Brittle Machining Issues in Single Point Diamond Turning of Aspheric Infra-Red Optics

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Abstract

The demands on advanced strategic instrumentation have propelled precision IR optical system developers to target near theoretical performance, under system budgets of weight, volume and foot-prints. These requirements can be met only by using aspheric profiles to compactize IR system and to compensate for wavefront aberrations caused by spherical surfaces.

In last few years, Single Point Diamond Turning (SPDT) has become the workhorse for aspheric profile generation, due to its deterministic ultra-high-precision deliverance criteria. SPDT offers both opportunities and challenges for IR optical system developers of all streams. The benefits include compact systems with desired resolution and image quality. But the SPDT fabrication poses severe operational hurdles to overcome. The brittle nature of the IR materials to be processed presents further difficulties, while meeting the desired surface quality criteria.

The major aspects of SPDT of IR Systems (while maintaining desired surface quality criteria) include: material characteristics, machining parametric optimization, selection of suitable diamond tool geometries, monitoring of progressive diamond tool wear, effect of tool wear on surface quality, profile errors due to thermal energy generated during SPDT, profile error compensation, optimal machining conditions, work-piece handling (pre – during-post SPDT) and machining protocols.

In this presentation we discuss briefly some of these concerns. We conclude with empirical guidelines for ductile regime machining of brittle IR materials and pointers for probable deterministic processing of IR optics.

Keywords: Single point diamond turning, brittle machining, aspheric surface fabrication and characterization, ductile regime machining, thermal diffusivity, profile error compensation.

1. INTRODUCTION

Brittle materials such as Silicon, Germanium, Ceramics and glass are widely used in semiconductor, optical, electronics and various other fields. The desired surface quality and finish in these applications are very stringent. Conventional Grinding and Polishing processes deliver Silicon surfaces within tight tolerances. Since grinding is a random & uncontrolled material removal process, brittle fracture and Sub-Surface Damage (SSD) are inevitable. These surfaces post-grinding cannot be directly used for precision applications. The post grinding-polishing process makes the surface highly finished, but this process is complicated, time consuming and is nondeterministic in terms of processing *Vs.* final surface quality.

Single Point Diamond Turning (SPDT) technology is of great importance for the fabrication of precision parts in various industrial sectors, such as optics, clean energy, information and communication technology, and others. It is capable of achieving a super smooth surface of not only the machinable metals but also the brittle materials, which is free from the conventional time consuming polishing. The brittle materials, however, are difficult to be machined due to their low fracture toughness and high hardness. Such properties tend to bring in some unwanted fractures, which finally results in a damaged or nontransparent surface. Hence, to achieve a crack-free surface, the top surface layer of brittle materials must be removed in ductile mode. To achieve a smooth surface of brittle materials also relies on machining environment, diamond tool performance, process parameters, tool geometry, cutting edge radius, as well as the properties of workpiece materials [1].

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Many non-ferrous materials such as aluminum, copper, electro-less nickel lend themselves nicely to diamond turning. Additionally, several polymers and crystals are also suitable for diamond turning. The crystalline materials that can be diamond turned are: germanium, zinc selenide, lithium niobate and silicon.

2. SPDT ISSUES OF IR MATERIALS:

The brittle nature of the IR materials such as Silicon, Germanium, Ceramics lend to a host of fabrication issues in terms of tooling, machining, tooling, thermal expansion, tool wear, progressively degrading surface quality with tool wear and increasing developmental costs. On the other hand, the surface quality and finish requirements for their applications are very stringent. Compared with the traditional grinding and polishing process, the nano-scale material removal by SPDT is gaining popularity to generate precision optical lenses and mirrors [1] as per the applications. To counter the brittle nature of these materials, suitable ductile regime machining is prescribed to control the profile quality within the allowed tolerances of surface form, figure and finish.

2.1. Thermal Issues in SPDT of Brittle Materials

A large majority of the IR materials are not good thermal conductors. As with the plastic materials, the residual thermal energy plays a major role in the development of precision components with brittle materials as well. In case of polymers, the surface profile alone was a major obstacle to deal with.

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.

