 3. Experimental setup for the cooling performance test

As can be seen from figure 4, the porous vacuum insert made of aluminum with pore diameters of 15 μm has the best thermal conductivity; at the same time, smaller pores are advantages for protecting the optical surfaces. Overall, aluminum with pore diameters of 15 μm is the best suited of the three materials. Yet the lowest temperature (10*°C*) with vortex nozzle is still higher than T_g (7*°C*), and a cooling device with higher power is inevitable.

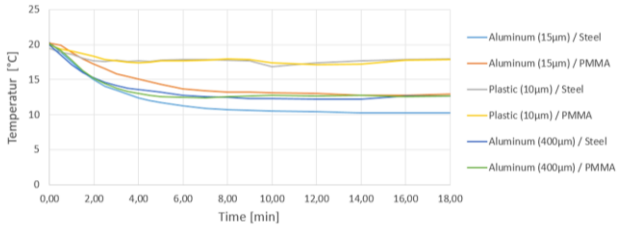

Figure 4. Cooling performance test results under different material combinations, legend: porous vacuum insert / blank.

4. Diamond turning of PMMA with FTS

Since hydrophobic materials must be cooled to be machined precisely, PMMA, which is common for IOL manufacturing, was chosen to test machinability with FTS. On the surface of a 60 *mm* diameter PMMA blank, a lens array composed of four concave lenses with diameter of 4.5 *mm* was processed using a machine tool 350 FG and NFTS 6000 from Moore Nanotechnology Systems (figure 5).

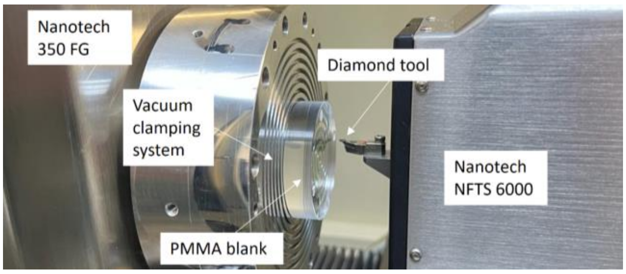

Figure 5. Experimental setup for the machinability test of PMMA

With the depth of cut a_p of 50 μm, feed rate v_f of 2 *mm/min*, turning speed *n* of 100 *1/min* and tool's corner radius r_ε of 0.5 *mm*, the above mentioned lens array is successfully processed with a rough surface quality, indicating principally the machinability of PMMA using FTS.

5. Conclusion and future work

We introduced the principle process design for off-axis diamond turning with FTS for the manufacture of hydrophobic IOLs. Two key aspects are addressed: testing materials for the porous vacuum insert and evaluating FTS feasibility for polymer processing. Experimental results favour porous aluminum (15 μm) for the vacuum insert, and FTS proves effective with PMMA. Future research will concentrate on developing and testing the complete off-axis clamping device with in-process cooling. We will investigate the processing parameters for machining hydrophobic polymer under cooled condition.

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