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Controlling stress in sapphire optics

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ABSTRACT

Precision optical fabrication is often influenced by surface stress introduced during processing. Various steps, such as lapping, grinding, polishing and coating, can influence optical figure and transmitted wave front in sapphire optics. The Twyman effect was used as a tool to measure the variation in stress from different processes and to investigate annealing treatments. Compressive stresses were generated by all fabrication techniques; however, the magnitude of stress varied considerably. The highest stress was generated during the transition from the brittle to ductile mode of removal; the lowest stress was observed during polishing with colloidal silica. Heat treatments were successful in removing machining stress from the parts. After heat treatment at 1450°C, the remaining grinding-induced stress levels were too small to measure accurately.

Keywords: Twyman effect, grinding stress, heat treatment, stress depth, polishing, lapping

1. INTRODUCTION

Stress in sapphire affects optical and mechanical performance in optical window applications. Stresses generated during fabrication have been shown to affect strength[1], wave front distortion and optical figure[2]. Several studies found that surface stress can act to increase the effective compressive strength of sapphire[1,3]. Generally, however, reducing stress is necessary to meet strict flatness and transmitted wave front specifications. Traditional methods for measuring optical figure have helped to assess the amounts and types (tensile vs. compressive) of stress generated by most fabrication processes. Still, some debate surrounds the effect of polishing and the transition from the brittle to ductile mode of material removal.

Extensive research on the fabrication of optical glasses has led to a good understanding of mechanisms and models of material removal. Material removal rates and subsurface damage have been successfully linked to the material's Young's modulus, fracture toughness, and hardness[4, 5, 6]. Crystalline materials, such as sapphire, do, however, add further complexity to the study of fabrication because of the inherent anisotropy; mechanical properties vary depending on orientation[7, 8]. Customarily fabricators experience radical variations in process time when lapping and grinding different sapphire orientations. Stress generated during fabrication steps on off-axis sapphire also shows anisotropic characteristics [9]. The bending of *c*- plane (0001) sapphire wafers polished on one side is spherical; similar wafers with 90-degree orientation to the *c*-axis bend in either a cylindrical or elliptical fashion[9].

Various techniques, such as etching, ion milling, polishing and heat treatments, have been used to remove stresses[10]. Times, temperatures and depths of removal should vary depending on material, process and orientation. This can become complex when working with different processes and orientations, and may require several iterations to arrive at the proper annealing cycle. Substituting trial and error methods with a process based on the known material properties will help in producing higher quality optics more efficiently.

Because of sapphire's desirable optical and mechanical properties and development of detectors in midwave IR (3-5μm) the use of sapphire has grown rapidly. Sapphire's strength and abrasion resistance are extremely attractive especially in harsh environments[8]. Therefore, a detailed description of sapphire's fabrication properties will be useful. This paper is intended to highlight some of the many differences between glass and sapphire.

Fabricators of precision optics are frequently asked to manufacture plano substrates or windows with aspect ratios greater than 25:1. Specifications such as flatness, parallelism, and transmitted wave front can be challenging in high aspect ratio components. If different finishing techniques are used on opposing surfaces, it is likely that different stress levels exist on opposing surfaces, and bending or distortion will occur (the Twyman effect)[7,10-13]. The Twyman effect was first reported by F. Twyman in 1905[2] and it relates to the bending of thin substrates from compressive stress generated during grinding. The Twyman effect is often observed in thin substrates with different surface preparation. Grinding-induced bending forces are generated by grinding stresses, which occur in a near-surface layer. This surface layer is denoted as the stress depth.

The prevailing hypothesis relating to the magnitude and direction of grinding-induced stresses states that compressive forces are generated during lapping and grinding, and that the magnitude of the grinding-induced bending force is generally reduced when the size of the abrasive is reduced[10,13]. In addition, the depth of the stressed layer may be reduced when smaller size abrasives are used. This leads to the important point that while the magnitude of the grinding-induced bending force is decreased with smaller abrasives, the actual grinding stress may be increased[13]. Furthermore, the transition from brittle to ductile material removal may increase the residual stresses by up to 4 times[14], with maximum surface stress values approaching the yield strength of the material[10].

