

PII: S0890-6955(96)00089-2

FIXED-ABRASIVE GRINDING OF BRITTLE HARD-DISK
SUBSTRATESTHOMAS G. BIFANO^{†‡} and PAUL A. BIERDEN[†]*(Received 28 March 1996; in final form 3 October 1996)*

Abstract—An industry shift from aluminum-based hard-disk substrates to ceramic or glass substrates presents new challenges in high-precision machining. In this paper alternative brittle substrate materials are described. A fixed-abrasive grinding process is implemented using a specially configured precision grinding apparatus, and this process is proposed as an alternative to lapping and polishing for brittle substrates. Ductile-regime grinding techniques are used to machine ceramic substrates in one brittle material—glassy carbon—to optical quality on a two-axis, twin air-spindle grinding machine with nanometer-scale in-feed control. The machine's design and performance is described, as are a series of grinding experiments to fabricate glassy carbon hard-disks. Process innovations have resulted in a machine capable of finishing 0.9 mm-thick ceramic hard-disk substrates to 8 nm rms roughness and 8 μm flatness without lapping or polishing. © 1997 Elsevier Science Ltd. All rights reserved

1. INTRODUCTION

There has been a significant change in computer hard-disk manufacturing over the past several years. The substrate material chosen for new product development is frequently ceramic or glass, instead of the traditional nickel-phosphorous-coated aluminum (Al/NiP). There are a number of reasons for this change, principally being increased memory capacity and decreased weight made possible by using alternate substrates. While there are clear advantages to be obtained by using brittle materials for hard-disk substrates, there is also at least one disadvantage: brittle glass and ceramic substrates are more difficult to machine than conventional Al/NiP substrates. Fabrication techniques appropriate for Al/NiP substrates are generally not useful for brittle substrates. To date all reported efforts to manufacture brittle hard-disk substrates have relied on double-sided lapping, sometimes followed by final polishing. Often such fabrication processes are slow to converge to the surface finish and flatness required of disk substrates, requiring hours of processing for a single batch of substrates. In this paper we describe research to identify a cost-effective, deterministic machine tool and machining process suitable for manufacturing brittle hard-disk substrates to the shape and surface finish required. This process of fixed-abrasive ultraprecision grinding is an alternative to slurry-based processes and it can be used to improve the convergence rate of substrate machining.

2. ALTERNATE SUBSTRATE MATERIALS

Table 1 lists five substrate materials and some relevant properties of those materials. Nickel-phosphorous-coated aluminum (Al/NiP) is the conventional substrate material. The other materials listed are borosilicate glass (a silica glass with additives that increase softening temperature), Canasite^{®§} (a glass and ceramic composite optimized for machinability and toughness), glassy carbon[¶] (an amorphous brittle material composed entirely of carbon), and silicon carbide (a polycrystalline, ultrahard ceramic). The four new materials

[†]Aerospace and Mechanical Engineering, Boston University, 110 Cummington Street, Boston, MA 02215, U.S.A.

[‡]Author to whom correspondence should be addressed.

[§]Canasite is a glass-ceramic blend manufactured by Corning.

[¶]Since this research was sponsored in part by a hard-disk company interested specifically in glassy carbon, that material will be the focus of our experiments. Glassy carbon is a proprietary material, described more fully later.

Table 1. Properties of hard-disk substrate materials

	Al/NiP	Borosilicate glass	Canasite	Glassy Carbon	Silicon carbide
Softening temperature (°C)	280	500	500	1200	2500
Density (g cm ⁻³)	2.7	2.5	2.7	1.6	3.21
Elastic modulus (GPa)	72	85	85	35	461
Hardness (kg mm ⁻²)	500	650	610	500	2500
Critical depth-of-cut (nm)	Ductile	27	32	44	180
Substrate cost	Low	Low	Medium	Medium	High

developed for substrate use have all been investigated recently by major hard-disk manufacturers [1].

The grinding experiments that are described in the later sections of this paper were all conducted on glassy carbon substrates. While each of the materials listed in Table 1 has advantages and disadvantages as a substrate material, the high purity, low density, high softening temperature and low cost of glassy carbon make it a leading choice as a substrate material for the next generation of hard disks, provided that it can be economically machined to the tolerances and surface finish required.

The properties listed in Table 1* are those that affect the material's performance as a substrate material (softening temperature, density, elastic modulus) and those that affect machinability (hardness and critical depth of cut). In addition, a relative ranking of substrate cost is tabulated for each material. While exact costs of these materials in commodity volumes is difficult to predict, the cost for small-quantity purchase in rough substrate shape ranges from more than \$20 (high) to less than \$1 (low).

One can increase the storage density of a hard disk by choosing a substrate that can withstand high annealing temperatures without deforming permanently. After the disk substrate is machined, a magnetic thin film is sputtered onto its surface. This film is the media upon which information will be written and stored. The hard disk is then annealed. One effect of annealing is to permanently increase the magnetic thin film's coercivity, which in turn affects the storage density achievable on the disk. Coercivity, defined as the magnetism that will remain in a material after a saturating magnetic field has been applied and removed [2], is maximized in disks that have been annealed at 600–700°C [3]. With increased coercivity, the physical bit-size corresponding to a readable magnetic signal can be reduced, allowing increased disk storage density. Of the substrates listed in Table 1, the four brittle materials can all withstand temperatures in excess of that achievable with Al/NiP, but only glassy carbon and SiC can withstand the annealing temperatures required for optimum coercivity.

Substrate density is of particular concern to the hard-disk industry, since a lighter disk permits smaller mechanical drive components. For the materials listed in Table 1, glassy carbon is the least dense by a significant margin.

One way to characterize "lightweight" materials (that is, those that are rigid in combination with low mass) is specific stiffness, defined as the material's elastic modulus divided by its density (E/ρ). For the materials listed in Table 1, SiC has the highest specific stiffness. The other materials all have comparable specific stiffness, though glassy carbon has the lowest specific stiffness of all these materials.

