Int J Adv Manuf Technol (2009) 41:468–480
DOI 10.1007/s00170-008-1496-3

ORIGINAL ARTICLE

Recent developments in grinding of advanced materials

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Received: 11 October 2007 / Accepted: 26 March 2008 / Published online: 7 May 2008

Abstract This article discusses the recent developments in grinding of advanced materials. Eighty-four journal papers published recently are briefly introduced. The topics are advances in grinding of brittle materials, grinding of silicon, dressing/truing of grinding wheels, grinding fluids, grinding of mirrors and vibration-assisted grinding, measuring/monitoring of grinding, optimization of grinding, modelling and simulation of grinding, and size effect. Ductile mode grinding of brittle materials has been and will continue to be an intensive research area because of its increasing industrial applications and academic demands for fundamental understanding of the ductile mode grinding mechanism. Highly precision manufacturing of silicon substrates faces more and more new challenges. Grinding of silicon continues to be a popular research topic. Using lasers to true and dress grinding wheels has attracted great research interest, because it has significant advantages over mechanical processes. Environmentally friendly grinding fluids are increasingly highly demanded. Vibration-assisted grinding is promising. Monitoring, modelling and optimization of grinding processes help to understand grinding mechanisms and achieve better grinding performance. The size effect is more prominent in grinding than turning and can be used for obtaining a controlled work-hardening surface layer with higher wear resistance and hardness.

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Keywords Grinding · Silicon · Ductile mode · Brittle material · Modelling · Dressing · Monitoring · Grinding fluid · Vibration · Size effect

1 Introduction

Manufacturing of a component must provide its basic size and shape with desired surface finish and tolerances. Grinding is one most widely used process to achieve material removal and desired surface finish with acceptable surface integrity, dimensional tolerance and form tolerance [1, 2]. It accounts for about 20–30% of the total expenditure on machining operations in industrialized nations [3]. Grinding is also the most complicated machining process [4], with unsteady process behaviour, whose complex characteristics determine the output quality [5].

Interest in grinding of advanced materials such as optical glass, WC, ceramics and silicon has substantially grown with the widespread use of precision components made of such materials in various applications [6, 7]. The grinding wheel plays a key role in a grinding process for obtaining high machining accuracy and good surface finish of the workpiece [8–10]. With recent developments in frontier industries such as semiconductor and microelectronics industries, there are increasing demands for highly-precision processing of hard and brittle materials [11]. The advances in the use of super-abrasive (CBN and diamond) grinding wheels have opened new possibilities to the industries. Important improvements in surface integrity, surface finish and productivity have become possible in the manufacturing of components made of difficult-to-machine materials [12].

This article discusses the recent developments in grinding of advanced materials. Eighty-four journal papers that are published recently are briefly introduced. The topics are advances in grinding of brittle materials, grinding of silicon, dressing/truing of grinding wheels, grinding fluids, grinding of mirrors and vibration-assisted grinding, measuring/monitoring of grinding, optimization of grinding, modelling and simulation of grinding, and size effect.

2 Grinding of brittle materials

Many advanced materials such as ceramics, silicon and optical glass are hard and brittle materials. Since 1980s, ductile regime grinding of brittle materials has been and is continuing to be an intensive research area because of its increasing industrial applications and academic demands for fundamental understanding of the ductile regime grinding mechanism.

Cross grinding and parallel grinding are two typical grinding modes. A significant comparison of these modes for grinding of brittle materials was not available in the literature, and thus it was conducted by Sun et al. [13]. Parallel grinding with a much higher material-removal rate (MRR) in the ductile regime is found to be possible than cross grinding. Conventional grinding of BK7 glass usually leads to brittle fractured surfaces with severe sub-surface damage and poor surface finish. Ductile regime grinding conditions do not necessarily depend only on MRR, because chip thickness is a function of the grinding mode and MRR. Non-uniform wheel wear in the primary removal zone affects chip thickness and can lead to a non-uniform distribution of micro-cracks. The grinding forces and the depth of sub-surface damage increase with chip thickness. With a chip thickness below the critical chip thickness, a high quality surface with surface finish better than 5 nm (R_a) and minimal sub-surface damage can be obtained.

