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Thermal Issues in Single Point Diamond Turning of Aspheric Polymer Lenses, Their Impact on Surface Quality Criteria: A Holistic Approach

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Abstract

In Advanced Optical Instrumentation, asphericss provide effective performance alternative. While Single Point Diamond Turning (SPDT) delivers rotationally symmetric aspherics, these profiles are characterized by contact profilometer through linear surface scans to analyze their Form, Figure and Finish errors.

In SPDT-based fabrication of non-ferrous and polymer aspheric profiles, the surface quality is greatly affected by the thermal energy generated by the interaction between diamond tool and work-piece. In the SPDT of polymer aspheric profiles, coolant use needs to be restricted due to Poly Methyl Meth Acrylate (PMMA)'s transmission properties at higher temperatures. This causes the heat generated to reside in the polymer components, causing the swelling of the surface profiles. The quantum of the swelling depends on PMMA's thermal diffusivity and on the geometry of aspheric profiles under SPDT. The repeated SPDT cycles will result in increased profile swelling. This swelling causes significant deterioration in the surface quality, in terms of form, figure and finish errors (of the aspheric profile), often beyond the prescribed tolerance limits.

To study these effects, we developed by SPDT, a series of bi-aspheric PMMA lenses of different dioptric powers for ophthalmic applications. We have calibrated the surface profile departures due to swelling during and after SPDT. For this, the surface quality is studied: ***a.*** immediately after SPDT and ***b.*** after a significant time delay (to allow for the settling of swollen profile post-SPDT). This data helps to modify the diamond tool path judiciously during the final machining cycle, to account for the geometrical departures and to maintain the desired surface profile features.

Future work includes a holistic approach of simulation studies and experimental verification of the thermal profiles of the polymer aspheric profiles by SPDT and the error profile compensation approaches.

Keywords: aspheric surface fabrication, single point diamond turning, aspheric characterization, form, figure, finish, thermal diffusivity, modified tool path, profile error compensation

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1. INTRODUCTION

Currently, polymer optics is increasingly deployed in the manufacture of optical systems for various applications. Commercially available polymers meeting polymer optical applications are Poly Methyl Meth Acrylate (PMMA), Polystyrene (PS), Polycarbonate (PC), Cyclic olefin copolymer (COC), Allyl diglycol carbonate (ADC), Polyetherimides (PEI), and Polyethersulfone (PES). Development of the polymer-based optical systems [1] with high performance lenses /modules is a specialized technology and needs sophisticated technique. However, due to the polymer material properties and issues of development process, large volume production of ultra-precision polymer optics is still an evolving and challenging process. A large majority of optical systems use spherical profiles, due to ease of fabrication and characterization. However, the progress in ultra-precision engineering demands as well as facilitates the use of aspheric profiles with low residual aberrations, improving system performances. Use of aspheric profiles also reduces the number of optical surfaces in the optical system, facilitating compactization of the system. In photographic optics, head-up-displays and helmet mounted displays, where volume and weight constraints are significant, aspheric profiles are often the only option. Semiconductor, consumer electronics, and aerospace systems depend on aspheric optics to increase the product performance.

In astronomical optics, reflective aspheric components are widely used. With the significant development of new plastic materials, low-cost molded aspheric refractive optics is finding their place in the large consumer market.

A general aspheric surface is, by definition, an optical surface that is not spherical in form. However in majority of (design, fabrication, assembly, utilization) contexts, optical profiles derived of rotationally symmetric conic sections are considered as aspheric surfaces.

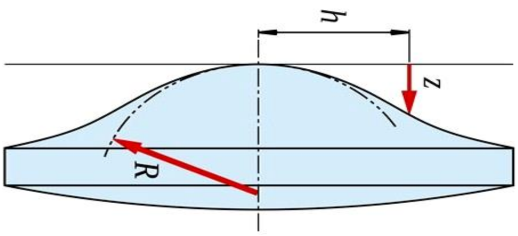

Fig.1: **Spherical & Aspheric surface profiles - Aspheric lens**

The general rotationally symmetric conic is described as:

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \alpha_1 r^2 + \alpha_2 r^4 + \alpha_3 r^6 + \alpha_4 r^8 + \alpha_5 r^{10} + \alpha_6 r^{12} + \alpha_7 r^{14} + \alpha_8 r^{16},$$

Where, *c:* Base curvature of the surface (inverse of radius of curvature) at the surface vertex; *k*: Conic constant; for Oblate Ellipsoid (rotating on its major axis) *k*> 0; for Prolate Ellipsoid

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(rotating on its minor axis) -1 <k< 0; for Sphere k = 0; for Paraboloid k = -1; for Hyperboloid k < -1; while A_i correspond to the constants of higher order conic terms.