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The amount of heat thus generated will increase with increasing of machining cycles. As these materials are good thermal conductors, the heat generated in SPDT is barely dissipated by radiation and conduction, and the residual heat is trapped within the component. The SPDT generated surfaces have a grating-like pattern which may give rise to a rain-bow type dispersive pattern on the diamond turned surface, due to inappropriate machining coupled with the remnants of the coolant in the grating pattern (Figure 1). Judicious selection of machining parameters and a suitable coolant will greatly reduce the grating like pattern generally seen on SPDT generated surfaces. To minimize these dispersive patterns, a sublimating-type alcohol-based coolant projected on to the tool-job interface with cold jets of compressed air (in mist form) is used.

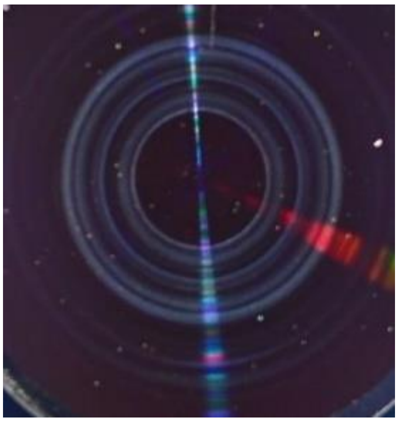

Figure 1: SPDT generated Si aspheric surface with improperly selected machining parameters & thermal 'hot zones'

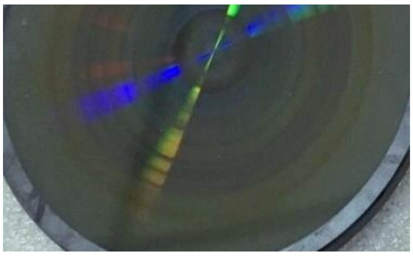

Figure 2: SPDT generated Si aspheric surface with Improved surface due to better machining parametric matrix, yet with thermal 'hot zones' (seen as differently hued color zones)

Figure 1 depicts a regular case of SPDT operation of silicon aspheric surface. For these brittle materials, the first step of SDPT operations is to explore and decide on an optimal machining parametric combination. In Figure 1 the colored star-like visuals clearly indicate that the spindle speed and feed are not optimally selected and suffer the effects of tool wear as well.

In Figure 2, this situation is somewhat improved, by deploying right combination of machining parameters. Additionally, in both figures, one can see the differently colored 'hot zones' due to non-uniform distribution of heat generated and trapped "within" the work-piece.

However, with these materials, their optical properties will also undergo significant changes due to the thermal energy trapped in these components. In our studies, it is noted that the precision silicon, germanium components during SPDT suffered with non-uniform distribution of the residual thermal energy. This gives rise to possible change in the refractive index of the material, which alters the ray path during the refraction (Figure 2). The challenge here is not only to predict it's orientation but also to control it.

A preventive method to deal with this problem is to re-organize the machining philosophy. It is seen that, in case of spherical surfaces, repeated cycles of shaping, rough grinding and fine grinding result in excessive sub-surface damage (SSD). SSD also, due to the trauma caused in the sub-cutaneous layers of the precision components, may result in altered ray path in the components. The SSD can be reduced only by a well-planned polishing process, wherein the top most layers of the component are gradually removed, without a. altering the component shape (form), b. further adding to the residual figure error and c. by effectively reducing the roughness (better finish), while not further damaging the layers just below the top surface. e just below t shape) of the component However, in the case of aspheric profiles, the multiplicity of machining cycles will result not only in SSD, but also give rise to 'hot zones' / 'hotspots' in the material, with potential refractive changes and altered ray-path than the intended one.

Only way to deal reduce these 'hot zones' / 'hot spots' is reduce the amount of machining. However, to compensate for the profile error, one needs repeated fine machining cycles. There is this dilemma of how many cycles are needed to correct the profile error, while controlling the count of 'hot spots' in the material. This calls for a hybrid approach of grinding-polishing and precision diamond turning, with judicious mix of dual processing cycles.

2.2. Diamond Tool Geometry –Tool Wear

SPDT of brittle materials is saddled with excessive diamond tool wear and increased tooling costs. We have conducted a typical diamond tool wear study to present the tool wear progression in the SPDT of an optical grade flat Si disc of 50mm diameter 50 mm and 15 mm thickness. For this study, we selected anon-controlled waviness single-crystalline natural diamond of -30° rake angle,15° clearance angle and with 0.5 mm tool nose radius (Contour make). The geometry impacts both wear of tool and quality of SPDT surface significantly.

