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An Advanced Ultraprecision Face Grinding Machine

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Cranfield Precision, Division of Landis Lund, has recently developed an ultraprecision face grinding machine which incorporates several automatic supervision features. The company supplied the machine to Cranfield University's Precision Engineering Group in order that the group can undertake research, particularly in the area of damage-free grinding with high surface and subsurface integrity. The paper discusses the design of the machine, initial machining trials and potential research projects. Such projects will benefit from the availability of such an advanced machine system which incorporates many state-of-the-art features for the automatic supervision and control of the machining process.

Keywords: Automatic supervision; Grinding; Machine tool design; Precision machining

1. Introduction

Cranfield Precision, which is a UNOVA Company, specialises in the design and manufacture of machines for cost-effective production of components in advanced materials including ceramics, glasses, intermetallics and hard alloy steels. The School of Industrial and Manufacturing Science (SIMS), Cranfield University, places great importance on developing close collaborative links with industry and is currently undertaking a range of ultraprecision and high-speed machining research projects including superabrasive machining, ductile machining of brittle materials and precision machining for the automotive industry. The complementary research interests of the two organisations have resulted in Cranfield Precision developing and supplying an advanced ultraprecision face grinding machine to the Precision Engineering Research Group within SIMS. This will enable the group to undertake a wide range of research programmes, particularly in the area of damage-free grinding with high surface and sub surface integrity.

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Materials processing with nanometric resolution and control is viewed as a mid- to long-term solution to the cost and time problems that plague the manufacturing of electro-optics and other precision components. For example, ductile grinding of brittle materials can provide surfaces, as ground, to nanometre smoothness and figure accuracy at higher production rates than usually encountered [1]. More significantly, a ductile ground surface experiences little or no subsurface damage, thereby eliminating the need for the subsequent polishing step associated with conventional grinding. The performance of many "microfeatured" products (e.g. semiconductor, optical communications systems, computer peripherals, etc.), as well as larger components for aerospace and automotive applications, depends increasingly on higher geometric accuracies and micro- and nanostructured surfaces. Recently, the automotive industry has indicated a future requirement for the surfaces of certain key transmission components to be of "optical" quality, with targets of 10 nm Ra surface finish to be economically produced on hardened steel by direct machining, without polishing.

The conditions under which damage-free surfaces can be produced on glasses and ceramics, and "optical" surfaces can be produced on hardened steel, are exacting, requiring (a) the use of a class of machine tool not normally found in even the best production facilities, e.g. high accuracy, smoothness of motion, loop stiffness [2], (b) the incorporation of ancillary features specially developed to suit the particular application (e.g. grinding wheel truing and conditioning), and (c) the use of the correct grinding technology for the application (many variables – wheel type, coolant, speeds, feeds, etc). All the conditions must be satisfied and the wafer face grinding machine has been developed to meet them.

2. Objectives

In order to meet the demands of surface integrity and productivity mentioned above, for a wide range of components, the principal objectives include the development of:

1. A machining process capability for the manufacture of sizeable components with high levels of surface/subsurface integrity.

2. Optimised "ductile mode" machining processes for brittle materials (glasses and ceramics).
3. A single process, with only one set-up, to replace the typical three-stage lapping, etching and polishing process, resulting in much higher productivity.

3. The Process

A prime requirement of the process is that it should be capable of machining extremely flat surfaces on workpieces up to 350 mm diameter. Further, the surfaces should be smooth (<50 nm Ra) and have minimum subsurface damage. Ideally the surface should be close to the quality obtained by polishing. In order to meet these demanding requirements rotation grinding is utilised. A feature of rotation grinding is that unlike conventional surface grinding, it has a constant contact length and constant cutting force. Figure 1 illustrates the grinding principle. Both the cup grinding wheel and workpiece rotate and the axial feed of the grinding wheel removes stock from the surface of the workpiece until it reaches its final thickness/geometry.

4. The Machine

The demanding requirements of the process and component quality necessitate a machine of extremely high loop stiffness. The design targets for the face grinding machine (Fig. 2) are:

1. Loop stiffness better than 200 N μm^{-1} with good dynamic damping, required to achieve submicron subsurface damage.
2. Control of pitch (wheel to component surface) to better than 0.333 arc seconds, required to achieve a total thickness variation (TTV) tolerance of 0.5 μm.
3. Control of cut-depth to better than 0.1 μm, required to achieve submicron subsurface damage.
4. Axial error motions of spindles better than 0.1 μm, required to achieve submicron subsurface damage.
5. Measurement and feedback of component thickness to 0.5 μm, required to achieve micron thickness tolerance.