Polishing has been used by many glass researchers as a way to remove stress; however, this has been questioned by several authors[9,15,16]. Polishing as a ductile removal may involve high residual stresses as demonstrated by using 1 and 3 μm diamond abrasives on glass substrates[14]. Thus, for crystalline materials like sapphire it is important to identify what type of polishing will remove stress, if any, and whether the surface polish quality is related to the grinding-induced bending stress. This study has been designed to: 1) measure stress levels from common fabrication techniques including two types of polishing; 2) evaluate stress removal methods; and 3) predict the magnitude of stress based on the process and material.

2. EXPERIMENTAL

In an effort to isolate the magnitude of stress attributable to each step, a number of sapphire substrates were prepared by different fabrication techniques. Two different experiments were run. The first experiment was designed to test the stress states from polishing and lapping and also to evaluate the effectiveness of heat treatments in reducing these stresses. The second experiment was designed primarily to investigate the brittle-to-ductile transition. To minimize the inherent anisotropy of sapphire, *c*- plane (0001) material was used.

Window blanks were cut from a 1.0" diameter centerless-ground rod for the first experiment. Half of the samples were lapped on both sides with 15 μm polycrystalline diamond and half with 30 μm polycrystalline diamond, both on cast iron, to approximately 0.060"(1.52 mm). Following the lapping process, some samples were heat treated. Two heat treatments were chosen: 1450°C (T/Tm = 0.75, with Tm as the melting point in degrees Kelvin) in air for 4 hours and 900°C (T/Tm = 0.5) in air for 4 hours. A list of the pre-polishing steps is summarized in Table 2.

Once lapping and annealing operations were completed, the substrates were separated into two sets (Table 3). Each set contained six samples that were waxed down to steel plates with sticky wax from Universal Photonics. Group one was given an inspection polish on one side with polycrystalline diamond, down to 1/4 μm on a tin lap. The second set was sent for a commercial pad polish using colloidal silica. The parts were finished to a thickness of 0.050" (1.27 mm) and polished to a flatness of roughly 1 wave of power convex, as measured on a Zygo Mark IV phase shifting interferometer while still mounted. Power was measured on the polished side of the sample, both before and after deblocking.

For the second experiment previously polished windows were ground and lapped on one side. Polycrystalline diamond abrasives were used on a cast iron lap. Samples were lapped with progressively finer diamond sizes and at each step a sample was removed. The abrasive sizes 45,30,15, and 6 μm were used. Samples thickness ranged from 0.5 mm to 1.0 mm.

Table 2. Experiment 1 Pre-polish variables

Designation	Variable
A1	Anneal @ 900°C 4 hr. in air
A2	Anneal @ 1450°C 4 hr. in air
NA	No Anneal
15 μ	Lap 15 μ m Poly diamond on cast iron
30 μ	Lap 30 μ m Poly diamond on cast iron

Table 3. Experiment 1 matrix

	1	2	3	4	5	6
Diamond	15μ, A1	15μ ,A2	30μ ,A1	30μ , A2	15μ, NA	30μ ,NA
Pad	15μ, A1	15μ ,A2	30μ ,A1	30μ , A2	15μ, NA	30μ ,NA

After polishing (experiment 1) or lapping (experiment 2), the parts were unblocked and remeasured for flatness in a free state. Any change in the curvature (power) between the mounted and dismounted state is the result of differential stress levels caused by variations in substrate preparation[10]. Curvature was measured with a Zygo Mark IV phase shifting interferometer on the polished side. Note that the measured curvature is the combined result of stress on both the polished and ground sides. Grinding-induced bending force per unit length, P(o), is calculated using the equation:

$$P(o) = \frac{1}{6} \times \frac{E}{1-\nu} \times \frac{h^2}{R}, \tag{1}$$

where E is the Young's modulus, ν is Poisson ratio, h is the thickness of the substrate and R is the radius of curvature of the substrate. Notice that equation (1) is valid for small deflections of isotropic thin plates. Grinding-induced bending force is proportional to the amount of energy stored in the surface, while the grinding stress (σo) is the force per unit area:

$$\sigma o = P(o) / \text{depth of stress}, \tag{2}$$

so that grinding stress (σo) is in stress units.