Bifano's model Eq. (1) is often used to determine the critical depth of cut, d_C, for ductile regime grinding of brittle materials [14, 15].

$$d_C = b\frac{E}{H}\left(\frac{K_C}{H}\right)^2 \tag{1}$$

where E is Young's modulus, H is hardness, K_C is fracture toughness, and b is a constant. It was found that the calculated d_C using b=1 in Eq. (1) was higher than those obtained from the experiments in machining of different glasses. Thus, b=0.15 was proposed by Venkatesh et al. [15] for micro-grinding of glasses. Partial-ductile or semi-ductile grinding followed by simple, mechanical polishing is promising and is relatively low cost for ophthalmic, infrared and laser optics applications. It can generate glass, Si and Ge surfaces with massive ductile streaks, which reduce polishing time. The development of a bondless diamond grinding-wheel can increase ductile streaks. General-purpose machines can give flexible output in terms of variety of lenses, without the need of special-purpose machines.

Brittle materials are characterized by Koshy et al. [16] with grinding-direction-related strength anisotropy attributed to the dual population of grinding-induced micro-cracks. The process kinematics proposed by Koshy et al. is realized by rotating the wheel by 90° in the horizontal plane from the configuration of conventional cylindrical grinding such that the grinding lay is along the longitudinal axis of the work-piece. Compared to conventional cylindrical grinding, the wheel-work contact area is independent of the grinding wheel width and is reduced, which leads to lower grinding forces, better geometric form and dimensional tolerances for grinding slender components, and more effective cooling. Compared to conventionally ground quartz samples, the material-adapted kinematics variant approach can enhance the characteristic flexural strength by 30%.

The Preston coefficient of a resin bond tool with 2–4 μm diamond abrasives was measured with BK7 as the test specimen, and compared to that of a similar bronze tool by Tong et al. [17]. The measured Preston coefficient of the resin tool was two to three times smaller than that of the bronze tool, and decreased rapidly as the pass number increased, because the excessive tool wear reduced the cutting efficiency of the tool, resulting in a rapid decrease in the Preston coefficient. The actual depth of cut of the resin tool did not reach a programmed depth of cut, eventually leading to tool failure. Compared with a bronze bond wheel, a resin bond wheel with similar diamond sizes produces a surface with better surface finish, but wears faster and can be less efficient. The resin may not hold the abrasives firmly in grinding of a hard glass, and many diamond abrasives are pulled out.

Diamond pins (ϕ5-mm) were used by Izman and Venkatesh [18] to produce plano surfaces on glass by vertical surface grinding. Chip clearance was difficult and this led to the formation of stalling and zero velocity tracks, which continued to persist even after polishing. Removing this residual roughness was almost impossible by lapping and polishing. Stalling tracks showed the formation of lateral micro-cracks, presumably the result of indentation instead of chip flow machining or ploughing. This problem was overcome using a central cavity, which could accommodate chips, promoting minimum quantity lubrication or 100% dry grinding. The grinding without the central hole resulted in gelling of silica chips. Gelling of glass chips would load the wheel, requiring frequent dressing of it. Stalling occurs because of lack of coolant penetration into the grinding zone. Another undesirable phenomenon is dragging mark on the ground surface due to the zero velocity effect that accumulates chips at the grinding pin centre. The introduction of a centre hole on the grinding pin eliminates these three problems.

Many researchers have conducted theoretical analyses and experiments on ductile regime grinding of brittle materials, but a persuasive theory is absent. The critical conditions for the brittle-ductile transition of brittle materials and the main factors affecting the surface quality need to be researched more deeply. Based on indentation tests, the critical conditions are investigated by Chen et al. The critical cutting depth d_{gc} for the brittle-ductile transition during grinding can be obtained by [19]:

$$d_{gc} = K_0 \cot\left(\frac{\alpha_0}{2}\right)\sqrt{\frac{2\lambda_0}{a}}\left(\frac{K_d}{H}\right)^2 \tag{2}$$

where λ_0 is the integrative factor, λ_0=(1.0–1.6)×10^4, H is the micro-hardness of the material, $2a$ is the feature size of indentation, α_0 is the indentation top angle, K_d is dynamic fracture toughness under the impulse load, and K_0 is the affecting coefficient of the coolant to brittle-ductile transition. Equation (2) considers the impulse loads in grinding and the coolant's effect.

Grinding is also one of the major machining processes for gem manufacturing. The largest gemstone in the jewellery market is cubic zirconia. Published work on high-speed grinding of gemstone and cubic zirconia is scarce. Jirapattarasilp and Rukijkanpanich have recently reported that the surface finish of ground cubic zirconia is improved with increased grinding speeds and abrasive grit sizes, and its surface roughness R_a can be expressed by the following correlation equation [20]:

$$R_a = \left(\frac{\beta}{C_P}\right)^\gamma \tag{3}$$

where C_P is Preston's coefficient, which is the total removal volume divided by the normal load, grinding speed and grinding time. β and γ are constants. For example, when 1000-mesh abrasive grit-size is used, β and γ are 0.0309 and 0.652, respectively.