Hardness of the substrate material is important because it determines the efficiency with which a material can be removed in a lapping or polishing process (which are conventionally used for substrate machining). Harder materials are not necessarily more difficult to lap or polish; they simply require more time to achieve a specified surface finish than softer materials, because of their low "Preston coefficient." Preston's equation defines the

*Most properties listed here are taken directly from manufacturers' data sheets. Because the hardness of Al/NiP and glassy carbon will be shown to be critically important in developing an appropriate substrate fabrication process, these were measured directly using a Vickers DPH system.

relationship between material removal rate and machining conditions for a given combination of workpiece material, machine and abrasive. Specifically,

$$Z = K_p FV \quad (1)$$

where Z is the material removal rate, K_p is the Preston coefficient, F is the normal lapping force and V is the relative tangential velocity between the lapping plate and the workpiece. A study by Brown and Fuchs [4] found that harder materials such as silicon carbide exhibit Preston coefficients as much as 20 times smaller than softer materials such as silica glass under identical conditions using state-of-the-art lapping equipment. Such a difference can make lapping or polishing unacceptably costly for harder disk substrates.

Critical depth-of-cut is a parameter that is important in fixed abrasive grinding. The critical depth-of-cut is defined as the maximum depth of cut that can be made by an abrasive grain in the grinding wheel without introducing fracture in the machined material. If the cutting "chip thickness" exceeds the critical depth-of-cut, fracture will occur on the surface of the material. One estimate of the critical depth-of-cut is given by the following [5]:

$$d_c = 0.15 \frac{EK_{cs}^2}{H^3} \quad (2)$$

where d_c is the largest chip thickness that can be tolerated without introducing fracture, E is the elastic modulus of the workpiece, H is the hardness of the workpiece and K_{cs} is the small-crack* fracture toughness of the workpiece surface. The model leaves out many important considerations that affect the grinding regime, including abrasive grain size, wheel-bond material, abrasive grain concentration and coolant chemistry. Moreover, it is only one of several models that have been proposed for fracture initiation in grinding (e.g. Zhang and Howes [7]). All brittle material removal models proposed to date, however, conclude that there is a critical load or grain depth-of-cut in microgrinding that marks a transition from damage-free grinding to damage-dominated grinding. The critical depth-of-cut model permits relative evaluation of a material's propensity to fracture in grinding. Materials exhibiting a large critical depth-of-cut are easier to machine without fracture in a fixed-abrasive grinding process than those exhibiting a small critical depth-of-cut.

By evaluating hardness and critical depth-of-cut, one can make a preliminary assessment of the relative tradeoffs between lapping and fixed-abrasive grinding for the materials listed in Table 1. As an example, the hardness of SiC, coupled with its large critical depth-of-cut, make fixed-abrasive grinding the favored process. For the other three brittle materials, the choice is less clear.

There are two main components to the cost of hard-disk substrates: raw material cost and machining cost. In Table 1 the raw material costs increase from left to right. With nickel-coated aluminum there is a well-established manufacturing method for fabrication using abrasive belt grinding. This is a relatively inexpensive process. When processing borosilicate glass there is also a well-established method of surface finishing that has been extensively developed for glass optical components: loose abrasive lapping and polishing. Canasite glass ceramic is suitable for processing in the same manner as glasses. Glassy carbon and CVD SiC have been found to be difficult to lap or polish. Alternative fabrication processes, including fixed-abrasive ultraprecision grinding, may prove more economically favorable for these materials.

*This correlation is strongly dependent on K_{cs} , and requires that this surface toughness is measured for crack sizes smaller than $1 \mu\text{m}$, particularly when the workpiece material exhibits R -curve behavior (e.g. most advanced ceramics). For a more detailed discussion see Scattergood *et al.* [6].

3. FIXED-ABRASIVE GRINDING OF BRITTLE HARD-DISK SUBSTRATES

In the following sections of this paper, we describe a research effort directed toward implementing a fixed-abrasive ultraprecision grinding system to machine glassy carbon hard-disk substrates. We modified an ultraprecision machine tool to achieve high stiffness and high precision, and then we used this machine to grind glassy carbon substrates for computer hard-disks. A ductile-regime grinding technique was implemented. Following fabrication experiments, substrate surfaces were evaluated for flatness and roughness. A comparison between grinding and lapping of glassy carbon substrates can be made on the basis of processing times and component quality results achieved in this project.

Conventional superabrasive grinding processes remove material from brittle workpieces through grinding-induced fracture. This process, sometimes called "brittle regime" machining, results in high material removal rates, with extensive subsurface fracture damage. Such damage must be avoided in the finished surface of hard-disk substrates. Therefore, fracture introduced by a brittle regime process must be removed through a material removal process that does not introduce additional damage. One such process of machining brittle materials without fracture is often called ductile regime grinding.

Recent advances in machine precision and control have made it possible to conduct fixed abrasive grinding processes so that abrasive grains in the grinding wheel experience forces and cutting depths similar to those achieved in polishing and lapping. The process has been demonstrated for production of brittle components requiring high precision, including quartz components [8, 9], space-based ceramic optical mirrors [10] and advanced glass optics [11, 12]. The technology has evolved to the point where real-time control of grinding quality is possible with in-process sensing and feedback [13–15].

Ductile-regime grinding was developed in the late 1980s and is based on the principle that plastic flow becomes energetically more favorable than fracture when the depth of cut made by an individual abrasive grinding grain is smaller than a particular threshold value [15]. The model described in Eqn (2) has been verified as a good first-order fit for many (though not all) types of brittle materials. Using values for the material properties of glassy carbon, its critical depth-of-cut should be ~45 nm. Ensuring a small grain depth-of-cut* can be done in one of several ways. The most obvious way to reduce the abrasive grain depth-of-cut is to reduce the feed rates (in-feed and cross-feed) on the grinding machine. Alternatively, one can increase the grinding wheel rotational speed, or use a more compliant grinding wheel bond. Each of these techniques has been found to reduce grinding fracture damage in machining brittle materials by reducing the grain depth-of-cut [16].