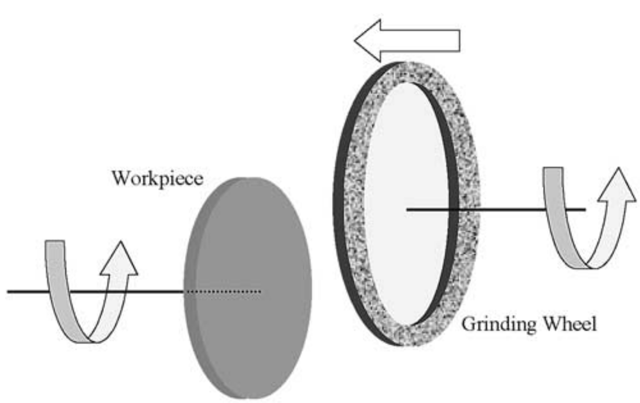

Fig. 1. Face grinding operation.

The geometry of the ground flat surface is determined by the relative position of the rotary axes of the grinding wheel and workpiece. Figure 3 indicates the relative machine motions and axes. There are 11 axes, plus three automatic robot loading motions (not shown), all driven under servo control. These are:

*S*1	Grinding spindle
C	Workhead spindle
Z	Infeed
X	Crossfeed
S2	Truing spindle
W	Dressing axis
A	Tilt pitch
B	Tilt yaw
S3	Chuck wash brush
P	Probe thickness
Wash arm	

As described below, the flatness accuracy can be achieved by the superimposed rotations of the rotary axes coupled with an appropriate spindle alignment strategy. Further, this prototype research machine benefits from the incorporation of the following state-of-the-art features for the automatic supervision and control of the machining process.

4.1 Adjustment of the Workpiece and Grinding Wheel Planarity

The relative alignment of the two rotary spindles *S1* and *C* (Fig. 3) is simplified because the geometry of the ground surface can be described by geometrical equations. The grinding process requires a specific angle between the plane of the grinding wheel and the plane of the workpiece to be maintained as the *Z*-axis infeed is applied. This angle is typically much less than a degree, so that the workpiece and wheel are nearly parallel. This angle is monitored by three gauging LVDT sensors which measure the displacement between the grinding spindle housing, and a precision-machined surface on the work-spindle housing. The gauging sensors are placed around the grinding spindle housing, roughly equidistant from the centre of the wheel spindle axis in the plane of the wheel, at a known separation. The information from these sensors is fed back into the control system to amend the control for the *A*- (pitch), *B*- (yaw) and *Z*- (infeed) axes. This is a unique feature of the machine, to maintain workpiece flatness because, as the workpiece subsurface damage reduces and the surface finish improves the grinding forces increase significantly. This has the effect of distorting the grinding spindle to workhead alignment, which then produces non-flat surfaces. On conventional machines this alignment is adjusted by mechanical trial-and-error adjustment, and relies on the force and deflection always being uniform. However, on this machine if the process conditions are changed, the alignment is automatically compensated for. This can then be optimised to suit the material and wheel conditions by changes in the software of the control system. A functional block diagram for the servo control of the *Z*-axis is illustrated in Fig. 4.

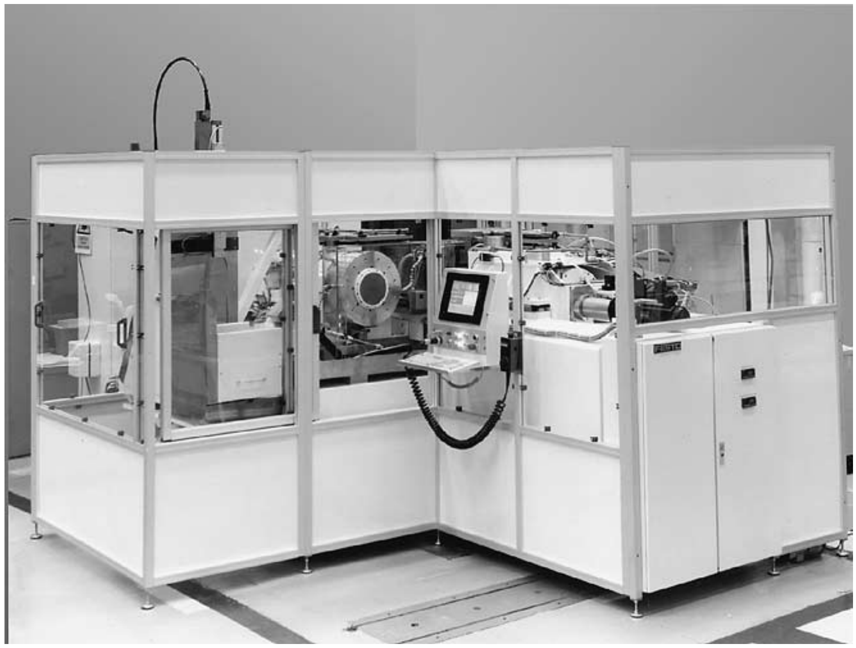

Fig. 2. Face grinding machine.