In addition to the stress measurements, the ground sides of samples in the first experiment were inspected using a Zygo New View and the polished sides were inspected using a Zygo Maxim. Surface roughness peak-to-valley (P-V) results may be integrated with the measured bending forces to help complete the description of the Twyman effect. Depth of stress is an important factor and varies with abrasive size, as does surface roughness. Moreover, the shape of the abrasive also plays an important role[10]. Sharp indentors have a higher surface stress state, but lower total depth of stress than blunt indentors, which is similar to the role of ductile vs. brittle removal on surface stress.

3. RESULTS

3.1 Grinding-induced bending forces

As predicted by the Twyman theory, the non-heat-treated samples polished on one side with either diamond or pad exhibited concave bending (Figure 1), represented as a positive measured bending force in Table 4. Values of corrected grinding-induced bending force (Table 4) are fairly consistent between the two polishing groups. Contrary to previous findings[12,13], however, the sample lapped with 15μm diamond had a higher grinding-induced bending force than the sample lapped with 30μm diamond.

Table 4 contains the measured and corrected values of grinding-induced bending force for lapping and polishing. Negative values in measured bending force indicate the sample is bowed convex; positive values indicate sample is bowed concave. The corrected bending force represents the amount of grinding-induced bending force on the lapped side for room temperature and 900°C samples; the corrected value was computed by subtracting the effect of the polished side. The value of bending stress residing on the polished side (side 2) was assumed to be equal to the 1450°C measured bending force.

This trend was verified in the second experiment, which showed that on a cast iron lap the highest grinding-induced bending force (Figure 2). Stress levels declined with both larger and smaller abrasive sizes. All samples processed on the cast iron lap had ground surfaces. Increased bending force caused by lapping with smaller diamond has not, traditionally, been documented on glass substrates until there is a transition from brittle to ductile removal, which normally occurs with abrasives in the 2-5μm range.