Figure 3: Un-Used Diamond Tool

Our study started with an unused diamond tool (Figures 3& 4). We measured its wear in terms of its geometry departure from its prescription. Figure 5 shows the departure in geometry / wear of an unused tool. Then we started a series of iterative SPDT operations to remove a calibrated amount of Si material in each machining cycle with a well-chosen matrix of machining parameters.

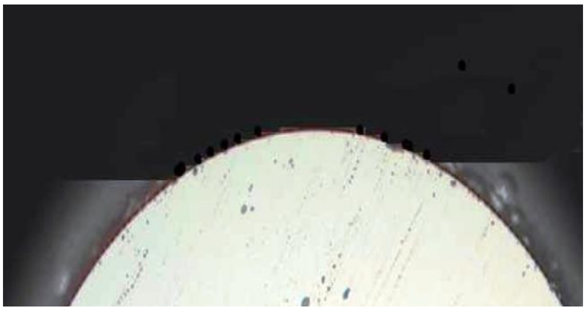

Figure 4: Nose of Un-Used Diamond Tool

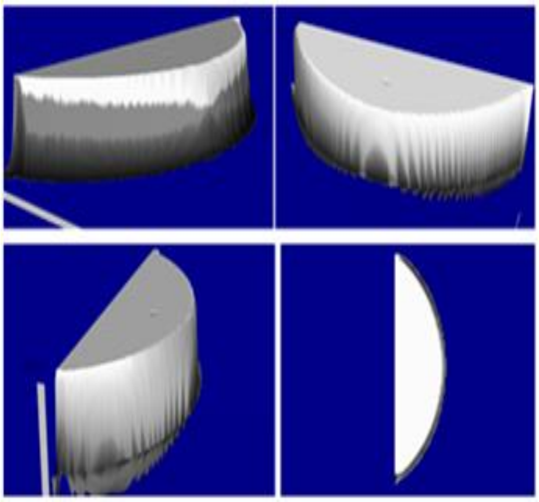

Figure5: Geometry of Un-Used Diamond Tool

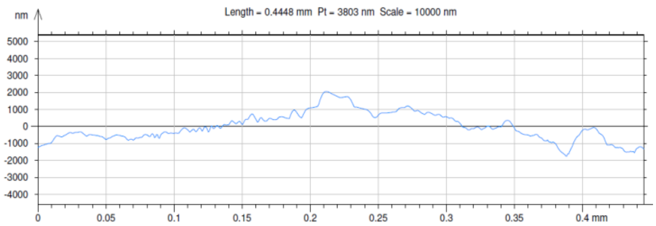

Figure6: Waviness (3.8 µm) of Un-Used Diamond Tool)