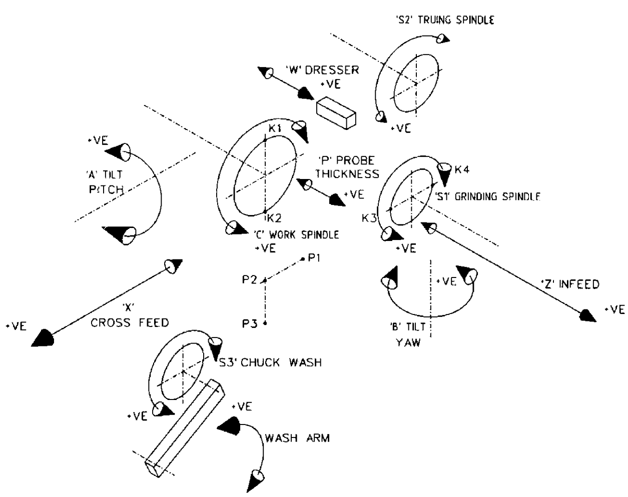

Fig. 3. Axes nomenclature.

4.2 Grinding Wheels

The roughing and finishing wheels are concentrically mounted on one spindle via a patented system which incorporates an advance/retract mechanism for the roughing wheel, as shown in Fig. 5. In order to maximise component throughput, a coarse-grained wheel is first used to obtain a high material removal rate. The fine-grained finishing wheel is then used to obtain the finished size and surface integrity.

4.3 Detecting Grinding Wheel Contact

Acoustic emission (AE) sensors are used to establish the initial touch between the grinding wheel and component. Because of the importance of establishing first touch to very fine limits, when finish grinding, ring sensors are used on the workhead and grinding spindles. These are extremely sensitive and are located at the front of the spindles, close to the signal source. An on-machine grinding wheel truing spindle is also fitted with AE sensors which enables "touch dressing" of the grinding wheel.

4.4 Automatic Measurement of Grinding Forces

Grinding forces are measured via sensors placed within the force loop away from external forces, such as lead screw nuts and their associated friction. Measurement of the grinding forces gives a good indication of grinding wheel wear.

4.5 Measurement of Grinding Wheel Wear and Component Thickness

Grinding wheel wear is monitored together with component thickness. A specially designed anvil and LVDT probe assembly are used to measure component thickness. This is done by initially datuming the anvil and probe on to the porous ceramic vacuum chuck face to which the component is fixed. When measuring the component thickness, the anvil, which is on the same slideway as the probe, contacts the chuck datum and the LVDT probe makes contact with the face of the component, thus giving a measurement of thickness. Grinding wheel wear can be found by reading directly the position of the Z-axis, and relating this to the chuck face datum position. Thermal growth is measured by pairs of eddy current probes mounted on the workhead and grinding spindles. Any growth is automatically compensated by adjusting the relative positions of the two spindles.

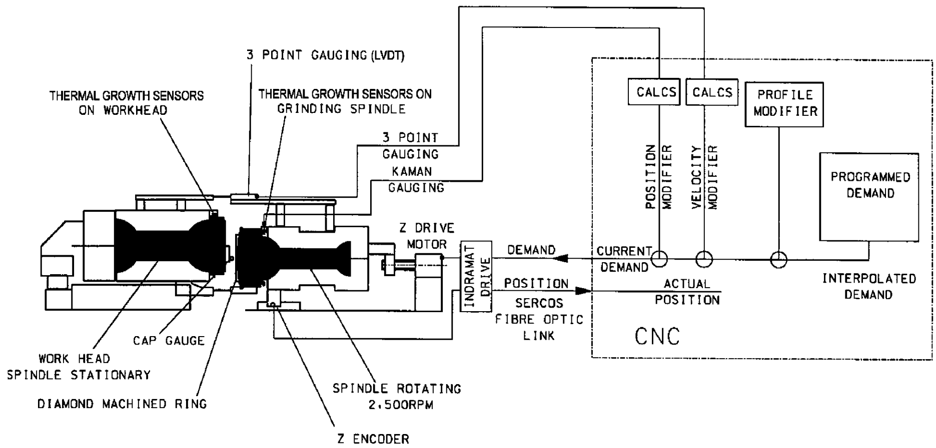

Fig. 4. *Z*-axis functional block diagram.

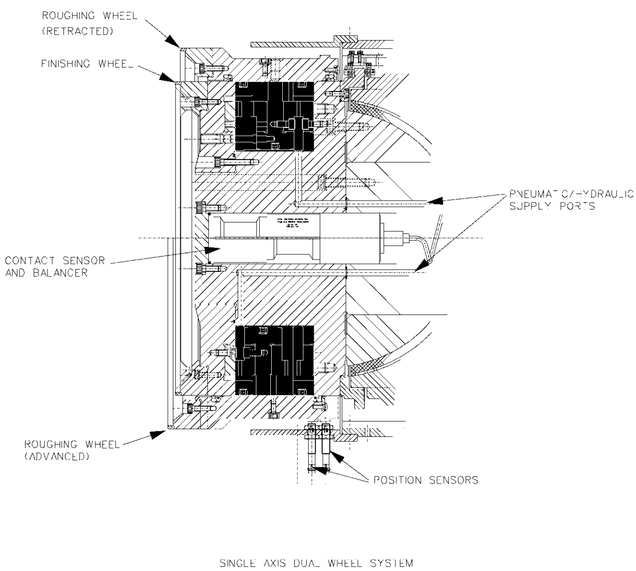

Fig. 5. Single axis dual wheel system.