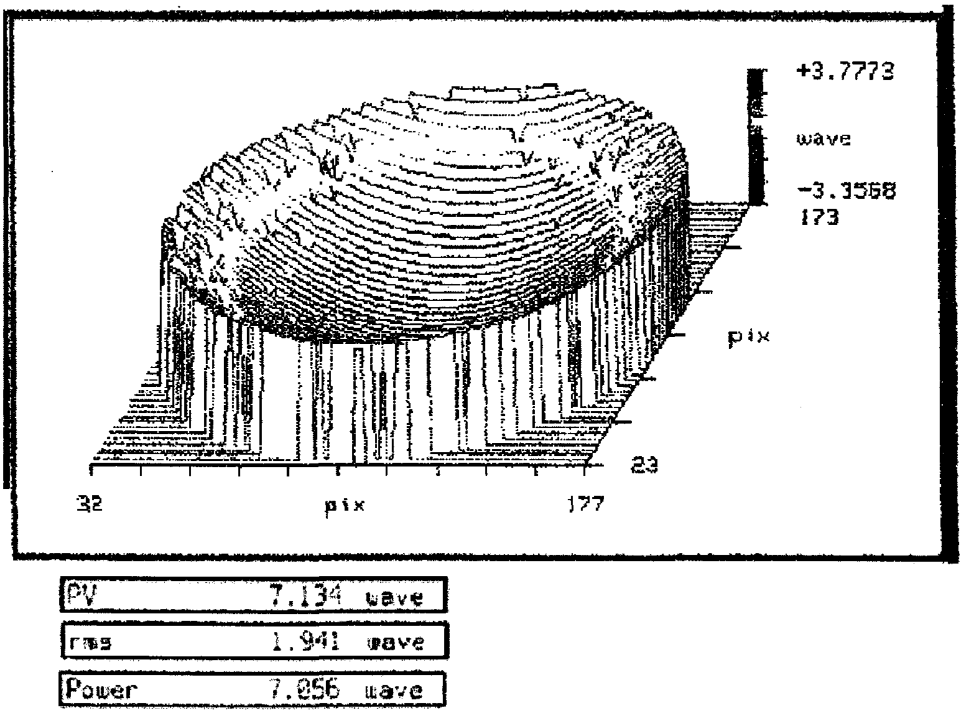


Figure 1. Zygo Mark IV interferogram data from a non-heat-treated sample lapped with 15 μm diamond on both sides and polished on one side with a commercial polish.

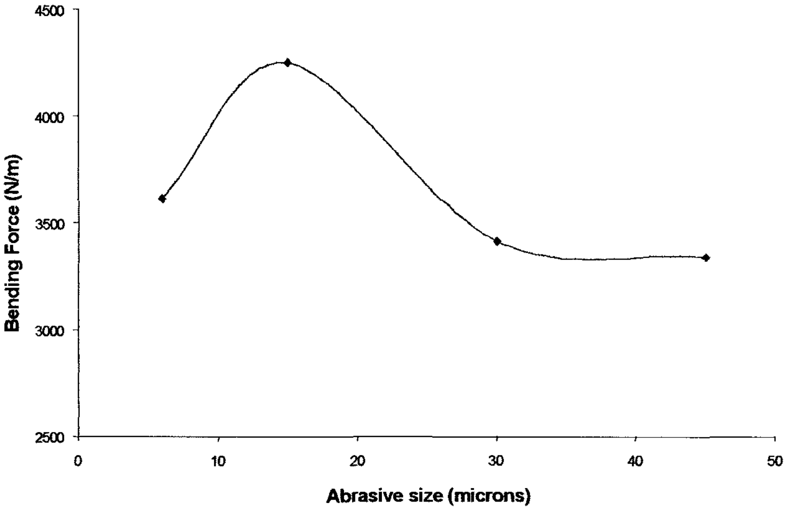
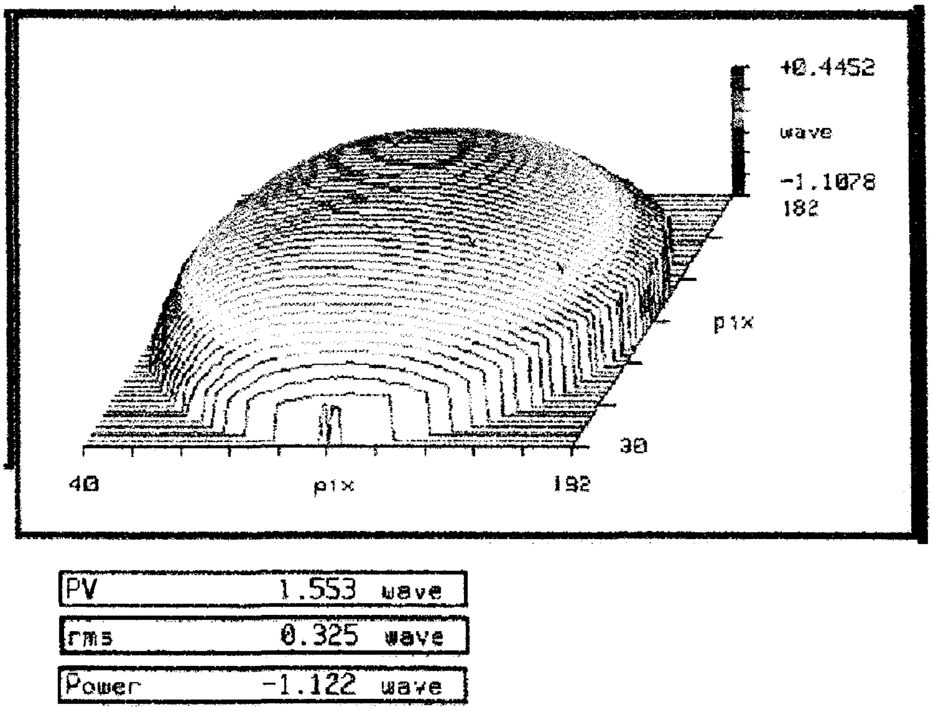