3 Grinding of silicon

Silicon is the most widely used substrate material for fabrication of integrated circuits (ICs). The continuing size shrinkage of IC features has imposed more stringent requirements on the Si wafer flatness [21]. Highly precision manufacturing of silicon [7, 22–24] substrates face more and more new challenges. Grinding of silicon continues to be a popular research topic.

The traditional lapping-based manufacturing method is unable to satisfy the ever-increasing demand for better flatness at a lower cost. One cause to the poor flatness is the central bumps on ground wafers. Sun et al. [21] investigated the generation mechanisms of the central bumps, and found that central dimples can be formed on the ceramic chuck and the wafer front surface before the wafer is removed from the chuck after grinding. The depths and radii of these two dimples determine what the wafer centre will be: flat, a dimple, or a bump. The wafer centre will be flat only if the dimple on the chuck and the dimple on the wafer front surface are identical before the wafer is removed from the chuck. These two dimples can be reduced or eliminated by using a steeper chuck shape, selecting a more rigid grinding wheel and choosing grinding conditions resulting in lower grinding forces.

The laser acoustic test based on surface acoustic waves is a potential future evaluation method for wafers. The damaged sub-surface characteristics of ground wafers can be investigated by stepwise removal of shallow surface layers and consecutive measurement of the dispersion characteristics of the remaining surface. The Young's modulus of ground Si wafers was determined by Paehler et al. [25] using a laser-acoustic method based on surface acoustic waves. A difference measurement procedure was applied to determine the Young's modulus of single layers of less than 0.02-μm thickness. The layers were removed stepwise from the damaged wafer by reactive ion etching, to identify a profile of the Young's modulus through the sub-surface region. This gave new insights into the distribution of the damage perpendicular to the wafer surface. The measurements were performed parallel, perpendicular and 45° to the grinding direction, revealing preferential orientations of the defects in reference to the machining directions and crystallographic orientation.

A silicon-on-metal-on-insulator (SOMI) substrate with a structured buried silicide layer was fabricated by Zimmermann et al. [26] on the wafer level using wafer bonding, CMP and back grinding technologies. A SOMI substrate consisting of a 300-nm thick top-Si, a buried thin $CoSi_2$ layer and a buried SiO_2 layer on a Si substrate was formed as the starting material. To achieve a top-Si thickness for device applications, grinding, spin etching and CMP were performed after bonding. The device wafer was back-ground without an etch stop layer to a thickness of 20 μm. Then the Si layer was polished to its final thickness by CMP.

Simultaneous double-disk grinding (DDG) is a powerful technology for machining Si wafers, using two opposite grinding wheels to simultaneously flatten both sides of the free-floating wafer between them. The extreme planarity degrees required by microelectronic devices with lateral features below 90 nm can be achieved. The basic characteristics inherent to the specific DDG kinematics can be understood using analytical calculations and the wafer geometry predicted with a simple model [27]. This model shows (1) a TTV of about 0.5 μm, (2) radial symmetry, (3) asymmetric front and back removals for standard counter-rotating grinding wheels, and (4) the dependence of the thickness profile on specific kinematics and dimensions.

Recently, back side thinning of fully processed product wafers is widely conducted in the semiconductor industry. Thin silicon offers new possibilities in microelectronics, solar and micro-mechanical industries for stacked dies, thin microelectromechanical packages and thin solar cells. To obtain reliable microelectronic products, detailed investigations of the strength and deformation of ultra-thin silicon wafers must be conducted. Wafers were thinned by grinding and subsequent spin etching for stress relief followed by separation into single dies by sawing or etching. The effects of three dicing technologies (sawing, dicing-by-thinning with sawn grooves and with dry-etched trenches) on the mechanical strength of thin Si samples were investigated by Schoenfelder et al. [28] with three-point bending tests. The results were statistically evaluated by the Weibull distribution based on the weakest link theory. Samples separated by dicing-by-thinning have much higher strength than simply sawed samples. If trenches are fabricated by the dry-etched process, the strength can be increased tremendously.

In one application of thinning Si dies (chips), the chip thickness had to be reduced from 85 μm to about 50 μm. Initially electroplated diamond grinding pins were used successfully but this left undesirable tracks that remained even after polishing. These pins were not ideal for the soft but tough chip package. A new binderless diamond grinding wheel was developed by Venkatesh and Izman [29] that had a width equal to that of the IC chip and the chip package with considerable success.