4. DEVELOPMENT OF A DISK GRINDING MACHINE

A precision grinding apparatus was used in this research. This machine was retrofitted from its former configuration as a diamond turning lathe. As a lathe, the machine configuration consisted of a belt-driven air-bearing workpiece spindle and a pair of orthogonal, stacked, "double-vee" plain-bearing slideways upon which the lathe tool was mounted. These plain bearing slideways use ground and lapped guideways to ensure straight, smooth motion in directions parallel and perpendicular to the workpiece spindle axis. Translation of the plain bearing slideways is accomplished with motorized lead-screws.

The retrofit for ductile grinding takes advantage of the inherent stiffness of the machine's structural loop, and replaces the single-point cutting tool with a motorized air-bearing spindle. Upon this spindle, the cup-shaped diamond abrasive grinding wheel is mounted. The final machine configuration then, is that of two opposing air-bearing spindles (one rotating the workpiece, the other rotating the grinding wheel), whose axes are nominally parallel, and at the same height (y). Grinding can be accomplished by advancing the

*Grain depth-of-cut is the maximum depth of penetration into the workpiece made by an individual abrasive grain in the grinding wheel.

spindles toward each other and/or by translating the spindles past each other (x) in a direction perpendicular to their axes (z). Figure 1 is a schematic of the apparatus.

The grinding wheel is mounted to the face of a 100 mm diameter air-bearing spindle.* The grinding spindle is driven by a d.c. servo motor through a helical-spring coupling†, which isolates the spindle from motor vibration. The grinding spindle and motor are mounted on orthogonal stacked double "vee" slideways (z - and x -axes), allowing in-feed and cross-feed motion. The in-feed (z -direction) slide is activated by a lead screw driven by a stepper motor through a belt-pulley system. Using this arrangement, each step of the stepper motor results in an in-feed of $2.5 \mu\text{m}$. A double hemispherical, self-compensating, 0.3 m diameter porous graphite air-bearing spindle‡ is used to hold the workpieces. Hard-disk substrates are mounted to the workpiece spindle with an aluminum vacuum chuck that was diamond turned on the machine before removal of the single-point tool holder.

All motion control for the ultraprecision grinding apparatus is achieved through a microcomputer controller built specifically for the hard-disk substrate grinding experiments. Controllable parameters are listed in Table 2.

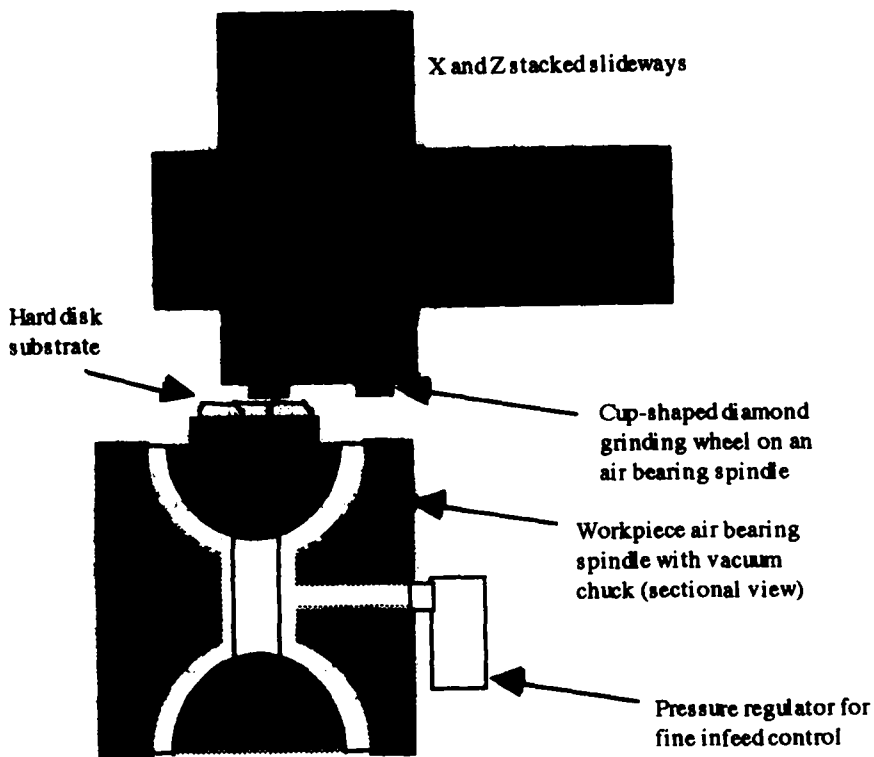


Fig. 1. Schematic plan view of the hard-disk grinding apparatus.

Table 2. Controllable grinding machine parameters

Parameter	Range	Resolution
Coarse in-feed	0.1 m	$2.5 \mu\text{m}$
Fine in-feed	$5 \mu\text{m}$	15 nm
Cross-feed rate	$0-170 \text{ mm min}^{-1}$	0.5 mm min^{-1}
Grinding spindle speed	0-3500 rpm	10 rpm
Workpiece spindle speed	0-1000 rpm	10 rpm

*Blockhead® 4B, Professional Instruments, Minneapolis, MN.

†Uniflex, StockDrive Products, New Hyde Park, NY

‡Excello®.

