Shape Adaptive Grinding (SAG): A Novel Fabrication Method for Freeform Optical Molds

Anthony Beaucamp (1), Yoshiharu Namba (1)
(1) Dept. of Mechcanical Engineering, ChubuUniversity, 1200 Matsumoto-cho, Kasugai, Aichi, Japan
beaucamp@isc.chubu.ac.jp, namba@isc.chubu.ac.jp

Abstract: A novel fabrication method for freeform optical molds is proposed: Shape Adaptive Grinding combines an elastic tool with rigid diamond bearing pellets. This process delivers roughness below 1nm Ra on molding steels and CVD carbides.
OCIS codes: (220.4610) Optical fabrication; (220.1920) Diamond machining; (080.2205) Fabrication, injection molding.

1. Introduction

Manufacturing of optical components by replication from molding dies has been increasingly adopted by the consumer electronics industry, where mass production at low cost is paramount. Typical manufacture methods include press molding of glass lenses from steel and carbide die inserts. The production of small molds by ultra-precision grinding [1,2] and polishing [3,4] has been well documented. However, the required apparatus and tooling remains costly, time consuming, and difficult to scale up to large mold sizes (above 100mm).

In this paper, a novel method called Shape Adaptive Grinding (SAG) is presented that may significantly reduce manufacture costs and time in the production of dies inserts for glass optics molding. Starting from a very rough machining state > 1 μm Ra, such as milling or CVD coating, this method can efficiently and predictably deliver surface roughness < 1 nm Ra without any need for periodical tool dressing. General tool compliance with curved surfaces also means that it can be used to process most freeform shapes, either convex or concave.

2. Principle of Shape Adaptive Grinding

The basic principle of the SAG tool consists of maintaining general compliance between the tool and freeform surface over a sub-aperture contact area of the workpiece, as shown in Fig. 1 (left). But at the same time, hard contact is achieved at relatively smaller scale by rigid pellets covering the surface of the elastic tool, such that effective grinding can take place (rather than a soft contact resulting in polishing). The process is shown in operation on a 7-axis CNC machine in Fig. 1 (right).

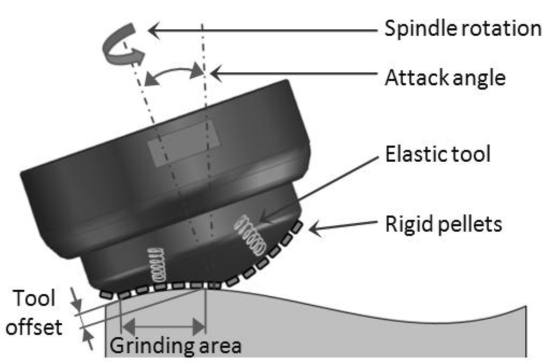

Fig. 1. Principle of Shape Adaptive Grinding (left) and operation on a freeform workpiece (right).

The operation of the SAG process builds upon precessed bonnet technology [5], and can be described as follows: The position and orientation of a spinning, inflated, membrane-tool are actively controlled as it traverses the surface of a workpiece. The workpiece may have any general shape, including concave, flat, or convex, aspheric or free-form. While a classical grinding tool is moving against the surface of the part and cutting as it moves, in the technique we describe the Z position and tool inclination (but not directly the contact-force) are actively controlled with a CNC machine tool. It is possible to numerically control the inclination angle, spindle speed, geometrical offset, and surface feed of the grinding spot to obtain variations in spot size and removal rate.

3. Experimental Results

Process characterization of the SAG tool was carried out on silicon carbide and Stavax (a molding steel). In the case of silicon carbide, small blocks were milled from graphite and coated with SiC by CVD. As for the Stavax samples, they were simply cut with a 5-axis milling centre. The SAG experiments were carried out on a 7-axis CNC machine normally used for polishing (i.e. low stiffness machinery, unlike the expensive high stiffness apparatus usually required for ultra-precision grinding). The experimental parameters are summarized in Table 1.

Table 1. Parameters of SAG tool experiments.