Using a cup grinding wheel can achieve mirror finishing of a device wafer on the same machine after back grinding. However, much heat is generated in dry grinding for thinning of device wafers, leading to deterioration of the adhesive agent and difficulty in controlling the form accuracy. Therefore, a new silica wheel is developed by Tani et al. [30], which can be used in a wet condition. Polyvinyl alcohol (PVA) is the bonding agent, and the absorbent swell leads to disturbance of water infiltration to the inside in cup grinding. A PVA wheel has high water-absorbing ability because of its sponge-like structure. This ability and the wheel hardness are important factors governing the grinding characteristics. Mirror finishing is achieved within 2 minutes because water penetration to the inside of the wheel surface is prevented by the existence of concentric grooves.

The sensitivity and resonance frequency of dielectric substrates can be improved when their thickness is decreased, because the oscillation frequency is inversely proportional to the thickness. Therefore, recently processing of ultra-thin substrates has also attracted much research interest. An ultra-thin dielectric substrate was obtained by precision grinding and lapping/polishing [31]. The substrate was thinned to 50 μm thick using fine-grained diamond wheels and a polishing pad. The substrates were thinned by lapping and polishing to 17 μm thick with good flatness. The good flatness was produced by the hard polishing pad made of polyvinyl chloride resin because of the mechanical properties of high fixed grain density.

4 Dressing/truing of grinding wheels

Dressing is a sharpening operation to generate a specific topography on the working surface of a grinding wheel. The conventional dressing methods do not produce consistent results because of dresser wear, which cannot produce sufficient protrusion of cutting grain edges [32]. It is difficult to sharpen super-abrasive wheels with high accuracy. A vitrified SiC brake-controlled wheel or a metal-bonded diamond truer is often used for truing, and an alumina wheel/stone is for dressing. These methods are time-consuming, generate pollution of the working environment and cause mechanical damage of the abrasive grains [33]. To achieve satisfactory truing/dressing quality and efficiency using single-tip diamond dressers is difficult. The potentials of super-abrasive grinding wheels have not yet been fully realized in most applications [34].

Recently, laser dressing and laser truing of grinding wheels have attracted great interest. Laser processes potentially have significant advantages over mechanical processes because lasers enable non-contact processing [34]. Early studies of laser dressing used pulsed lasers and most of them concentrated on comparison of the grinding performance of laser dressed and diamond dressed wheels. Laser-assisted simultaneous truing and dressing was also attempted to overcome the problems associated with mechanical dressing, but the studies did not address the nature of physical changes. Some earlier reports on laser dressing did not show a great advantage over conventional dressing, because a high powered laser could damage the abrasive grains, which would lead to higher grinding forces and higher wheel wear [32]. In addition, few studies have dealt with laser processing of vitrified CBN wheels. There were not many reports on laser processing of small vitrified CBN wheels [34]. Furthermore, the effect of the fused and re-solidified bond material on the grinding performance in laser dressing of metal bonded wheels is not clearly known and a relatively high energy level is needed for material removal leading to grit failure or graphitization of diamond grains [33].

As one of the examples discussed in this section, the incident angle for laser processing of small vitrified CBN grinding wheels was optimized by Wang et al. [34]. A model predicted the effects of processing parameters such as incident angle and focal offset on absorbed energy and the effects of incident power and processing speed on the volume of material removed. Re-solidification of molten ceramic exhibited a porous structure different from the original wheel surface. As another example, a high power laser is used by Jackson et al. [32] to clean metal chips from the grinding wheel surface and dress a vitrified grinding wheel. Experimental results reveal that laser modified grinding wheels have comparable performance with conventionally cleaned and dressed grinding wheels.

A pulsed-Nd:YAG laser is used by Hosokawa et al. [33] for thermal dressing of a bronze bonded diamond wheel. The laser beam is irradiated on the wheel surface and the bond material is partially removed. To efficiently remove the bond material, it is necessary to direct an air jet on the spot irradiated by the laser to blow away the molten binder before it solidifies again. Less damage of diamond particles such as micro-cracks or graphitization occurs. During grinding with a laser-dressed or a conventionally dressed wheel, the grinding forces are almost the same. One disadvantage of laser dressing is high initial cost. However, the technical advantages such as short dressing time, non-consumable dresser and applicability for any wheels can offset this disadvantage.

Compared with metallic materials, relatively less research has been conducted on laser surface modifications of ceramics. Most of the approaches have had limited success in realizing the full potential of non-contact laser dressing such as in-process dressing, consistency in workpiece finish, low cost of production and improved productivity. An approach to laser dressing of alumina wheels is proposed by Harimkar and Dahotre [35] based on solidification microstructures associated with rapid cooling rates, which result in the formation of highly refined multifaceted grains that facilitate the micro-scale material removal during machining. An increase in faceted surface grain size is attributed to the slower cooling rates associated with higher laser fluences. Increase in laser fluence increases the spatially efficient assembly of faceted grains in the surface layer. The melting depth in laser-dressed wheels increases with laser fluence. The faceted grain size and the melting depth of the laser-dressed grinding wheel can be controlled by the laser processing parameters.

