Fixed Abrasive Vertical Spindle™ process to generate mirror finishes on a variety of advanced ceramic components

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Introduction:
Some of the recent trends in the semiconductor industry have included decreasing size of device circuitry (smaller line widths), increasing device size and wafer diameter, while the storage industry on the other hand has seen increasing storage density, wafer size and decreasing device size. Such trends have meant tighter flatness requirements, finer surface finishes and better surface integrity. Traditional loose abrasive processes for ceramics have followed a familiar trend seen in Figure 1. As the quality of surface roughness improves there is an associated drop in productivity.

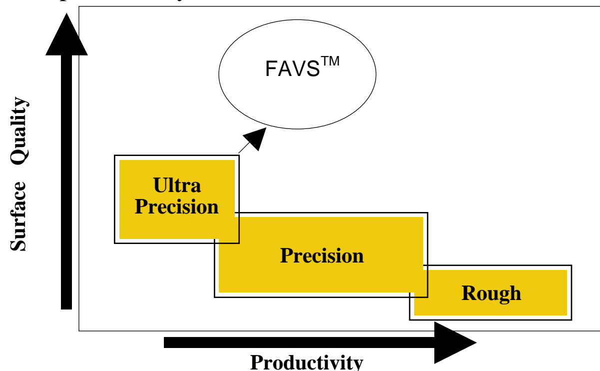


Figure 1. Objective of FAVS™

The FAVS™ approach however results in processes where high level of surface quality (mirror finishes) can be obtained without a loss of throughput.

Grinding Machine Features:
The FAVS™ process consists of a platform supporting two pairs of high precision air bearing grinding wheel and work chuck spindles. Grinding machines combine the benefits of ultra fine control on the infeed rate along with fine diamond abrasives to produce mirror finishes with minimal sub- surface damage.

FAVS™ Kinematics:
The most common configuration of the FAVS™ concept is shown in Figure 2. The middle of the

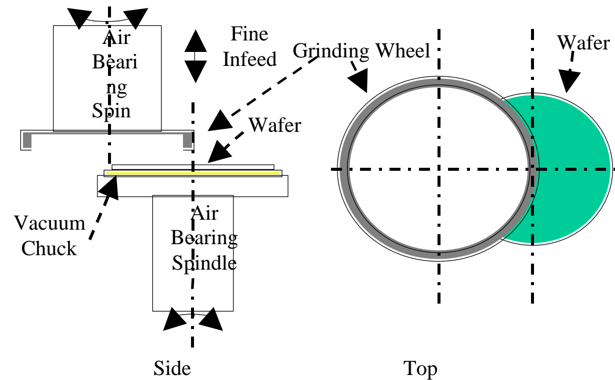
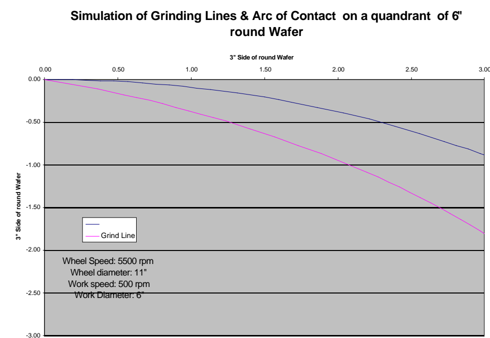


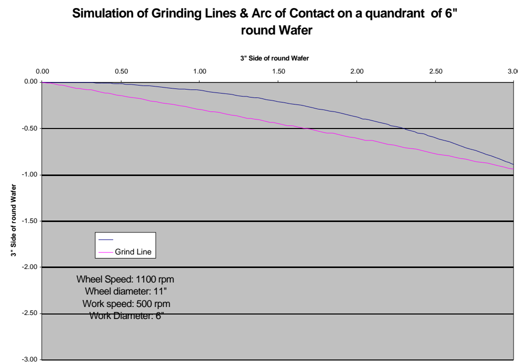
Figure 2. Schematic of FAVS™ process



Figures 3-A&B: The simulated cutting path of a an idealized abrasive grain on the surface of a 6" wafer, shown above on a 3" quadrant at 5500 and 1100 rpm respectively.

grinding wheel abrasive rim typically grinds on the centerline of the work piece. The contact area between the wheel and the workpiece is defined by grinding wheel rim thickness, size of the part and the angles between the axis of the chuck and grinding wheel spindles. If the axes of rotation of the wheel and the part are parallel then the wheel makes contact on the part at both the entry and the exit of the grind.