The overall stiffness or "loop" stiffness of the machine tool must be high to ensure adequate precision and deterministic performance of the grinding machine. Loop stiffness is defined as the stiffness in a direction perpendicular to the plane of grinding contact (e.g. stiffness in the z -direction). While this is perhaps the most important component of stiffness, large stiffnesses in the x - and y -directions are also needed. Loop stiffness can be roughly approximated by identifying the stiffness of individual components and calculating their collective stiffnesses, similar to springs connected in series. A more direct method of determining the loop stiffness of the machine is to measure the deflection of the machine with a displacement probe situated between the workpiece and the wheel while a known normal load is applied. Since loop stiffness is rarely linearly dependent on load, it is important that the load applied is comparable to the grinding forces expected during machining. A piezoelectric actuator was used to apply a small load normal to the contact region. The piezoelectric actuator used for this measurement is a circular cylindrical stack with a range of $10\ \mu\text{m}$. A strain gage load cell was connected in series with the piezoelectric actuator to measure axial force. This transducer pair (load cell and actuator) was supported between the grinding wheel face and the workpiece. Displacement was measured using a noncontact capacitance gage*, sensing normal displacement between the wheel surface and the workpiece during loading. By dividing the applied normal load by the measured deflection, the normal stiffness of this machine was found to be $50\ \text{N}\ \mu\text{m}^{-1}$. This is about an order of magnitude larger than is usually achieved on a conventional grinding machine, and is typical of the loop stiffness of ultraprecision machine tools.

5. PRESSURE-REGULATED FINE IN-FEED ACTUATION

It was determined that smaller in-feed steps would be needed for ductile regime grinding than were achievable using the lead-screw and stepper-motor. An independent precision in-feed actuation system was developed for that purpose. This auxiliary in-feed motion control was obtained by controlling the air pressure supplied to the workpiece spindle. Increasing the air pressure to the spindle increases the axial forces on the hemispherical thrust plates at either end of the spindle. This increased force elastically deforms the cylindrical portion of the rotor, resulting in axial displacement of the workpiece in the in-feed (z) direction. Varying the spindle supply pressure from 425 to 800 kPa causes the front plate of the spindle to advance $5\ \mu\text{m}$. The relation between supply pressure and displacement is nearly linear. An air spindle pressure controller was implemented using a current-to-pressure transducer, allowing open-loop computer control of the grinding in-feed with a resolution of 15 nm.

Specifications for the four grinding wheels used in these experiments are summarized in Table 3. All were type 6A2, 100 mm diameter cup wheels with 6 mm wide rims. The coarse wheel ($140\ \mu\text{m}$ abrasive grain size) was used to shape the workpiece in a brittle-regime grinding process. There was a large amount of damage after using this wheel. The medium grit wheel ($4\text{--}8\ \mu\text{m}$ abrasive grain size) was used to remove the damage that was introduced in the coarse grinding process. The two resin wheels ($2\text{--}4$ and $0\text{--}2\ \mu\text{m}$ abrasive grain size) were used as finishing wheels.

Table 3. Fixed abrasive grinding wheels used

Abrasive grain size	Bond	Concentration
$140\ \mu\text{m}$	Bronze	75
$4\text{--}8\ \mu\text{m}$	Bronze	100
$2\text{--}4\ \mu\text{m}$	Resin	75
$0\text{--}2\ \mu\text{m}$	Resin	50

*ADE 3401, ADE Corporation, Newton, MA.

6. GRINDING PROCEDURE

Two possible procedures for grinding hard-disk substrates with the grinding system that was developed are illustrated in Fig. 2. For both, wheel and substrate counter-rotate. On the left is plunge grinding, requiring only an in-feed motion. On the right is cross-feed grinding, requiring a step in-feed followed by a constant-velocity cross-feed. In the latter configuration the wheel axis is tilted with respect to the z -direction to reduce the grinding contact area.

In plunge grinding, the grinding wheel spindle and the workpiece spindle are oriented with their axes parallel and at the same y height, with an offset in the x -direction equal to the radius of the grinding wheel. The spindles counter-rotate while the grinding wheel is advanced in the in-feed (z) direction. The cup wheel contacts the disk substrate along an arc that passes through the disk substrate center hole and extends to the edge of the substrate in two places. The grinding contact width is equal to the width of the rim of the cup-shaped grinding wheel (6 mm for our wheels). This grinding technique has recently been employed for ductile-regime ultraprecision grinding of brittle materials by Namba and Abe [17], Yasunaga *et al.* [18] and Daito *et al.* [19], among others. Its advantages are simplicity and speed. No cross-feed (x) axis motion is required, and the achievable flatness is almost entirely a function of the parallelism of the spindle axes and the stiffness of the machine. Because a large portion of the wheel is in contact with the workpiece at any given time, the material removal rate is large, even with small in-feed rates. One disadvantage is that the large contact area between grinding wheel and workpiece can result in very large grinding normal forces. Since the specific grinding energy for ductile regime grinding is much larger than the specific grinding energy for brittle regime grinding on the same workpiece [5], one expects this disadvantage to be especially prevalent in the later stages of grinding, with small-grit wheels. In fact, it was found that the forces generated in finish grinding using the plunge grinding configuration exceeded the capacity of the motor drivers and the load limits for our grinding wheel spindle. In a production system, larger motors and spindles might be employed to overcome these difficulties.