Figure 2. Measured grinding-induced bending force for 0.75" diameter sapphire windows.

The bending force in 15 and 30 μm lapped, 900°C heat-treated samples polished with 1/4 μm diamond on a tin lap, changed from concave to convex. This indicates that the side (S1) with the inspection polish has a higher compressive grinding-induced bending force than the side (S2) with the heat-treated lapped surface. The commercially polished samples retained the concave shape suggesting that the compressive grinding-induced bending force in the lapped heat treated surface is greater than on the polished side. The magnitude of the corrected measured bending forces in all 900 °C heat-treated samples is less than the room temperature samples. Therefore, it appears that the 900 °C treatment removed most of the stress induced during lapping, which is a step towards producing high quality surfaces with less toil.



PV 1.553 wave
rms 0.325 wave
Power -1.122 wave

Figure 3. Interferogram of a 15 μm lapped window after polish and a 1450°C heat treatment. Notice the difference from the identical window (Figure 1) without the heat treatment.

Table 4. Grinding-induced bending forces

Heat Treatment (Deg C.)	Side 1 (S1), Lapped with (μm)	Side 2 (S2) Polishing Process	Measured Bending Force on S2 (N/m)	Corrected Bending Force(N/m)*
27	15	1/4μm diamond	5287	6548
27	15	Pad/colloidal silica	7525	7621
27	30	1/4μm diamond	1741	3038
27	30	Pad/colloidal silica	3342	3490
900	15	1/4μm diamond	-493	768
900	15	Pad/colloidal silica	2097	2193
900	30	1/4μm diamond	-901	396
900	30	Pad/colloidal silica	1202	1350
1450	15	1/4μm diamond	-1261	1261
1450	15	Pad/colloidal silica	-96	96
1450	30	1/4μm diamond	-1297	1297
1450	30	Pad/colloidal silica	-148	-148

The 1450°C heat treatment was performed for 4 hours, as for the 900°C treatment. This temperature was chosen because prior results[19] indicated that heating to 1450°C for 4 hours was effective for removing all fabrication stresses; thus any bending should be purely the result of the polish performed after the heat treatment. The curvature of the parts is consistent with the assumption that the 1450°C treatment removes all grinding stresses (Table 4). The polished sides of all the samples in this group bent convex (Figure 3). This suggests that the polish, done after the heat treatment, is contributing compressive stress to the parts. There was a significant difference in the amount of bending depending on the polish, but a very minor difference between samples polished with the same technique and lapped with different sized abrasives. The small difference in bending between samples lapped with 15 and 30μm diamond indicates that the heat treatment successfully removed the grinding stress from lapping.

The difference in the polishing-induced bending force between the polish with 1/4μm polycrystalline diamond on a tin lap and the polish using colloidal silica on a synthetic pad is apparent. High grinding-induced bending forces, and thus high stresses, were produced by the 1/4μm diamond polish; very little grinding-induced bending force, and thus low stresses, were produced by the pad polish. Stress generated by the mechanical diamond polishing appears to be roughly 10 times as high as the chemo-mechanical method.

3.2 Surface quality

The peak-to-valley (P-V) and root mean square (rms) roughness values for the ground surfaces show the typical correlation to the size of the abrasive (Table 5). The P-V and rms readings of the two types of polishes, however, are somewhat surprising (Table 5). The inspection polish has a slightly lower P-V reading and a lower rms reading than the commercial polish. This is not in itself remarkable; but as described above, the inspection polish has considerably more grinding-induced bending force than the commercial polish. Thus, a clear relationship between surface stress and polished surface characteristics appears to be invalid. It appears that surface stresses are more process dependent.