The maximum cutting depth (undeformed chip thickness) taken by a single abrasive grain is shown here as 'h' [Reichenbach, G. S., et al]. The expression shown below was derived for straight surface grinding and is used here as an approximation. The parameter 'h' is useful in predicting the depth of cut taken by a single abrasive grain while travelling along a path shown above in Figure 3A&B. Using continuity analysis i.e. making a material balance between



volume of chips produced at all the cutting points and bulk material removal, the following expression can be approximated for 'h'.

$$h \quad \sqrt{\frac{V_w}{V_s} \times \frac{d}{D_e}^{\frac{1}{2}} \times \frac{1}{kC_g}}$$

The C_g term denotes the number of grains in the grinding zone per unit area, while the 'k' term denotes geometry factors of the abrasive grain itself. The number of grains in the grinding zone per unit area increases exponentially with decrease in grain size. As a result, there is a significant decrease in chip thickness, as the abrasive grain size becomes smaller as one would find in ultra fine diamond wheels. [Subramanian,K., et al] have shown that by controlling the value of 'h', one can grind advanced ceramics in either ductile or brittle mode. Treating each interaction between the wheel and workpiece separately, controlling the chip thickness, abrasive grain size and the number of grains in the wheel C_g (coarse or fine grains), one can control the force per grain. As the grain size decreases the force per grain also decreases.

Unlike in loose abrasive lapping where the grain depth of cut is a probabilistic event, in grinding, the depth of cut is deterministically controlled by the work and wheel speeds and the down feed rate of the machine. In grinding the 'h' value can be lowered significantly by increasing wheel speed (V_s) while lowering 'h' in lapping typically means lowering abrasive grit size. In Figure 4 is shown an example of a "mirror finish" grinding on AlTiC material using the grinding parameters in Table –1, resulting in low chip thickness values.
The 15 Angstrom R_a finish shown in Figure 4 is a result of the low 'h' values that are obtainable in grinding. As can be seen from the expression for chip thickness, the ability to grind in either ductile or brittle mode is now controlled by the user. Conversely, one can use larger particle size abrasive grains and still grind with a low value of chip thickness 'h' by altering the machine operating parameters. This allows the user to optimize the process, potentially using a higher removal rate with a coarse wheel during roughing and a finer grit wheel for ductile grinding to get a fine surface roughness with minimal sub-surface damage.

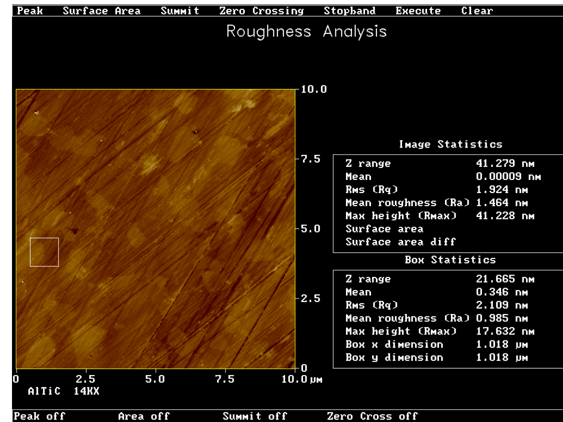


Figure 4. Atomic Force Microscope (AFM) of fine ground AlTiC material

Work Piece Dimensions:	4.5" square – 6" round – AlTiC
Wheel:	5 micron sized diamond
Wheel diameter:	11"
Wheel speed:	64 m/s
Work Speed:	500 rpm
Infeed rate:	0.1-0.3 μm/s
Coolant:	DI Water
Machine	Strasbaugh 7AF