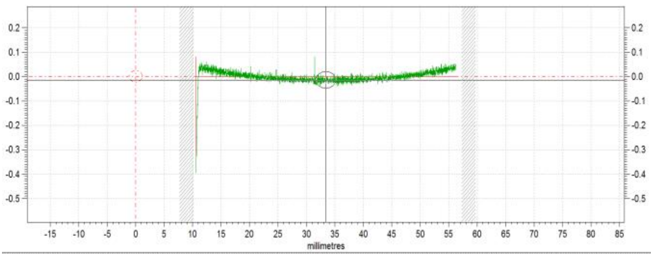

Figure 7: Roughness (Ra: 15 nm) - SPDT by Un-Used Diamond Tool

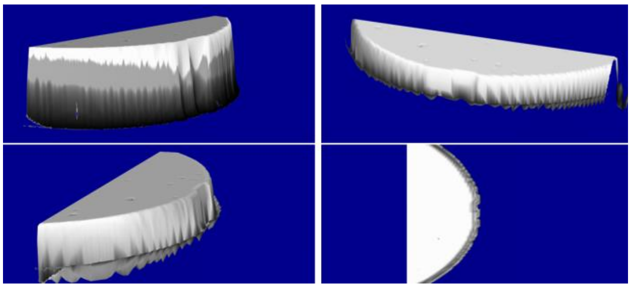

Figure 8: Geometry of Worn (50 Cycles) Diamond Tool

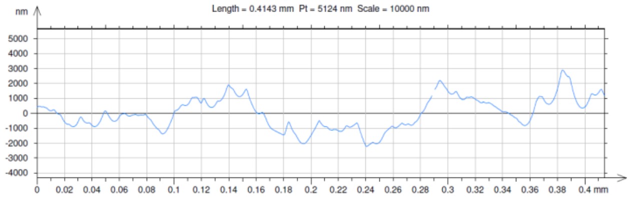

Figure 9: Waviness (5.1 µm) of Worn (50 Cycles) Diamond Tool

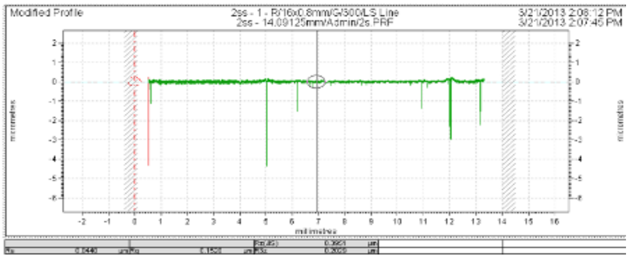

Figure 10: Roughness (Ra: 44 nm) - worn (50 Cycles) Diamond Tool

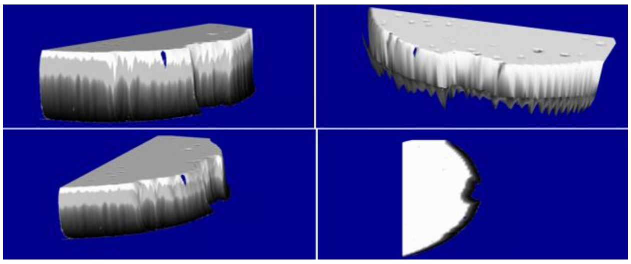

Figure 11: Geometry of Worn (100 Cycles) Diamond Tool

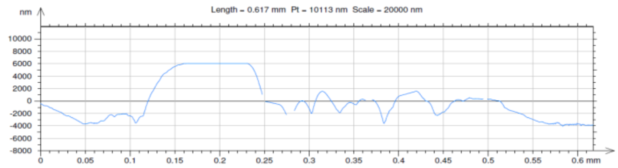

Figure 12: Waviness (10.1 µm) of Worn (100 Cycles) Diamond Tool

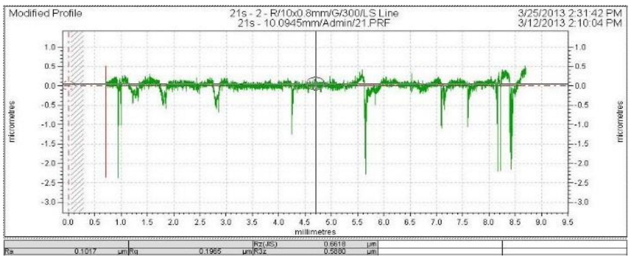

Figure 13: Roughness (Ra: 102nm) worn (100 Cycles) Diamond Tool

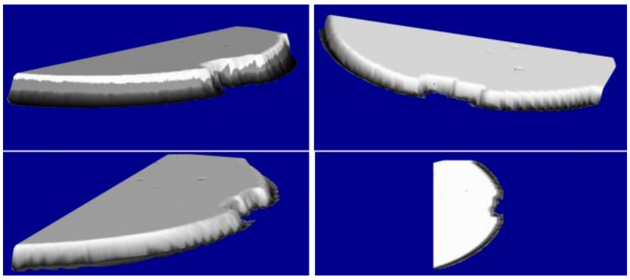

Figure 14: Geometry of Worn (150 Cycles) Diamond Tool

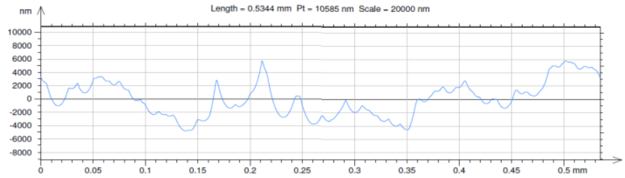

Figure 15: Waviness (10.6 µm) of Worn (150 Cycles) Diamond Tool

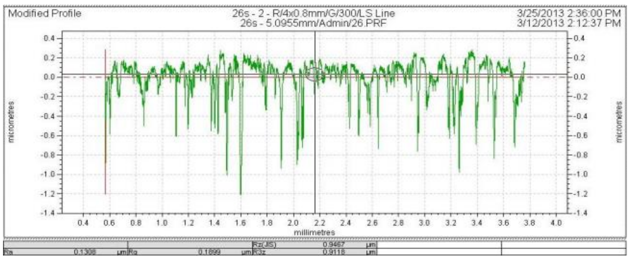

Figure 16: Roughness (Ra: 131nm) worn (150 Cycles) Diamond Tool