Table 5. Surface characteristics from lapped and polished samples

Surface Preparation	P-V	rms (nm)
30 μm polycrystalline diamond, cast iron lap	14600 nm	788 nm
15 μm polycrystalline diamond, cast iron lap	6400 nm	396 nm
0.25 μm polycrystalline diamond, tin lap	17.1 nm	1.5 nm
Colloidal silica, synthetic pad	17.8 nm	2.5 nm

4. DISCUSSION

The results indicate that fabricators have several options for controlling the shapes of sapphire parts, and that the magnitude of stresses is strongly dependent on the fabrication process used and not necessarily the surface finish. It also appears that a more thorough investigation of polishing stress is necessary. Generally, this work was intended to generate additional information and techniques so that less cost and time are spent reaching the desired optical figure and wave front distortion specifications. To this end, several techniques appear promising.

4.1 Grinding-induced stress from lapping

Actual lapping stresses are higher in sapphire (Table 6) than reported in glasses[13]. It is clear that varying degrees of stress are generated depending on the abrasive size, but there does not appear to be a direct relationship to abrasive size.

Earlier works[10,14] detail a high grinding stress but shallow stress depth related to ductile mode material removal, and lower grinding stress but deeper stress depth from large abrasive sizes and brittle mode removal. This is not entirely consistent with the data on sapphire. There appears to be an intermediate high stress removal mode that has characteristics of both ductile and brittle removal, resulting in a combination of deep stress depth and high grinding stress. Moving from the intermediate mode towards a complete brittle mode of material removal reduces the grinding stress[13] and, it appears, the depth of stress may not increase as quickly as found in glass. The result is a lower grinding-induced bending force. In a similar fashion, moving towards a totally ductile mode of grinding may increase the grinding stress slightly, but reduce the depth of stress dramatically. Therefore, higher grinding stresses, measured on the samples lapped with 15μm polycrystalline diamond on a cast iron plate, may be generated when the mode of removal is transitioning from brittle to ductile. This interpretation is consistent with the data gathered on grinding of glass-ceramics[20] which shows that microgrinding with 10-20 μm abrasives gave lower grinding-induced forces than 2-4 μm abrasives. On the other hand, Bender and Wahl[21] report that for lapping silicon with 30 and 9 μm abrasives, the grinding-induced force diminished with decreasing abrasive size from about 970 N/m to 770 N/m. Typically, with glass substrates, ductile mode grinding is initiated by abrasives in the 2-4 μm range, which has been shown to create larger grinding stresses[14]. This illustrates the need to vary procedures depending on the material properties. As in the case of sapphire, it would be better to stop at the coarser 30 μm abrasive step or continue past the 15 μm abrasive step to improve flatness.

Table 6. Summary table of grinding-induced forces and corresponding surface roughness values for sapphire.

Process	Grinding-induced Bending Force (N/m)	Surface Roughness P-V	rms
Lapping, 30μm poly diamond	3264	14,600 nm	788 nm
Lapping, 15μm poly diamond	7084	6,400 nm	396 nm
Polish, 0.25μm poly diamond	1279	17.1 nm	1.5 nm
Polish, pad/colloidal silica	122	17.8 nm	2.5 nm