Workpieces	Graphite coated CVD silicon carbide, Stavax stainless steel.
Tool Type Grinding Cloth Tool Diameter Pressure Range	Rubber reinforced with Kevlar Intertwined textile/metal fabrics 10 to 40 mm 0.5 to 2.0 bar
Tool Path Mode Track Spacing Attack Angle Surface Feed Range Spindle Rotation Speed	Raster 0.15 mm 10 to 20 deg 10 to 1000 mm/min 100 to 3000 rpm
Abrasives Grain Size Range Pellet Binder	Diamond 3, 9, 40 µm Nickel and resin

Several types of pellets were used in these experiments: nickel pellets with 9 and 40 µm diamond abrasives for the rough grinding stage, and resin pellet with 3 µm diamond abrasives for the finishing stage. The surfaces were measured before and after grinding by confocal laser microscope with 100x objective, and white light interferometer with 50x objective. The results from these experiments are shown in Fig. 2 and 3.

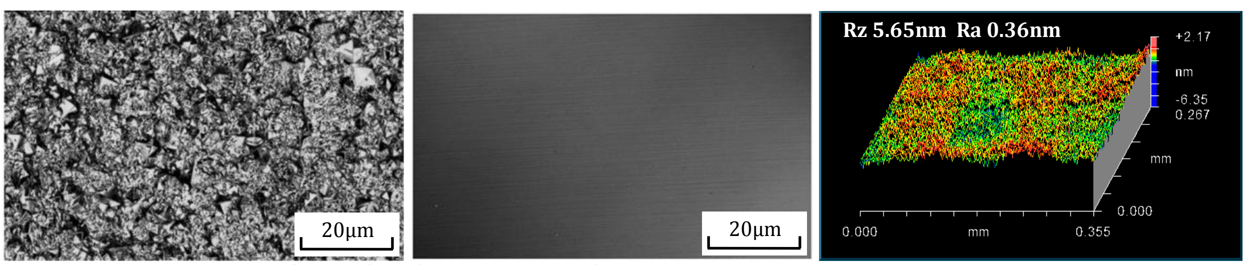

Fig. 2. 100x micrographs of SiC surface after CVD coating (left), and SAG machining (center). Final micro-roughness at 50x (right).

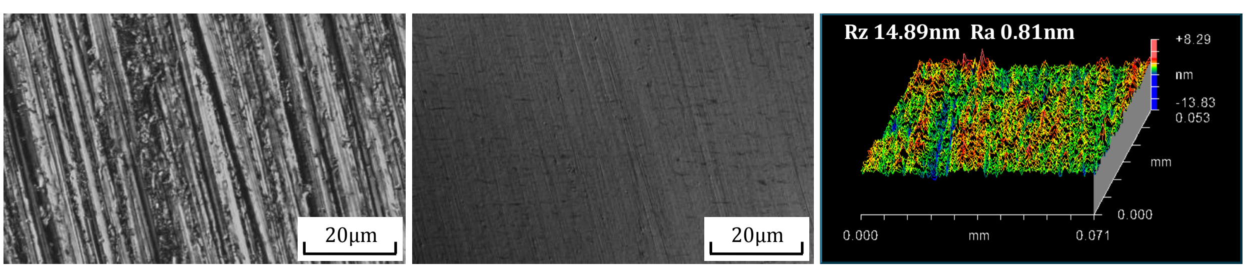

Fig. 3. 100x micrographs of Stavax surface after milling (left), and SAG machining (center). Final micro-roughness at 50x (right).

The micrographs show clearly that the SAG process can operate in ductile mode grinding, with no break-up of the surface material. While such performance traditionally requires very stiff apparatus, frequent dressing of the grinding wheel, and maintaining low amounts of material removal, the opposite is true for all criteria in the case of SAG machining, making this method very attractive from both cost and time point of views.

Micro-roughness below 1 nm Ra could be achieved consistently on both SiC and Stavax with the 3 µm resin pellets used for finishing, suggesting that this technique is suitable for manufacturing optical surfaces.

4. Comparison with Conventional Grinding

The variation in surface roughness as a function of pellet type and time is shown in Fig. 4 (left), with logarithmic scale applied along the Y-axes (data gathered on CVD SiC). The horizontal axis shows the time spent grinding a 5x5 mm area. Final Ra between 1~100 nm could be achieved with the various combinations of pellet and grain size. The finest roughness was achieved with 3 µm resin pellets, though reaching a stable surface condition with required a much longer grinding time (10 min) than for nickel pellets (0.2 min). Combining 2 or 3 different pellet types is thus recommended for optimizing overall process time.