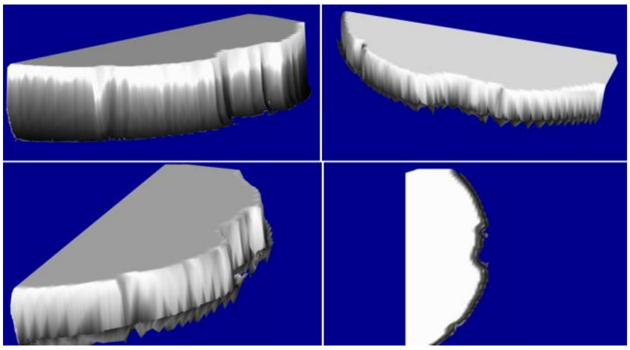

Figure 17: Geometry of Worn (200 Cycles) Diamond Tool

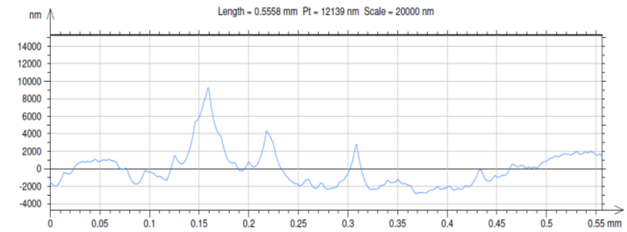

Figure 18: Waviness (12.2 µm) of Worn (200 Cycles) Diamond Tool

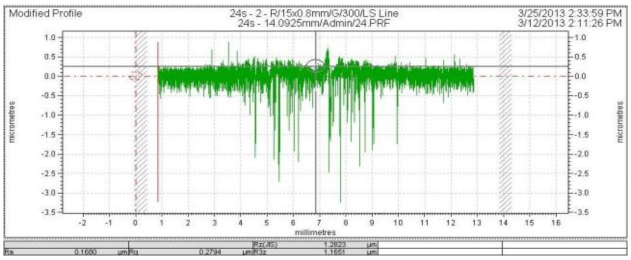

Figure 19: Roughness (Ra: 168nm) worn (200 Cycles) Diamond Tool

There is no wear for the new tool and its waviness (Figures 5-6) as measured to be 3.803µm. Figure 7 shows the roughness (15 nm) of the diamond turned Si surface with new (unused) diamond tool.

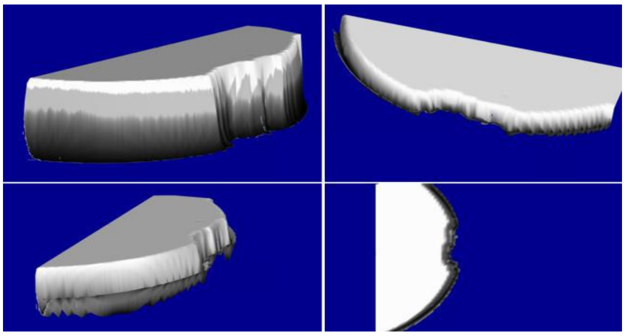

Figure 20: Geometry of Worn Diamond Tool after 270 cycles

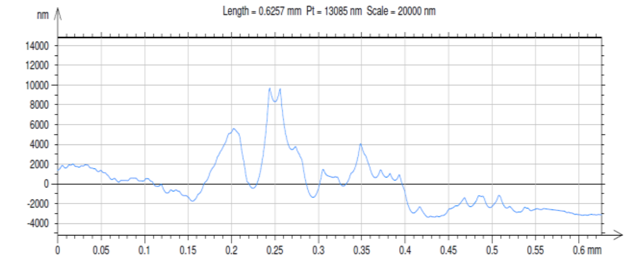

Figure 21: Waviness (15.8 µm) of Worn (270 Cycles) Diamond Tool

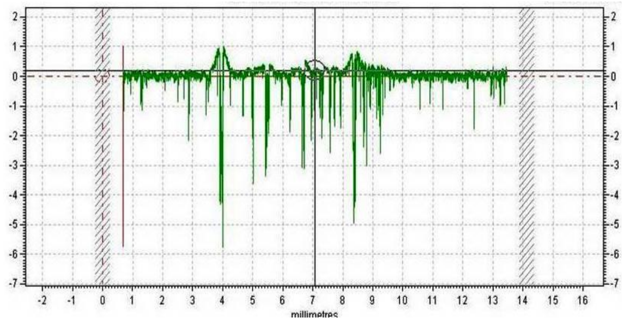

Figure 22: Surface Roughness - by worn Diamond Tool after 270 SPDT cycles

We studied the tool wear after 50 cycles (Figures 8-10), 100 cycles (Figures 11-13), 150 cycles (Figures 14-16), 200 cycles (Figures 17-19) and finally 270 cycles (Figures 20-22) of iterative SPDT operations.