4.6 Ancillary Features

The machine also has facilities for on machine component and chuck washing and also a robotic loading and unloading capability to load and unload automatically components onto and from the workhead spindle.

5. Machine Commissioning

Machine services consist of an air supply, grinding coolant supply and motor coolant supply, as well as three-phase electrical power. Air is provided by a high performance supply and conditioning system, which delivers clean dry air at 13 bar at over 5000 l min^{-1}. The air consumption within the face grinder machine is around 2000 l min^{-1} in the air bearings, the remainder being for the various air purge and cleansing systems. The air is filtered to 0.1 μm and dried to a pressure dewpoint of −40°C as required for the operation of ultraprecision air bearings.

Coolant supply is by recirculating water. This is pumped at 4.5 bar at a flow rate of up to 100 l min^{-1}. Coolant is distributed to various coolant nozzles, under individual control, as required by the machine process. Used coolant is returned to the collection tank, and then fed to the main coolant tank by a scavenge pump. Some water-borne debris (workpiece and grinding wheel residues) settles out here; the remainder is removed by filtration on the machine in various stages down to 0.01 μm.

Services provision requires a multiplicity of controlled process fluid distribution points, together with appropriate safety interlock and performance monitoring systems.

5.1 The Control System

The control system is in two parts, based on an industry standard Isagraph PLC, and a Cranfield Precision CNC system. Machine I/O is on a distributed Interbus S system and servo control is implemented by a Sercos fibre-optic ring.

The PLC program required only minor modification during commissioning, most effort being concentrated in further development of the CNC program, particularly in grinding touch sensing, and in the truing and grinding operations.

5.2 Machine Preparation

In preparation for grinding operations, an assessment of several areas was critical:

1. Machine alignments.
2. Balance of spindles.
3. Condition of wheels.
4. Application of coolant.
5. Control of machine motions.

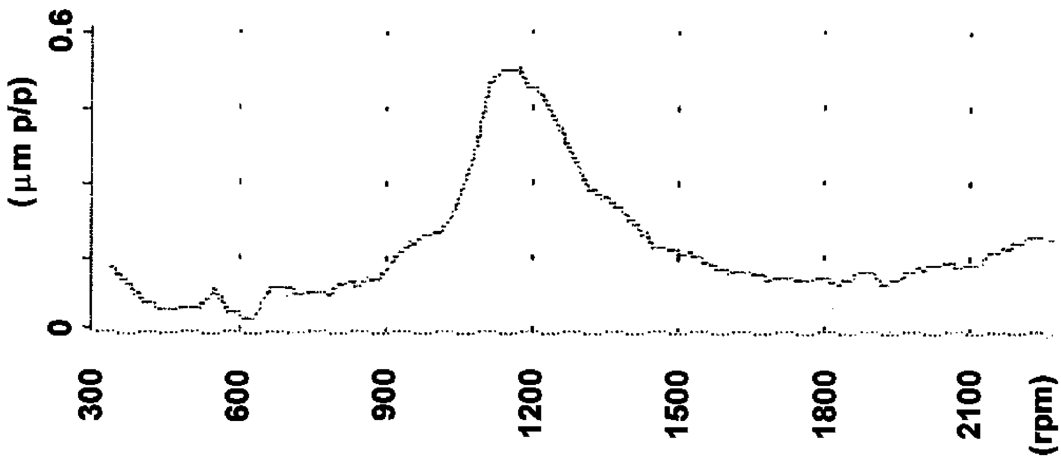

Fig. 6. Grinding spindle – horizontal amplitude response to out-of-balance forces.

These are the major determinants of grinding surface quality, and were tackled in order.

5.3 Machine Alignments

The machine tool builders had set most machine alignments accurately; metrology checks confirmed these to be in order. However, the critical alignment datum (alignment between workspindle axis and grinding spindle axis) had been lost, since the grinding spindle had to be removed, prior to relocating the machine in the Precision Engineering Laboratory.

This alignment datum had to be re-established by using a miniature eddy current probe (with a measurement range of around 6 μm) mounted on the grinding spindle faceplate. A special purpose alignment jig was mounted on the workspindle faceplate. Measuring the variation of distance of the probe from features on the alignment jig, as the two spindles were independently rotated, allowed the angular alignment of the two spindle axes to be determined, using a multiparameter least squares fit.

5.4 Wheel Balance

The machine is configured to enable automatic balancing on the grinding spindle. This is included on the machine to accommodate the automatic selection of grinding wheels. The grinding spindle carries two concentric segmented cup wheels, rough and fine grit; the rough wheel is of slightly larger diameter. The roughing wheel can be selected automatically by sliding it parallel to the spindle axis, under air piston control, to engage in one of two face tooth couplings, so that it either projects or is just below the face of the fine wheel. These two configurations, with rough or fine wheel selected, have marginally different out-of-balance moments, and the automatic balancing is included to compensate for this.