1. THERMAL EFFECTS: CAUSE – EFFECT

Poly Methyl Meth Acrylate (PMMA) is a much favored polymer for mass production of precision components, lenses, and precision optics (from precision molds), in a many applications including bio-medical instrumentation (prosthetics/prosthesis), consumer instruments, security systems, industrial instrumentation, communication systems, etc. The favorable properties of PMMA, viz: its ductility, rigidity, toughness, impact strength, low mold shrinkage, high transmission, low haze, high degree of light stability, processability, moldability, and of course, its low cost, recommend it to be an ideal candidate for these applications. Hence, PMMA is gradually replacing optical glass modules in many strategic and precision instrumentation applications. To study and understand the behavior of polymers during Single Point Diamond Turning (SPDT), PMMA is selected for this study [2].

During the tool – work-piece interaction during SPDT, material removal takes place by shearing of the top layer of work-piece material. This interaction gives rise to a significant amount of thermal energy. The amount of heat thus generated will increase with increasing of machining cycles. It is to be noted here that, PMMA is a not a good thermal conducting material. Hence, the heat generated in SPDT is barely dissipated by radiation and conduction, and the residual heat is trapped within the component.

Fig 2: Nanoform X SPDT Equipment (Precitech make)

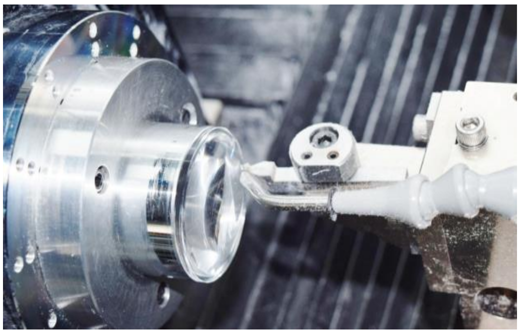

Fig. 3: SPDT of PMMA aspheric profile

During the SPDT, it is seen that, conventional coolants leave residual marks (groove patterns) on the machined surfaces, giving rise to rainbow like light patterns. To minimize these dispersive patterns, generally a sublimating-type alcohol-based coolant propelled on to the tool-job interface with cold jets of compressed air (in mist form) is used. This coolant and PMMA do not react at room temperature. However, at elevated thermal context in SPDT, the coolant tends to react with the top-most layer of PMMA disk, thereby affecting its transmission characteristics progressively, with increased coolant use.

Hence, in this study, it is decided to do away with the coolant and only cold compressed air jets are applied to cool the tool–job interface. Nevertheless, these compressed cold air jects are inadequate to quell the heat generated, though a good part of the heat is conducted through the diamond tool. PMMA being not a good thermal conductor, the major portion of the residual heat is trapped by the work-piece, causing a significant swelling of the surface profile. This swelling increases progressively with each cycle of (rough, fine and ultra-fine) machining.

The final SPDT machining cycles aim at profile error compensation (necessitated due to other reasons like tool wear, tool path variation etc) with minimal material removal [3-4]. Now this swelling (and recovery) adds to the profile change (both in terms of waviness and roughness) during the diamond turning, causing a (highly) probable transgression of prescribed tolerance limits of the aspheric surface profiles. In this scenario, the final machining cycle becomes very significant in order to account for the extra profile errors caused by this swelling.

The comprehensive study of the this thermal phenomenon calls for a holistic approach inclusive of detailed simulation studies, followed by experimental verification for a variety of optical grade polymer materials, profiles, precision machining equipment, tooling inventories, and surface quality requirements. This presentation is restricted to the presentation of the broad idea of the profile departure due to swelling.

2. MACHINING EXERCISES

Based on the initial studies by R&D community [2], the Aspheric Group at Optics & Allied Engg. Pvt. Ltd., a leading Precision Optics Industry in India has taken a lead in this direction, in terms of prototype development through limited production by fine-tuning the process-chain with innovative production technology inputs. Using the optical grade PMMA (Refractive index: 1.491), the design group has re-designed the popularly used 20D and 28D Indirect Ophthalmoscopic Bi-Aspheric lenses (by ophthalmologists for the fundus examination in eye-care centers and hospitals). Based on an earlier machining parametric study [2], an optimum combination of depth of cut (DoC), tool nose radius (TNR), tool over hang (TOH), tool feed rate (TFR) and spindle speed (SS) is selected for SPDT operations on the aspheric profiles of the PMMA bi-aspheric surfaces in both these powered lenses.