We see that, the diamond tool wear is progressively increasing (Figures 6, 9, 12, 15, 18 & 21) and the surface (Ra) is also becoming increasingly rough (Figures 7, 10, 13, 16, 19 &

22)between 0 – 50 – 100 – 150 - 200 – 270 cycles of diamond turning.

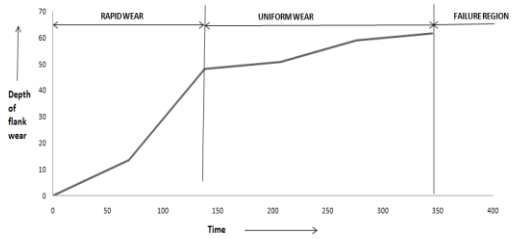

Figure 23: Depth of Flank Wear *Vs.* Time

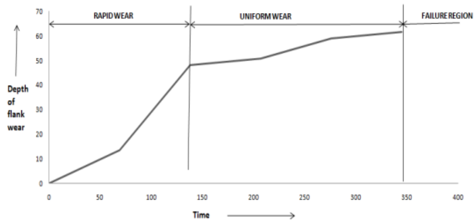

Figure 24: Width of Flank Wear *Vs.* Time

This study gives us an idea of the diamond tool wear under regulated conditions and machining cycles. In normal SPDT processing this regulation doesn’t exist. Hence, the diamond tool wear may progress in unsteady process. Hence, it is necessary to bring some semblance of systematic operational protocol and to design the SPDT cycles towards diamond tool wear of some guestimate. This helps us in predictable surface quality and some control over the tooling costs.

2.3. Relative Vibration between Tool &Workpiece

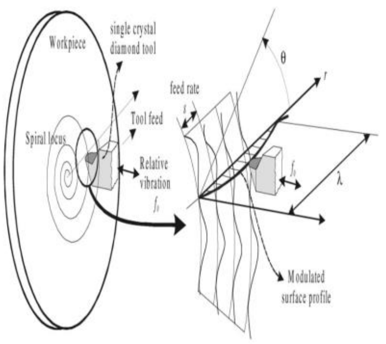

Figure25: Undulations due to Relative Vibration between Diamond Tool & Work-piece

A small-amplitude low-frequency relative vibration exists between diamond tool and the work-piece. These vibrations cause waviness not only in the cutting direction but also in the tool feed direction. This effect is termed as tool-workpiece vibrations. It causes the sinusoidal variation in height of the spiral groove of the tool path. Figure 11 shows the scheme of undulations formed on the surface machined in the presence of vibration.

2.4. Micro-friction force

In SPDT of brittle materials, the cutting parameters are always configured to yield extremely small under-formed chip thickness, and the order of which is comparable to the lattice size of materials as machined. In this case, the size effect appears, and the effect of micro-friction force between diamond tool and work-piece becomes more significant, which in return heavily affects the material removal [1].

3. CONCLUSION

The proliferation of Single Point Diamond Turning investigations over the past decades has enabled the generation of optical finished surfaces on brittle materials. In ductile-regime machining, brittle materials can be machined in a ductile mode with the mirror finish and without cracking. The key point is to identify the machining conditions to achieve the ductile regime machining and whether these identified parameters are optimal. The Tool feed rate, Depth of cut and Spindle Speed play a major role in obtaining a good surface finish on brittle material [2]. In this study, experiments are channelized towards the brittle machining issues in single point diamond turning, wherein optical quality surface finish can be achieved on brittle material by SPDT [2].

The SPDT experiments are conducted on Nanoform X (Precitech make) aspheric surface generator. The machined surface is characterized by PGI-1200 Phase Grating Interferometer (Taylor-Hobson make).

References

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2. Neha Khatri, “An experimental investigation on the influence of machiningparameters on surface finish in diamond turning of silicon optics”, SPIE (2015)