Table 1. Grinding conditions used for ductile grinding in Figure 4

Comparison of lapping /polishing versus grinding:
Based on the expression for chip thickness it is possible to explain why grinding is able to achieve high quality surface finish with very low depth of damage typically observed only with lapping and polishing (Table 2 & 3). From the expression for chip thickness it can be shown for grinding that 'h' is inversely proportional to the product of cutting speed (wheel speed) and C_g the number of grains per unit area. Hence in grinding the chip thickness is proportional to (d_g/V_s), where d_g is the abrasive grain diameter and V_s is the abrasive speed. From empirical data (Figures 6&7) it may be observed that the

15 Angstrom R_a finish was obtained with a 5 μm diamond size grinding wheel. However a similar finish of 30 angstroms R_a was obtained with polishing with a 0.5 μm abrasive. This shows that for a given range of finish the grinding wheel can use a coarser abrasive allowing productivity improvements

Lapping/Polishing vs. Grinding		
GRINDING	*Operating Parameters*	LAP/POLISH
15	*Vw - Work speed [m/s]*	1
65	*Vs-Wheel Speed [m/s]*	1-2
5	*dg -Diameter of Grains [μ m]*	0.5
low	*Cg -Grains /unit Area*	higher

Table 2. Comparison of attributes of Lapping / Polishing vs. Grinding.

Lapping/Polishing vs. Grinding		
LAP/POLISH	*ATTRIBUTE*	GRINDING
Loose / slurry	*abrasive*	Fixed / Wheel
Low	*Wheel Speed*	High
Batch	*Process*	Single /Multiple
Manual	*Load /Unload*	Cassette to Cassette
Excellent	*Finish*	Excellent
Environmental, issues	*Other*	Better on multiphase materials? Process simplification

Table 3. Comparison of Lapping /Polishing vs. Grinding attributes.

Machining Multi Phased Materials:
Unlike loose abrasive lapping and polishing, grinding is a deterministic process in which the machine infeed controls the actual removal from the material. However in loose abrasive lapping of multi-phase materials (Figure 5), the abrasive slurry – work interaction occurs mainly as a function of the hardness, toughness and wear resistance of the diamond abrasive in the slurry and the different phases in the work material.

In Figure 6, the effect of non-uniform material removal due to the random nature of interactions between abrasive grain and work material in loose abrasive polishing of AlTiC can be observed.

	Al_2O_3	TiC
Hardness [Gpa]	19	30
Toughness [MPam $^{(1/2)}$]	3.5	4
Wear Resistance [$H^{(1/2)}$ K_1c]	12.3	15.5
Vol%	70	30

Table 4. Physical property measurements

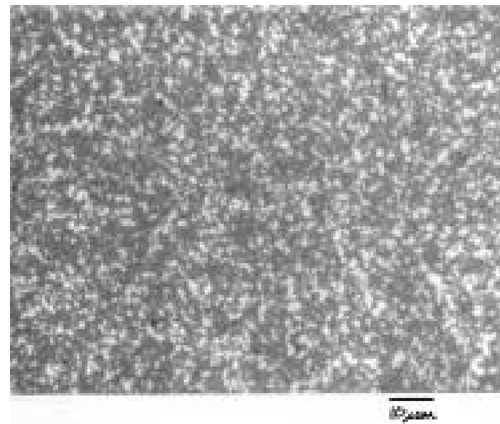


Figure 5. Micrograph of multiphase AlTiC material

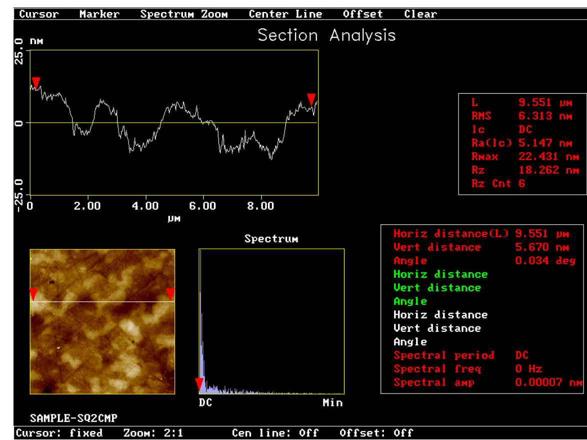


Figure 6. Atomic Force Measurements (AFM) of two phase AlTiC material after polishing (note recessed Al_2O_3 phase versus TiC phase).