Figures 6 and 7 show the amplitude and phase response for a balance (displacement) sensor in a horizontal orientation, located at the grinding spindle nose, over a range of revolutions per minute (rpm) shown along the *x*-axis of the figure. The *y*-axis represents a nominal peak-to-peak displacement at that rotation rate of the grinding spindle. These data were obtained subsequent to fine (single plane) balancing of the grinding

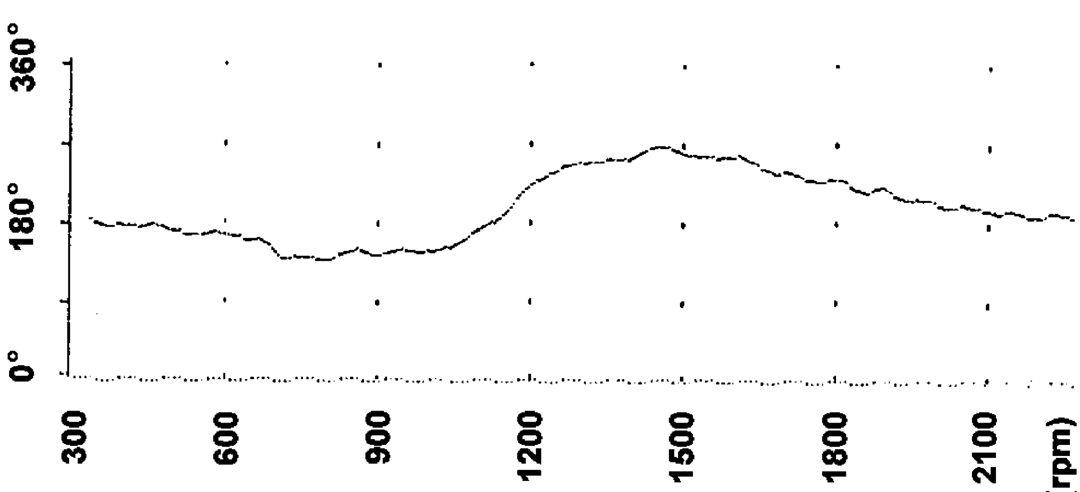

Fig. 7. Grinding spindle – horizontal phase response to out-of-balance forces.

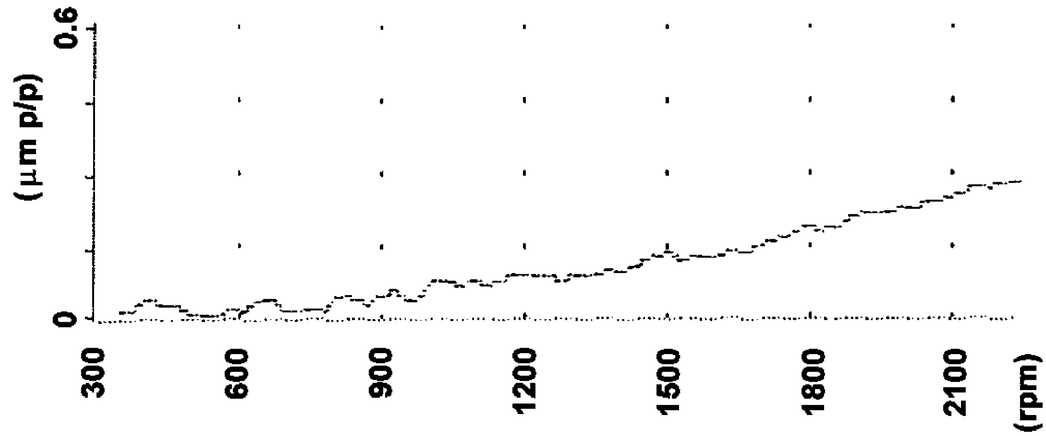

Fig. 8. Grinding spindle – vertical amplitude response to out-of-balance forces.

spindle. A strong resonant response can be seen at around 1200 rpm (or 20 Hz). Figure 8 shows the amplitude response for the balance (displacement) sensor in a vertical orientation. The resonant behaviour is entirely absent. Subsequent investigation has revealed that the source of the resonance is compliance in the "B" grinding wheel tilt axis (a vertical axis), as shown in Fig. 3, which is why this is only apparent to a horizontally oriented sensor.

The truing wheel balance is also critical. Figure 9 shows the horizontal response of the truing spindle, subsequent to fine balancing. Again a small resonance is apparent in the horizontal direction, at around 4000 rpm (67 Hz). The truing spindle is mounted on the X-axis carriage, and this horizontal resonance is in the direction of the X-axis motion. Once more this is due to the compliance of the motion system in its drive direction. This has a lower impact on grinding performance than grinding spindle balance, although truing the spindle out-of-balance motion will impart a small-scale cyclic topography on to grinding wheels, which in turn affects grinding quality.