4.2 Grinding-induced stress from polishing

Lapping sapphire on tin with 1/4 μm diamond is a ductile grinding mode process that is considered polishing when used on sapphire. The ability of a polish to remove the stresses left over from the previous steps has traditionally been unchallenged; however, the computed residual bending stress calculated for the mechanical (1/4 μm diamond) polish is clearly higher than the stresses left by the chemo-mechanical polishing. Research on ductile mode grinding by several researchers[14, 17] has shown that the surface stress as computed by equation (2) is roughly equal to the yield strength of the material. The yield strength of sapphire computed from the expanding cavity model of Hill[18] is 10.4 GPa for *c*- plane (0001) sapphire. Assuming each polish used in this study has removed the stress generated in the previous step, the depth of stress for each polishing process can be determined experimentally. Substituting the yield strength in equation (2) for grinding stress, and using the measured grinding-induced bending force associated with each polish, the depth of stress can be determined. For example, using the data from table 6, we find the stress depth to be about 0.12 μm for the 0.25 μm diamond polish; and the stress depth is about 0.01 μm for the commercial polish. Therefore, the chemo-mechanical polish has a much shallower stress depth than the mechanical polish, which is consistent with theory[13].

4.3 Removal of stress by heat treatments

This study demonstrated the effectiveness of heat treatments in reducing stress (Table 7). Prior studies by Crystal Systems using heat treatments after the polishing step showed [19] that stress could be relieved and thin parts brought back to nominally flat. The effect of this heat treatment on the quality of the polish was not well known; thus, it was deemed desirable to correct optical figure before polishing. Correcting figure before polishing requires some approximation of the stress following the polish. In the case of the colloidal silica and pad polish, the bending stress is low and may be neglected, but with the mechanical polish the bending stress must be corrected for.

Heat treatments at 1450°C and 900°C for 4 hours in air were successful in removing fabrication stresses. The lack of variation in measured bending stress between samples lapped with different abrasives (15 and 30μm) and then heat treated to 1450°C indicates that the treatment effectively removed all the stress introduced during lapping. Treatment at 900°C is somewhat less effective in reducing stress. Thus, the temperature of the heat treatment and the time can be adjusted to produce the desired amount of residual stress. For example, if a fabricator is producing wafers with a mechanical polish on one side and a ground surface on the other some stress should be left on the ground surface to compensate for the polish. In fact, the flattest wafers made with the inspection polish were produced using a 900°C, not a 1450°C heat treatment.

The authors contend that the extent of stress relief by heat treatment is limited by the yield stress of the material at that temperature, i.e. only stresses in excess of the yield stress can be relieved. For example, the yield stress in shear for flow on the basal plane is 20 MPa at 1450°C, but 300 MPa at 900°C [22]. Thus, if ductile mode grinding at room temperature induces stresses of the order of the yield stress at room temperature (estimated at about 10.4 GPa), flow by basal slip for a long time implies that heat treatment at 900°C is expected to reduce the stresses by a factor of 17, while heat treatment at 1450 °C will reduce the stresses by a factor of 250 (N.B. yield stress in tension is twice that in shear). These approximate views of the effect of heat treatment assume that heat treatment has occurred for a sufficiently long period of time, and neglect the mobility on the ground surface at elevated temperatures.

Table 7. Magnitude of grinding-induced bending force relaxed by different heat treatments.

Heat Treatment	15 μm diamond, cast iron lap		30 μm diamond, cast iron lap	
	N/m	% of total	N/m	% of total
900°C (T/Tm =0.5)	5604	79	2391	73
1450°C (T/Tm = 0.75)	7084	100	3264	100

4.4 Future work

The necessity of understanding the anisotropy of grinding and machining stresses for further advancements in sapphire aspheres and conformal optics warrants follow-on studies using the Twyman effect as a metrology tool for measuring stress levels of varying crystallographic orientations. In addition, heat treatments approximating those used in this study may be helpful for optical glass manufacturers.