The significant differences in hardness between the alumina (2100 knoop scale) and TiC (2800 knoop scale) phases translates into higher removal of the softer phase (here Al_2O_3). One

common problem that this phenomenon causes in the storage industry is termed pole tip recession. The local planarity on the surface of a read-write head has to be at the sub-micron level [Anna Mathai et al]. By contrast the AFM trace in Figure 7 shows much more uniformity in material removal as the wheel down feeds at a fixed rate showing no preferential treatment for either material.

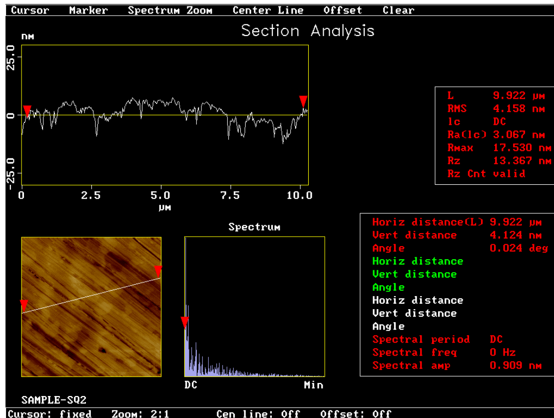


Figure 7. Atomic Force Measurements of AlTiC after grinding (note uniformity of material removal in both phases)

Total Thickness Variation and Shape:
Since the grinding process is deterministic, it is possible to control the thickness variation (TTV), flatness and shape to a higher degree using a combination of good stiffness and low grinding force. This combination allows one to grind ceramic components by imparting minimal pressure leaving the parts relatively stress free. The total thickness variation on 200 mm silicon wafers can for instance be reduced to less than 0.5 μm by keeping tight control on processing and ambient conditions.
The shape of the ceramic components can also be closely controlled to obtain convex, concave or flat surfaces as required. This is done by adjusting the angle of tilt between the work chuck and the grinding wheel spindles. In addition by controlling up or down grind along with spindle angles for rough and finish grind even hard to grind advanced ceramic materials can be ground flat even if only one side requires grinding.

Range of Materials:
The FAVS™ process has been tried on a variety of advanced ceramic materials. By controlling the chip thickness, even tough to grind materials like silicon carbide, sapphire, fully dense alumina or AlTiC can be thinned down using grinding at relatively high rates of removal. This ability is what allows the user to use the FAVS™ approach with a roughing and finishing wheel to often replace several rough lapping, finish lapping and polishing operations with one grinding machine. This leads to both increases in throughput and lowered manufacturing cost. Materials ground producing mirror finish with the FAVS™ approach range in hardness: from very soft (glass = 500 Knoop Scale) to very hard (TiC = 2800 Knoop), in fracture toughness: as low as 0.7 $MPa.m^{1/2}$ for glass; in strength: as high as 880 MPa for AlTiC and in thermal conductivity: as low as 2.7 W/m.K (Sapphire). It is expected that due to the kinematic advantages of the FAVS™ approach is likely to work on a wide variety of work materials.

What Lies ahead for FAVS™:
Different materials are being worked on currently to achieve surface roughness close to that obtained by loose abrasive lapping and / or polishing. The future goal is to achieve surface roughness as close to one Angstrom.

Acknowledgements:
The authors of this paper are indebted to Dr. Jeri Ikeda and Mr. Jason Wilson for their many contributions to this work.

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