5.5 Wheel Condition

On this machine, wheel form is imparted through a truing operation, and wheel condition is maintained through subsequent dressing, in between relatively infrequent truing operations. The truing (forming) operation specified in the machine design involves a plunge "grind" similar to the wafer grinding operation, although in this case the cup grinding wheel and parallel truing wheel make contact at their periphery. The grinding wheel form was found to be in error by 0.2° (12 minutes of arc). The truing operation was amended to rectify this. Truing is now accomplished by a plunge and a subsequent traverse of the X-axis. Correctly applied, this can produce the

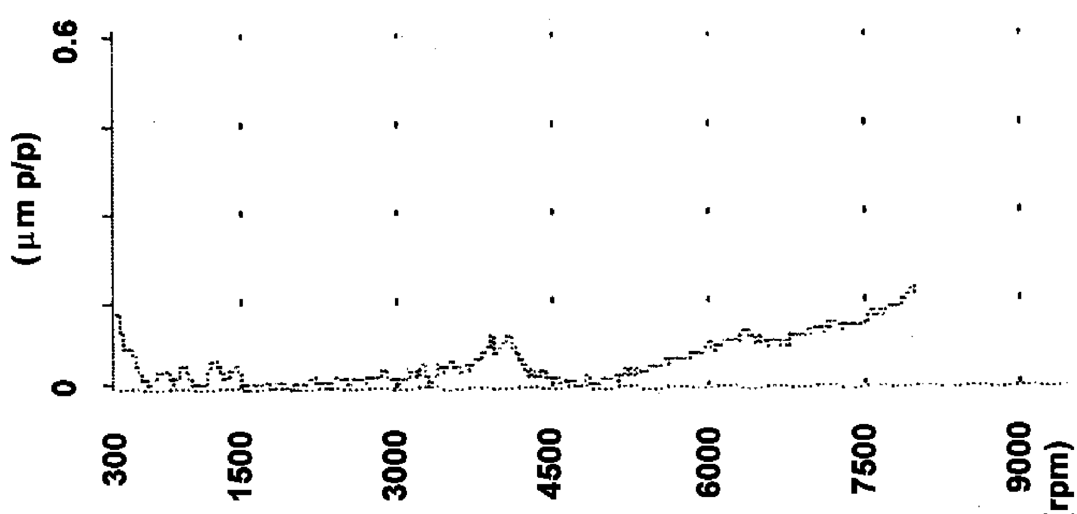

Fig. 9. Truing spindle – horizontal amplitude response to out-of-balance forces.

correct (planar) wheel form, since the grinding spindle axis had previously been set accurately to be perpendicular to the X-axis motion.

5.6 Coolant Application

Considerable effort was concentrated in the alignment of the coolant nozzles, in order to deliver sufficient coolant into the grinding interface. This is particularly important here where the grinding arc of contact is so long, at approximately 200 mm for a 200 mm wafer.

5.7 Motion Control

New grinding routines and complex motion profiles were developed for the grinding. A full wafer grinding cycle consists of an initial rough grind, followed by a finish grind. In each grinding phase, the work and grinding spindles are set to rotate, coolant is then applied, and the grinding spindle is fed into the work rapidly until the acoustic emission sensor detects a touch. Following rapid deceleration, the spindle is fed in further, in three stages, at successively lower feedrates, and for successively smaller feed depths. Finally, after a dwell (spark out) time, the grinding spindle is retracted.

This in-feed motion sequence is complicated by the simultaneous slaved motion of the A and B tilt axes. Completely coplanar plunge grinding is likely to result in non-planar grinding results. In order to achieve planarity in the finished surface, a slight angle must be maintained between spindle axes at first contact, and this angle is gradually reduced to zero (nominally) at the conclusion of grinding. A further modification to the infeed motion is imposed by the results of the three-point gauging, which monitors, in-process, the deflection of the machine due to the high static grinding forces. The measurements of the gauges modify the demanded angle between spindle axes throughout the grinding process.

6. Initial Grinding Trials

Initial grinding trials were conducted on monocrystalline silicon, using 200 mm wafers. Initial grinding trials were conducted, using parameters selected on the basis of extensive research experience in silicon grinding. Wheel speeds were selected to give minimum excitation of machine resonances (as indicated in Figs 6 and 9) i.e. ~2000 rpm for the grinding wheel and 5100 rpm for the truing wheel, whilst still maintaining adequate grinding efficiency. The requirement for the total grinding depth for roughing is set by the need to remove any swash on the wafer, and the requirement for total grinding depth for finishing is set by the need to remove subsurface damage caused by the roughing process. Relative wheel speeds during truing were set so to give a non-integer ratio. The parameters for truing, rough grinding and fine grinding are shown in Tables 1–3.

A Talysurf form trace indicated that the surface roughness achieved in the roughing operation was approximately 200 nm Ra. Other measurements indicate a sub-surface damage depth of around 5 μm. It is this subsurface damage depth that dictates the total machining depth for the fine grinding operation.

Table 1. Truing parameters.