In cross-feed grinding, the process consists of repeated cycles of incremental in-feed followed by a constant-velocity cross-feed. Again, the spindles counter-rotate, but in this configuration the grinding wheel axis is angled slightly ($\sim 2^\circ$) with respect to the in-feed axis. The workpiece spindle remains parallel to the in-feed axis, and the in-feed and cross-feed axes remain perpendicular. The perpendicularity of the x -axis (i.e. the cross-feed slide) to the z -axis (i.e. the central axis of the workpiece spindle) is an important feature in this grinding procedure. If the two axes are not orthogonal, the part will have either a "cup" or "cone" shape after cross-feed grinding. The grinding contact region for cross-feed grinding is determined by the angle of offset of the grinding spindle axis and the radius of the wheel. In the actual grinding experiments this area of contact was estimated

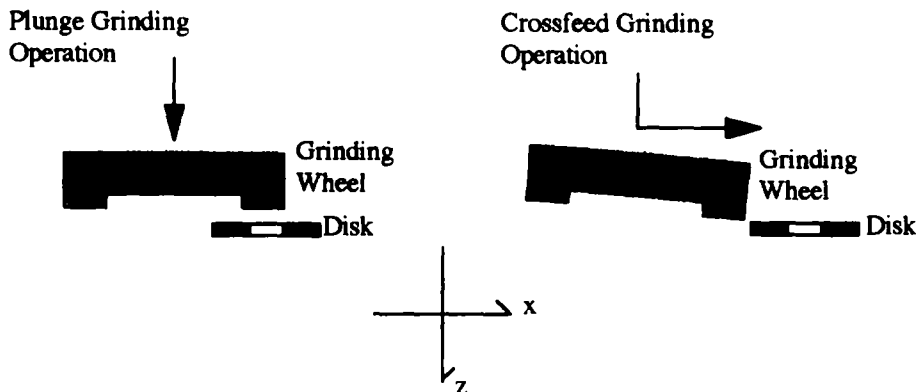


Fig. 2. Two potential grinding configurations for substrate fabrication.

to be on the order of 1 mm^2 , more than two orders of magnitude smaller than the contact area estimated for a plunge grinding operation on the same machine.

It was found to be possible to complete a rough-grinding (brittle-regime) operation with the plunge configuration. For subsequent finer grinding operations, the cross-feed configuration was used.

7. DISK GRINDING EXPERIMENTS

The grinding procedure consisted of a series of machining and analysis steps. The procedure is summarized in the flow chart of Fig. 3. Before each grinding experiment, a new workpiece* was mounted to the vacuum chuck and centered. The coarse grit grinding wheel ($140 \mu\text{m}$ grit, bronze bond) was mounted, centered and then trued using a lapping paste until its axial peak-to-valley profile was smaller than $1 \mu\text{m}$, as measured with a capacitive displacement gage. The wheel was rotated at 3000 rpm (active grinding zone peripheral speed: $\sim 15 \text{ m s}^{-1}$), and the workpiece at 1000 rpm (outer diameter peripheral speed: $\sim 5 \text{ m s}^{-1}$, inner diameter peripheral speed: $\sim 1 \text{ m s}^{-1}$). A plunge grinding operation was then executed, with an in-feed rate of $30 \mu\text{m min}^{-1}$, for 5 min, resulting in a total removal depth of $150 \mu\text{m}$. The workpiece was then removed from the vacuum chuck,

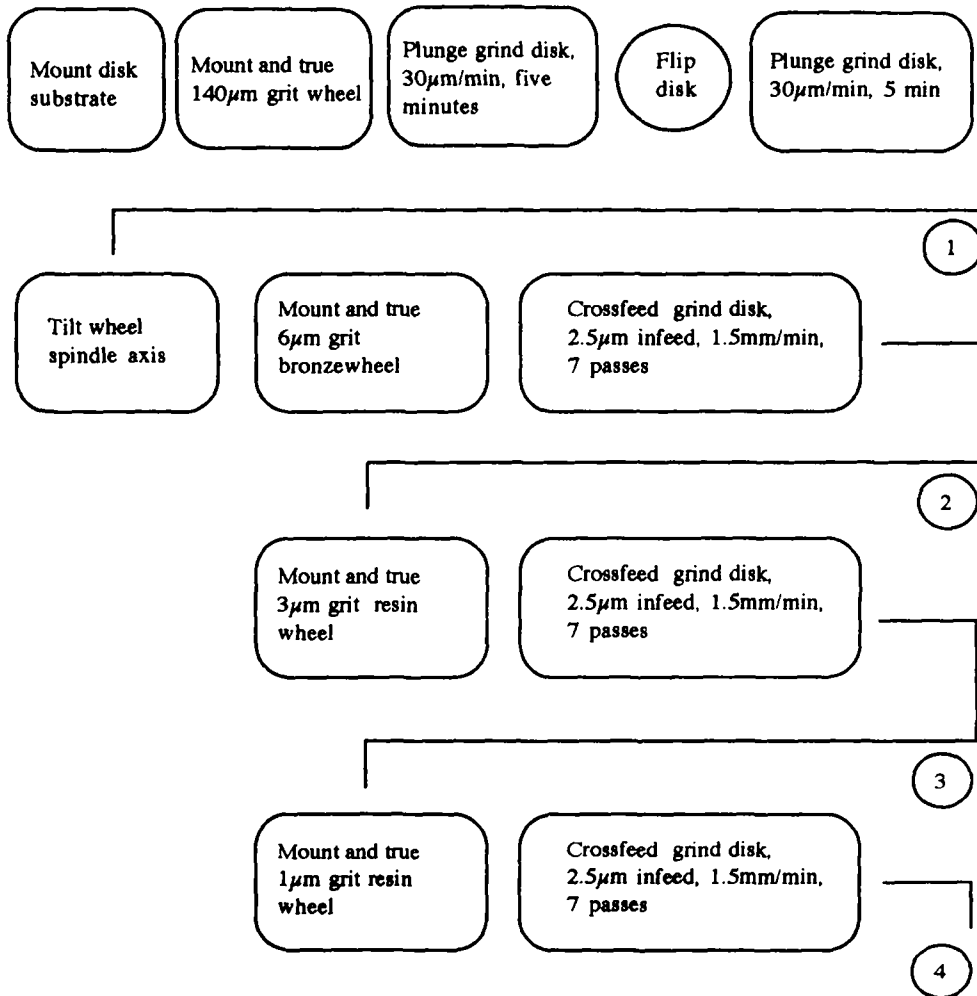


Fig. 3. Flow chart of grinding procedure.