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REFERENCES

1. M. M. Tojek and D. Green, "Effects of residual stress on the strength distribution of brittle materials," J. Ceram. Soc. **72**, pp. 1885-1890, 1989.
2. F. Twyman. "Polishing of glass surfaces," in *Proc. of the Optical Convention,* p. 78, 1905.
3. H. P. Kirchner, R. M. Gruver and R. E. Walker, "Chemical strengthening of polycrystalline alumina," J. Ceram. Soc. **51,** pp. 276-281, 1968.
4. A. G. Evans and D. B. Marshall, "Wear mechanisms in ceramics," *Fundamentals of Friction and Wear of Materials*, D. A. Rigney, ed., pp. 441-452, 1981.
5. J. C. Lambropoulos, P. D. Funkenbusch, D. J. Quesnel, S. M. Gracewski, and R. F. Gans, "Mechanics and material issues in optics manufacturing," *Proc. of the Ninth Annual Meeting of the Amer. Soc. for Precision Engineering,* pp. 370-373, 1992.
6. J. C. Lambropoulos, "Fracture & Flow Processes in Grinding and Microgrinding of Optical Glasses," Amer. Soc. of Precision Engineering **13,** pp. 39-44, 1996.
7. C. A. Brookes, J. B. O'Neil and B. A. W. Redfern, "Anisotropy in the hardness of single crystals," Proc. Roy. Soc. London **322,** pp. 73-78, 1971.
8. V. G. Govorkov, E. P Kozlovskaya, Kh. S. Bagdasarov, N. N. Voinova, and E. A. Fedorov, "Anisotropy of local plastic deformation in corundum crystals," Soviet Physics-Crystallo. **17,** pp. 518-523, 1972.
9. M. Smith, F. Schmid, C. Khattak, D. Golini, J. C. Lambropoulos, M. Atwood, Y. Zhou, and P. D. Funkenbusch, "Sapphire fabrication for precision optics," Proc. SPIE **2857,** pp. 99-112, 1996.
10. J. C. Lambropoulos, Su Xu, T. Fang and D. Golini, "Twyman effect mechanics in grinding and microgrinding," App. Opt. **35,** pp. 5704-5713, 1996.
11. F. Twyman, *Prism and Lens Making* (Hilger and Watts, London), Chap. 9, 1994.

12. A. J. Dalladay, "Some measurements of the stresses produced at the surfaces of glass by grinding with loose abrasives," Trans. Opt. Soc. London **23,** pp. 170-173, 1922.
13. O. Podzimek, "Deformation energy under optical surfaces," *High Power Lasers: Sources, Laser-Material Interactions, High Excitations and Fast Dynamics*, E.W. Kreutz, A. Quenzer, and D. Schuoecker, eds., Proc. SPIE **801,** pp. 221-225, 1987.
14. D. Golini and S. D. Jacobs, "Physics of loose abrasive microgrinding," Appl. Opt. **30,** pp. 2761-2777, 1991.
15. E. G. Nikolova, "Review: On the Twyman effect and some of its applications," J. Mater. Sci. **20,** pp. 1-8, 1985.
16. F. Ratajczyk, "Die Abhangigkeit des Twyman effekts von der Dicke der abpolierten Schicht der geschliffenen Glasoberflache," Feingeratetechnik **16,** pp. 254-256, 1967.
17. W. J. Rupp, "Twyman effect for ULE," *Optical Fabrication and Testing Workshop,* Opt. Soc. of Amer., Wash., D.C. pp. 25-30, 1987.
18. R. Hill, *The Mathematical Theory of Plasticity,* (Oxford U. Press, New York), pp. 97-105, 1950.
19. Crystal Systems, Inc., "Sapphire Window Development Activity in Advanced Composite Structures Development Program," Joint Monthly Subcontractors Report, prepared for Fiber Materials Inc., Biddeford ME, December, 1996.
20. J. C. Lambropoulos, B. Giullman, Y. Zhou, S. D. Jacobs, and H. J. Stevens, "Glass-ceramics: Deterministic microgrinding, lapping, and polishing," (see these proceedings).
21. J. W. Bender and R. L. Wahl, "Work-induced stress and long-term stability in optically polished silicon," Proc. SPIE **1533,** pp. 264-276, 1991.
22. K. P. D. Lagerlof, A. H. Heuer, J. Castaing, J. P. Riviere, and T. E. Mitchell, "Slip and twinning in sapphire (α-Al_2O_3)," J. Amer. Ceram. Soc. **77,** pp. 385-397, 1994.