Truing wheel type	Plated wheel ZD107N200g
Truing wheel diameter	180 mm
Truing wheel speed	5100 RPM (48.05 m s^{-1})
Feedrate to first touch	40 μm s^{-1}
First grinding feedrate	5 μm s^{-1}
Second grinding feedrate	0.3 μm s^{-1}
Total machining depth	20 μm
Grinding wheel speed	2000 rpm

Table 2. Rough grinding parameters.

Wheel type	46 μm resin VD46-C75-B117
Wheel diameter	370 mm
Wheel speed	2000 rpm (38.75 m s^{-1})
Feed rate to first touch	150 μm s^{-1}
First grinding feedrate	2 μm s^{-1}
Second grinding feedrate	1 μm s^{-1}
Third grinding feedrate	0.5 μm s^{-1}
Total machining depth	15 μm
Work speed	10 rpm

Table 3. Fine grinding parameters.

Wheel type	6/12 μ, resin bond AD6/12-C75-B118
Wheel diameter	305 mm
Wheel speed	1800 rpm (28.75 m s^{-1})
Feedrate to first touch	80 μm s^{-1}
First grinding feedrate	1 μm s^{-1}
Second grinding feedrate	0.2 μm s^{-1}
Third grinding feedrate	0.05 μm s^{-1}
Total machining depth	8 μm
Work speed	200 rpm

The appearance of the finish ground wafer surface was very good (Fig. 10) for these initial machining trials. Very faint "ghost" arc lines are discernible, although these are not evident on the Talysurf traces, nor are they visible on the photograph. They do, however, show a cyclic pattern, which is a product of the grinding wheel rotation rate and the workpiece rotation rate – i.e. their effect is exacerbated by any out-of-balance effect of the grinding spindle. The cosmetic appearance is optimised by maximising the rotation rate of the wafer during grinding, although this slightly worsens the measured surface roughness. The grinding parameters given above represent a compromise; the best surface roughness figures (around 10 nm Ra using the current configuration and tools) can be obtained for very low workpiece rotation rates ($<$1 rpm) although the cosmetic appearance is worse, owing to the more prominent appearance of the cyclic pattern.

7. Assessment of the Machine

The wafer face grinder has produced some very impressive results, following limited process development due to the short

Fig. 10. 200 mm wafer as finish ground – 15 nm Ra.

timescale of the programme. There are some areas of potential improvement.

The impact of servo compliance in B- and X-axes as indicated by the displacement measurements for spindle balance (Figs 6–9) suggest that improvements in servo dynamic stiffness and improvements to spindle balance can have immediate and significant effects on ground surface quality – given that the "once-per-rev" signature from the grinding spindle is a major factor in the machined surface topography.

8. Research Programmes

The machine is currently undergoing final commissioning within Cranfield University's Precision Engineering Laboratory and a number of research programmes, including those outlined below, have been identified which will benefit directly from the availability of the face grinding machine.

8.1 Micromachining and Planarisation of Piezoelectric Ceramics

Piezoelectric ceramics such as those based on the lead zirconate titanate system offer the capability for high-accuracy fine-scale movement coupled with high stiffness and the ability to generate high forces. Such materials are widely used in a host of devices ranging from low-cost mass-market applications like buzzers through inkjet printers [3] to high-end products such as tunable etalons [4]. The latter devices show considerable promise for channel selection in wavelength division multiplexing [4]. There is also considerable interest in the integration of piezoelectric materials with silicon for microsystem devices. Much work is currently focused on the use of directly deposited thin- and thick-film materials [5]. However, there are advantages to the use of high-temperature sintered and hot-pressed bulk materials. Firstly, the piezoelectric coefficients which can be achieved are much higher. Secondly, the use of bulk materials opens the possibility of using thicker materials, leading to greater longitudinal displacements for a given applied field. Thirdly, and perhaps most interestingly, it opens the possibility of using multilayer actuator technology, an option that is not currently available in directly deposited material. (In this technology the piezoelectric ceramic is made as a multilayer cofired stack with interleaved metal electrodes, giving higher displacement for a given drive voltage than a monolithic device.) One can consider using a process such as anodic bonding to bond a very flat PZT surface (formed on either a bulk or multilayer material) directly to a silicon wafer, then machine-down the opposite face to leave a flat parallel material bonded to silicon, but exhibiting all the advantages of the bulk material. Clearly such an idea could also be applied to the bonding of PZT to other materials such as optical glasses. Thus there are many areas where piezoelectric materials are used or have the potential to be used. In many cases, for example for the optical applications, there is a need to make high-flatness, low-damage surfaces at high speed and low cost. Work at Cranfield University [6–9] has demonstrated the potential for using ductile mode machining for achieving very low damage, excellent surface finishes in hard and soft PZTs. The intention will be to apply the machine to the preparation of such surfaces for practical applications.

8.2 Monitoring of Surface Integrity During Grinding

The aim of this programme is to optimise the grinding parameters to maximise material removal rate whilst ensuring that ductile material removal mechanisms dominate. Further, the dynamics of the grinding process ensure that the optimum grinding parameters will change, for example, as the grinding wheel wears, the grinding force increases and the grit/workpiece interaction changes. There is clearly a need to monitor the grinding process with the aim of optimising the ductile regime material removal conditions.