*Workpieces were raw glassy carbon hard-disk substrates (60 mm o.d., 15 mm i.d.) supplied by KAO Inosystems Co., Plymouth, MA.

flipped over, remounted to the vacuum chuck and recentered. In this way, uniform fixturing conditions were achieved for the part, by precision grinding the back side of the disk. Next, the front side of the disk was machined in exactly the same manner. At this point the disk was removed and measured for flatness and roughness. Then a new disk was processed in exactly the same way, in preparation for the grinding experiments using the medium grit wheel. This wheel (4–8 μm grit, bronze bond, also denoted as 6 μm grit in the figure) was mounted, centered, trued and dressed. Truing and dressing were accomplished using a diamond paste lapping procedure described elsewhere [5]. The grinding wheel spindle axis was angled by 2° , and then used in a cross-feed grinding operation consisting of seven grinding passes. Each pass consisted of a 2.5 μm in-feed followed by a constant velocity cross-feed at 1.5 mm min^{-1} . Then this disk was removed and measured for flatness and roughness. A third part was processed in exactly the same way, in preparation for the grinding experiments using the fine grit wheel. This wheel (2–4 μm grit, resin bond also denoted as 3 μm grit in the figure) was mounted, centered and trued. The grinding wheel was then used in a cross-feed grinding operation consisting of seven grinding passes. Each pass consisted of a 2.5 μm in-feed followed by a constant velocity cross-feed at 1.5 mm min^{-1} . Then this disk was removed and measured for flatness and roughness. A fourth and final part was processed in exactly the same way, in preparation for the grinding experiments using the very fine grit wheel. This wheel (0–2 μm grit, resin bond also denoted as 1 μm grit in the figure) was mounted, centered and trued. The grinding wheel was then used in a cross-feed grinding operation consisting of five grinding passes. Each pass consisted of a 2.5 μm in-feed followed by a constant velocity cross-feed at 1.5 mm min^{-1} . Then this disk was removed and measured for flatness and roughness. For all grinding experiments, flood cooling using deionized water was employed.

8. FLATNESS AND ROUGHNESS CONVERGENCE RESULTS

At each of the numbered positions along the flow chart in Fig. 3, flatness and roughness of the substrates were measured. For rough ground samples, flatness was measured along a line across the diameter of the disk with a LVDT gage with a sensitivity of 0.1 μm . Circumferential symmetry was assumed. For fine-ground samples, flatness over the entire surface was measured with an optical interferometer. Surface roughness was measured using a contacting surface profilometer*. The scan lengths were 500 μm and the speed was $\sim 20 \mu\text{m s}^{-1}$. No filtering was employed and the stylus tip was measured to be 2.5 μm in diameter.

The series of grinding passes depicted in Fig. 3 yielded the desired finish and contour accuracy on glassy carbon substrates, as shown in the bar graphs in Fig. 4. For these experiments the first process was a 5 min plunge-grinding operation. All subsequent grinding process cycles were achieved using multiple cross-feed passes with a fixed in-feed. Process times for each cycle are indicated on the bar graph data. Because the conditions of grinding were specified to be conservative with respect to subsurface damage generation and machining rate, and because cross-feed grinding was used instead of faster plunge grinding, the processing times are relatively long. Processing time can be reduced in each of the last three operations by converting to a plunge-grinding operation, without compromising surface flatness or finish. At this time, production-scale experiments are underway to demonstrate the achievable reductions in processing time.

The comparison of grinding time to workpiece flatness shows that the surface can be shaped to the required flatness specifications (8 μm P-V) in a small amount of time (~ 5 min). Further processing produces an ultimate flatness of 3 μm . The flatness of the workpiece does not improve after 30 min. The convergence rate for surface roughness of the hard-disk substrate is more gradual, requiring all four successively finer grinding operations and a total of 320 min to achieve the required 8 nm rms roughness (150 μm scan, 2 μm stylus profilometer, no filter).

*Dektak II.