In this exercise, SPDT is conducted on a Precitech make Nanoform X aspheric generator; surface characterization is done on Taylor-Hobson make PGI 1200 Talysurf aspheric contact profilometer. In order to estimate the effect of swelling on the surface profile error, two sets of surface scans are taken: one set *immediately* after the SPDT cycles and second set of scans well after the surface is completely *cooled-off* (five days after diamond turning). Also, to confirm the consistency of profile errors, each surface is scanned and analyzed thrice with 60º angle between each scan. However, for brevity purposes, only set of scans are presented.

For this PMMA SPDT exercise, we developed a series of shallow and deep aspheric profiles re-designed for 20D & 28D

Indirect Ophthalmoscope. We have diamond turned the shallow and deep aspheric surfaces of 20D and 28D lenses with a maximum waviness tolerance (Pt) of one wavelength. Accordingly, we have designed our rough, fine and final correction SPDT machining cycles on all these four (two shallow and two deep) aspheric profiles.

Fig.4: 20D PMMA Bi-convex aspheric lens

Fig.5: PMMA Bi-convex aspheric lens

3. RESULTS:

We characterized each aspheric PMMA surface *immediately* after the SPDT cycles to include the *swelling* of the profile. And then each aspheric PMMA surface is allowed to *cool-off* normally for a period of about five days. After this *cooling-off* period, each aspheric PMMA surface is again characterized.

Figures 6-9 correspond to surface characterization curves of shallow profiles of 20D lens and Figures 10-13 are for 28D lens. The surface analysis results are presented in terms of Pt (peak-to-valley aspheric profile error in µm), Pq (rms aspheric profile error in µm) and RoC (base radius of curvature of aspheric profile in mm) in Figures 6, 8, 10 & 12; and the roughness values: Ra (arithmetic average roughness in nm), Rt (peak-to-valley roughness in µm / nm) in Figures 7, 9, 11 & 13.

Figure 6 refers to waviness (Pt & Pq) and changed RoC, characterized *immediately* after SPDT of 20D lens. While, Figure 7 corresponds to roughness (Ra & Rt), characterized *immediately* after SPDT of 20D lens.

Correspondingly, Figure 8 refers to waviness (Pt & Pq) and changed RoC, characterized after the *cooling-off* period for 20D lens; while, Figure 9 correspond to roughness (Ra & Rt), characterized after the *cooling-off* period for 20D lens.

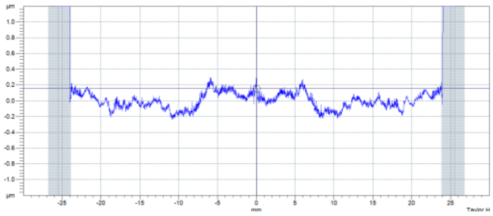

Fig.6: 20D – Instant Metrology - Profile Error (Pt: 0.5254µm, Pq: 0.1µm, RoC: 74.3758mm)

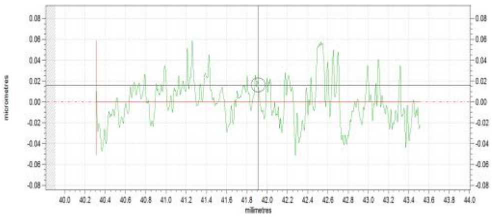

Fig.7: 20D– Instant Metrology - Roughness (Ra: 15.9nm, Rt: 0.110µm)

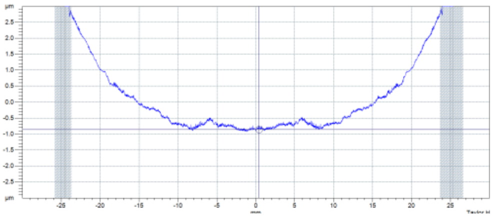

Fig.8: 20D – Delayed Metrology - Profile Error (Pt: 3.7983µm, Pq: 0.9668µm, RoC: 74.4461mm)

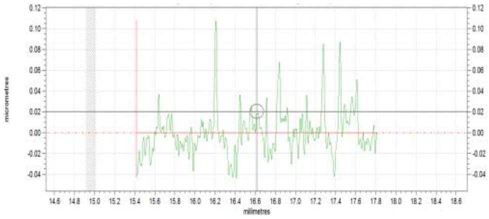

Fig. 9: 20D – Delayed Metrology - Roughness (Ra: 15.3nm, Rt: 0.151µm)