A promising method which could be applied for the continuous monitoring of the grinding process, is acoustic emission (AE). The boundary conditions between the ductile and brittle grinding regimes are distinct and reflect a change in material removal mechanism from the shear mode "ductile" (plasticity dominated) to the brittle, fracture-controlled processes. This change in mechanism is abrupt as demonstrated by the sharp transitions observed at critical depths of cut. Such a change in the mechanism should provide a change in AE signal which can be used to control the grinding parameters in real time.

The wafer grinder is fitted with an AE system and includes three sensors, one in the grinding spindle, a ring sensor around the workhead and a ring sensor around the truing spindle. The AE system is highly sensitive and detects a wide range of events that influence the grinding process. These events can be isolated, and because of the very short response time, real-time adjustment of the grinding process is possible.

AE signals will be analysed and correlated with the grinding conditions and surface integrity of the workpiece material. In addition the AE signal will be related to the force, stock removal rate and specific grinding energies. This should enable the change in contact conditions within the grinding zone to be monitored and the approach of the ductile/brittle transition identified. Thus, avertive action can be taken as the critical transition is approached.

8.3 High-Efficiency Precision Grinding of Hard Metals

Amongst the most difficult materials to finish are hardened tool steels and bimetallics that are often used for applications requiring an exceptional combination of wear resistance and toughness. A good example is their use as barrels and dies in extruder technology [10]. These components are exposed to a variety of degradation mechanisms but must maintain their surface finish and dimensional control throughout their lifetime. Not only is surface finish important, but also surface integrity, since machining damage introduced into the surface can have a deleterious effect on the wear resistance and thence the component performance and lifetime.

Low-stress grinding (LSG) of these hard metallic alloys is possible in order to minimise microcracking and surface burn and phase transformations. However, LSG requires the use of a rigid, vibration-free machine tool with soft wheels, low wheel speeds and frequent wheel dressing. This results in lower rates of material removal, low grinding ratios (typically 1–5) and a significant increase in production costs [11].

Manufacturers have investigated the use of grinding to finish machine barrels [12], but the use of resin-bonded diamond or CBN form wheels was found to be uneconomic due to the frequent need for wheel dressing. Attempts to increase material removal rates resulted in surface damage, in particular microcracking, which is a common problem in these types of material [13]. For this reason, current practice in finish machining of bimetallic extruder barrels uses single-point CBN tooling, which itself is slow and expensive. Typically, finish machining accounts for over 50% of the total manufacturing costs [12].

The problem of machining hard, tough tool steels and bimetallics is common to many industries and there is clearly a requirement for a grinding process that will provide the required level of surface integrity and finish, whilst removing metal at economic rates. A current research project aims to achieve this through the application of electrolytic in-process dressing (ELID) to the grinding process. ELID has been shown to be an effective method for maintaining cutting grit protrusion and preventing wheel loading. The results to date have been outstanding, demonstrating the ability to produce surface finish at the nanometre level, at realistic material removal rates [1]. This work has been undertaken on small flat test pieces and the next stage will be to scale up the process to demonstrate a capability on larger components of more complex form. This will require both roughing and finish grinding cycles. The face grinder will be used to investigate the interaction between the roughing and finishing stages, to grind components in a single grinding cycle, using coarse CBN resin bond wheels for the roughing stage and finer metal bond CBN/ELID-assisted grinding for the finishing to optical quality. The primary aim will be to optimise the roughing stage to maximise material removal whilst minimising the introduction of subsurface damage to a level that is easily removed by the finishing cycle.

9. Concluding Remarks

The availability of an advanced machine tool with such extensive machine/process monitoring and automatic supervision features will enable the development of optimised process models for a wide range of advanced materials and components.

The requirements for nanometre regime surface finishes and minimum surface/subsurface damage are becoming increasingly demanding and novel approaches are required, including the development of a new range of specifically designed ultraprecision machine tools for various products. A major beneficiary, following the development of optimised process models, will therefore be precision machine tool manufacturers such as Cranfield Precision, who have already developed wafer and memory disc edge grinding machines for the semiconductor and computing industries. End users will also benefit as the benefits of ultraprecision machining are exploited and extended to a wider product base. This includes applications such as those listed below:

1. Optoelectronic components for the improved manufacture and performance of components for high-performance semiconductor lasers, light wave communication systems and optical parallel processing.
2. Pressing and tooling dies in ceramics for high-precision replication of appropriate polymetric materials for a wide range of applications.
3. Piezoelectric devices for a host of devices including mass-produced sensors, actuators, inkjet printers, and special tunable etalons for wavelength division multiplexing.
4. Optical components including large aspheric optics, X-ray lenses and mirrors for space applications, etc. certain automotive hard steel transmission components for which there is a future target specification of 10 nm Ra surface finish together with a material removal rate of 30 mm^3 min^{-1}.

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