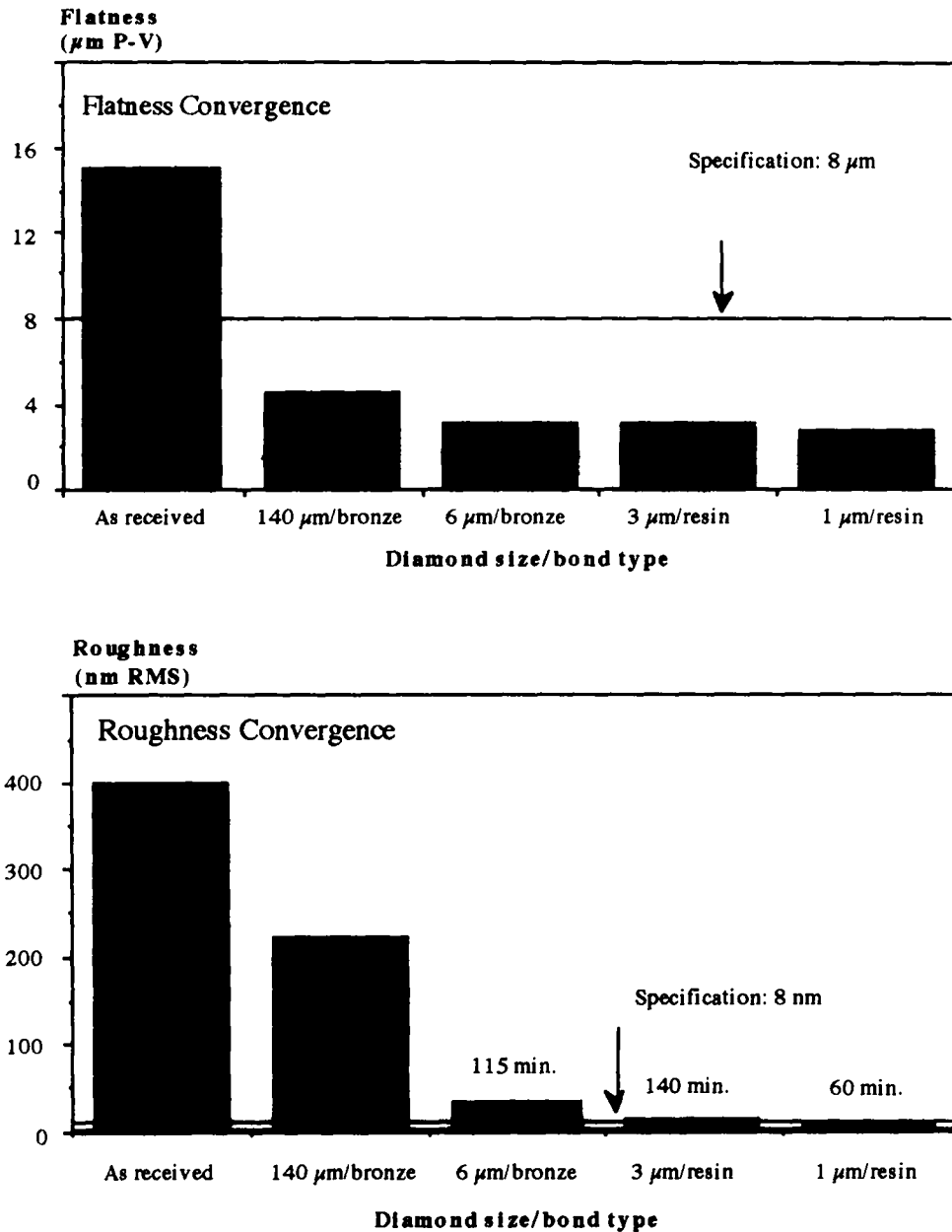
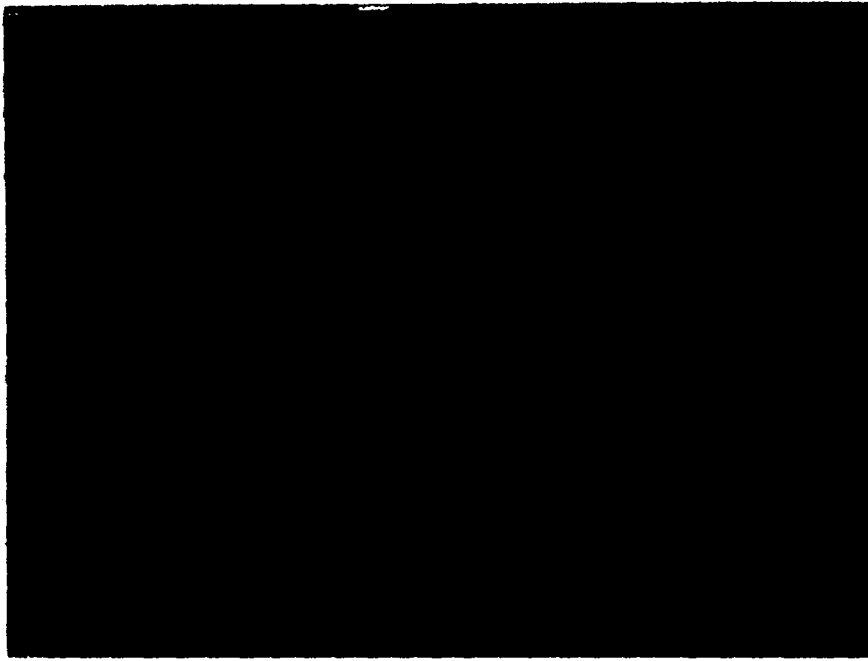


Fig. 4. Flatness and roughness convergence for four successive fixed-abrasive grinding processes on glassy carbon hard-disks.

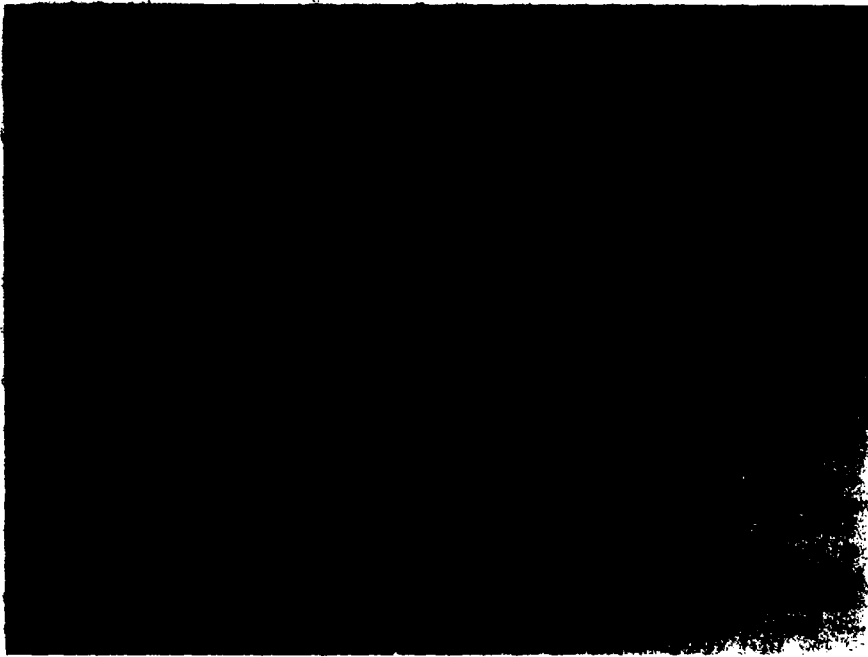
Conventional lapping times are somewhat shorter (~ 90 min) for overall cycle time, though flatness convergence in lapping is not as rapid as that exhibited in grinding.