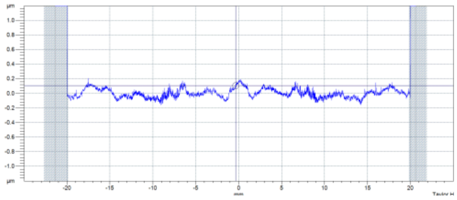

Fig.10: 28D – Instant Metrology - Profile Error (Pt: 0.3650µm, Pq: 0.061µm, RoC: 52.6834mm)

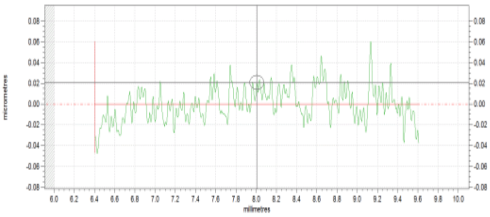

Fig.11: 28D – Instant Metrology - Roughness (Ra: 12.4nm, Rt: 107.5nm)

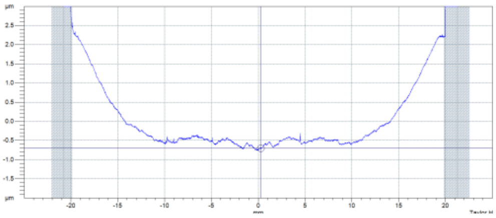

Fig.12: 28D – Delayed Metrology - Profile Error (Pt: 3.3352µm, Pq: 0.8395µm, RoC-52.7395mm)

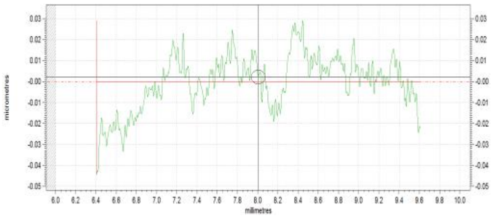

Fig.13: 28D – Delayed Metrology - Roughness (Ra: 10.2nm, Rt: 73.4nm)

Figure 10 refers to waviness (Pt & Pq) and changed RoC, characterized *immediately* after SPDT of 28D lens. While, Figure 11 refers to roughness (Ra & Rt), characterized *immediately* after SPDT of 28D lens. Correspondingly, Figure 12 refers to waviness (Pt & Pq) and changed RoC, characterized after the *cooling-off* period for 28D lens; while, Figure 13 refers to roughness (Ra & Rt), characterized after the *cooling-off* period for 28D lens.

The steep profile data and results are not presented due to paucity of space. However they also follow the same trends of shallow profiles.

4. DISCUSSION:

From these figures it is seen that: There is a significant variation in (base) Radii of curvature in both shallow and deep profiles in both 20D & 28D bi-aspheric PMMA lenses due to *swelling.* It is also seen that the RoC variation is more in 20D lens compared to 28D lens, due to *cooling-off*. Additionally, in both the 20D & 28D lenses, the shallow surfaces register larger RoC variation compared to deep surfaces due to thermal effects.

From Figures 6, 8, 10 & 12, corresponding to waviness analysis, it is seen that the effect of swelling on the peak-to-valley (Pt) waviness is very significant (beyond tolerable limits), while the rms waviness (Pq) also shows a clear change of magnitude due to swelling, (and may lead to rejection).

From Figures 7, 9, 11 & 13 corresponding to roughness analysis, it is seen that the effect of swelling on (arithmetic) average (Ra) roughness is practically non-existent, while the peak-to-valley (Rt) roughness assumes some significance due to swelling and hence contributes to the change in profile waviness error as seen above.

5. CONCLUTION

In order to guestimate the profile departure due to the thermal energy trapped within the material during SPDT and its gradual dissipation, the after-effects thereof and the relevant profile error compensation to be incorporated in final machining cycle can’t be oversimplified in a short presentation. However, it is necessary to acknowledge the presence of this effect and to plan accordingly to develop the aspheric profiles accordingly [5].

The comprehensive study of the this thermal phenomenon calls for a holistic approach inclusive of simulation studies, followed by experimental verification for a large cross section of work-piece materials, component profiles, precision machining equipment, tooling inventories, and surface quality requirements. The current presentation is restricted to the presentation of the broad idea of the profile departure due to swelling.

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