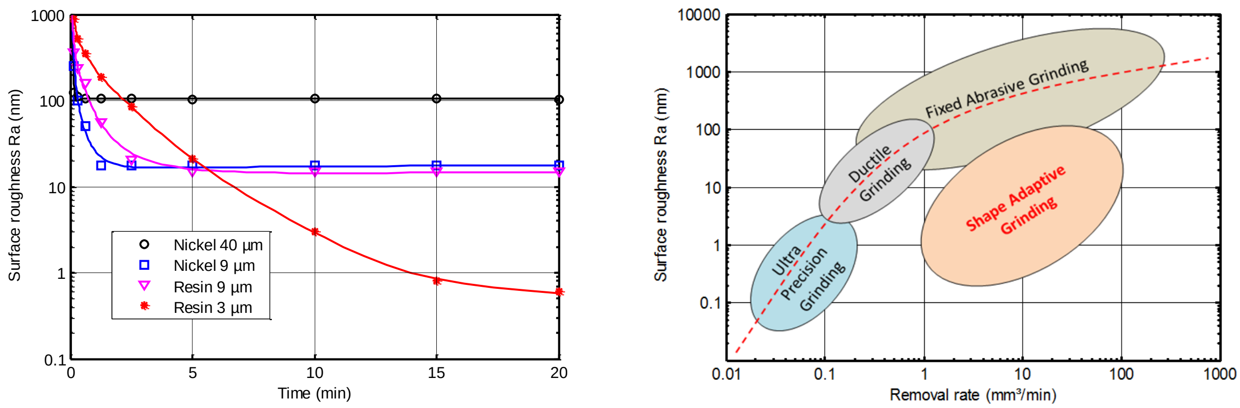

Fig. 4. SiC surface roughness as a function of time and diamond size (left), comparison of conventional and shape adaptive grinding (right).

In conventional grinding, there exists a direct relationship between removal rate and the achievable surface roughness. The red line in Fig. 4 (right) shows the typical path followed when going from brittle to ductile grinding regime, and then going on to ultra-precision grinding. Ultra-precision grinding has been shown to deliver roughness less than 0.1 nm Ra on plano surfaces, but necessitates very low removal rates [6]. The SAG tool offers an alternative to this traditional path by delivering low surface roughness down to less than 0.4 nm Ra while maintaining very high removal rates (up-to 2 orders of magnitude higher than conventional methods).

When combining these high removal rates with the lack of tool dressing, the SAG process appears to be a very promising method for high throughput manufacturing of optical molding dies. Future papers will explore corrective shaping ability by SAG, demonstrating the ability to produce ultra-precise optical form.

4. Acknowledgments

This work was supported by JSPS Grant-in-Aid for Scientific Research (B) No. 22360063, from the Japan Society for the Promotion of Science.

5. References

[1] Semba T., Tani Y., Sato H., “Development of Melanine-Bonded Diamond Wheels with High Porosity for Smooth and Mirror Finishing of Die Materials”, Annals of the CIRP, **45/1**, 315-318 (1996).

[2] Suzuki H., Moriwaki T., Yamamoto Y., Goto Y., “Precision Cutting of Aspherical Ceramic Molds with Micro PCD Tool”, Annals of the CIRP, **56/1**, 131-134 (2007).

[3] Suzuki H., Hamada S., Okino T., Kondo M., Yamagata Y., Higuchi T., “Ultraprecision Finishing of Micro Aspheric Surface by Ultrasonic Two-Axis Vibration Assisted Polishing”, Annals of the CIRP, **59/1**, 347-350 (2010).

[4] Beaucamp A., Namba Y., Inasaki I., Freeman R., “Finishing of optical moulds to λ/20 by automated corrective polishing”, Annals of the CIRP, **60/1**, 375-378 (2011).

[5] Walker D., Freeman R., Morton R., McCavana G., Beaucamp A., “Use of the Precessions Process for Prepolishing and Correcting 2D and 2.5D form”, Optics Express, **14/24**, 11787-11795 (2006).

[6] Namba Y., Kobayashi H., Suzuki H., Yamashita K., Taniguchi N., “Ultra-precision surface grinding of chemical vapor deposited silicon carbide for X-ray mirrors using resinoid-bonded diamond wheels”, Annals of the CIRP, **48/1**, 277 (1999).