These results are currently being used as the basis for an economic and technical assessment of fixed abrasive grinding for hard-disk substrates. Current research directions include two process modifications: scaling the process by using multiple disk workpiece holders; and speeding the process by employing a plunge-grinding operation as opposed to multiple cross-feed passes.

Figure 5 shows a pair of photomicrographs at $200\times$ magnification comparing the surfaces of a ground glassy carbon hard-disk substrate with that of a lapped and polished substrate.



DUCTILE-GROUND GLASSY CARBON



POLISHED GLASSY CARBON

Fig. 5. Comparison between ground and polished glassy carbon hard-disk substrates (200 \times optical photomicrographs).

9. CONCLUSIONS

To meet industry demand for new processing techniques appropriate for brittle hard-disk substrates, a study was made of the potential for fixed-abrasive grinding on glassy carbon substrates. Relevant disk properties were described in terms of their influence on disk performance and disk machinability. A precision grinding machine tool was developed and used to surface finish glassy carbon samples. While this research was performed on glassy carbon, the machine and techniques are appropriate for many of the substrates currently being developed for the next generation of hard disks. It was been shown that the machine is capable of producing workpieces with the surface tolerances

specified by the hard-disk industry ($8\ \mu\text{m}$ flatness and $8\ \text{nm}$ surface roughness) using a fixed abrasive ductile-regime grinding technique.

The process employed was found to be time intensive. Development of a machine tool capable of large-area plunge grinding instead of cross-feed grinding will significantly speed the process, as will development of multi-substrate mounting chucks. Alternatively, a combination of a fixed abrasive grinding followed by loose abrasive lapping and polishing may prove to be a more economical fabrication process.

Acknowledgements—This work was supported by grants from KAO Infosystems Inc., and the National Science Foundation (DDM9202377). Grinding wheels were donated by Norton Company.

REFERENCES

- [1] J. Weiss (Editor), *Proc. IDEMA 2nd Symp. on Alternative Substrates*, San Jose, CA, 28 September (1993)
- [2] H. E. Burke, *Handbook of Magnetic Phenomena*. Van Nostrand Reinhold, New York (1986).
- [3] H. Inoue, Ultra densified amorphous carbon substrates for hard disks. *IDEMA 2nd Symp. on Alternative Substrates*, San Jose, CA (1993).
- [4] N. Brown and B. A. Fuchs, Brittle to shear grinding mode transition for loose abrasive grinding. *Proc. Workshop on Optical Fabrication and Testing*. OSA Technical Digest Series, Vol. 13, Optical Society of America, p. 23 (1988).
- [5] T. G. Bifano, T. A. Dow and R. O. Scattergood, Ductile regime grinding: a new technology for machining brittle materials, *Trans. ASME J. Engng Ind.* **113**, 184 (1991).
- [6] R. O. Scattergood, S. Srinivasan, T. G. Bifano and T. A. Dow, R-curve effects for machining and wear of ceramics, *Ceram. Acta* **3**(4-5), 53 (1991).
- [7] B. Zhang and T. D. Howes, Material removal mechanisms in grinding of ceramics, *Ann. CIRP* **43**(1), 305 (1994).
- [8] T. G. Bifano and I. Hosler, Precision grinding of ultra-thin quartz wafers, *ASME J. Engng Ind.* **115**(3), 258 (1993).
- [9] J. Yoshioka, K. Koizumi, M. Shimizu, H. Yoshikawa, M. Miyashita and A. Kanai, Ultraprecision grinding technology for brittle materials: application to surface and centerless grinding processes. *Milton C. Shaw Grinding Symp.*, edited by R. Komanduri and D. Maas, ASME PED Vol. 16, p. 209. ASME, New York (1985).
- [10] T. G. Bifano, W. K. Kahl and Y. Yi, Fixed-abrasive grinding CVD silicon carbide mirrors, *J. Precision Engng* **16**(2), 109 (1994).
- [11] K. L. Blaedel, P. I. Davis and D. L. Nikkei, Ductile grinding of glass. Lawrence Livermore National Laboratory Document UCRL-53868-89, p. 4.1 (1989).
- [12] P. P. Hed and K. L. Blaedel, Advanced fabrication of optical materials. Lawrence Livermore National Laboratory, Document UCID-21041-86 (1986).
- [13] J. A. Webster, I. D. Marinescu, R. Bennett and R. Lindsay, Acoustic emission for process control and monitoring of surface integrity during grinding, *Ann. CIRP* **43**(1), 299 (1994).
- [14] T. G. Bifano and Y. Yi, Acoustic emission as an indicator of material-removal regime in glass microgrinding, *J. Precision Engng* **14**(4), 219 (1992).
- [15] T. G. Bifano and S. C. Fawcett, Specific grinding energy as an in-process control variable for ductile-regime grinding, *J. Precision Engng* **13**(4), 256 (1991).
- [16] T. G. Bifano, Ductile-regime grinding of brittle materials. Ph.D. Dissertation, North Carolina State University, NC (1988).
- [17] Y. Namba and M. Abe, Ultraprecision grinding of optical glasses for obtaining optical surfaces. *Proc. American Society for Precision Engineering 1993 Ann. Meet.*, Seattle, WA, p. 17 (1993).
- [18] N. Yasunaga, Y. Samitsu, K. Abe and K. Hatta, Surface characterization of mirror polished and ductile-mode ground Si wafers. *Proc. of the American Society for Precision Engineering 1993 Ann. Meet.*, Seattle, WA, p. 25 (1993).
- [19] M. Daito, A. Kanai and M. Miyashita, Design strategies of an ultraprecision surface grinding machine for ductile mode surface finishing of brittle materials. *Proc. of the American Society for Precision Engineering 1994 Ann. Meet.*, Cincinnati, OH, p. 366 (1994).