Alumina wheels dressed with a laser induce change in the morphology of the wheel surface. The altered grain structure on the wheel surface gives laser dressing another advantage over conventional mechanical methods. Morphological modification during laser dressing is strongly affected by the microstructure, which is formed during the rapid solidification process and depends mainly on the cooling rates. Laser dressing leads to a decrease of the porosity amount in the re-solidified layer on ceramic materials because of the surface structure consolidation. Orientation imaging microscopy was used by Khangar et al. [36] to determine the grain orientations in the re-solidified layer on the dressed surface. There is a preferred orientation of grains along the (110) planes. This can be a reason for the formation of grains with multi-faceted surfaces having cutting edges and vertices.

Super-abrasive grinding leads to new applications but also new problems. The high hardness of metal bonded super-abrasive wheels makes truing/dressing (T/D) a very difficult task with many problems. Mechanical T/D with diamond tools shows important limitations: high wear of T/D tools, high T/D forces and the maximum grit protrusion of only ~20–30% of the grit size, affecting wheel performance. CBN wheels are used for grinding of ductile materials and large grit protrusion is required to accommodate the long chips. Electrolytic in-process dressing uses the electrolytic effect between the electrode and the wheel and the conductive bonding material is removed from the wheel during grinding. Little work was done on electro discharge dressing (EDD) of large-grit size super-abrasive wheels. Therefore, EDD process is applied to large-grit-size CBN wheels by Sanchez et al. [12]. Improvements in the grinding performance can be obtained by maximizing grit protrusion while avoiding grain loss. Electrode size and wheel speed directly affect process stability, while discharge current and pulse time are mainly related to bonding MRR. Compared to a mechanically dressed wheel, grinding forces are 50% lower in the case of the EDD'ed wheel, which can be used with higher depth of cut because of the higher grit protrusion obtained. The problems in EDD of large-grit size wheels are different from those of small-grit size wheels. The origin of the problems is that the gap is smaller than grit exposure, and the wheel grinds the electrode, leading to excessive gap contamination. A special technology must be developed to optimize the process.

Experiments are conducted by Kim et al. [11] to measure the vibration signals of the sintered carbide workpiece during grinding with an in-process electrolytic dressing method. Components with low frequency vibration signals have a very close relation to the undulation of a ground surface and components with high frequencies to the surface roughness. The vibration signal changes significantly when the grinding depth changes. The time of processing termination can be determined by predicting the surface state. Surface waviness in mirror surface grinding is largely influenced by table speed, and surface roughness is largely influenced by grinding depth.

Previous research has focused much on the development of micro-grinding technologies with tooling and equipment, but not much was reported on parametric investigations of micro-grinding. Therefore, a parametric investigation for grinding micro aspherical mould inserts was performed by

Chen et al. [37]. A method using a metal bond cup wheel was also developed for truing resin bond micro (ϕ1-mm) wheels. An increase in work rotational speed slightly improved the surface finish. The surface finish of the ground insert improves as the grinding trace spacing decreases. Micro aspherical inserts with diameters of 0.2 and 1 mm were ground using a parallel grinding method with effective wheel preparation and form error compensation techniques. When grinding a small insert of ϕ0.2 mm, surface roughness of ~4 nm and a form error of ~0.4 μm are obtained.

An AE method is good for certain feedback control systems, but its in-process measurement of a profile grinding wheel during grinding operations may not be adequate because of the adverse effects of the grinding fluid, eccentricity, cutting force, machine or thermal deformations. An online dressing system for profile grinding wheels is introduced by Young and Chen [8]. A non-contact image measuring method is applied to evaluate deviation of the grinding wheel's edge to determine the timing and amount of dressing. The dressing force is a key parameter for determining the number of passes needed for high efficiency dressing so that the dressing time and waste of the dresser and grinding wheel can be minimized. The minimum dressing pass needed to restore the sharpness of the grinding wheel can be determined by the ratio of the dressing force. The dressing cycle is completed when the dressing force ratio settles to a constant.

In cross-grinding, wheel wear occurs in a restricted contact area of the wheel, affecting the profile accuracy of the ground surface. A geometrical analysis was performed by Hwang et al. [38] for generating a constant wheel radius, which was adopted for the parallel grinding of aspheric mould inserts. In the wheel truing process using a cup truer, the wheel radius is determined by the distance and angle between the truer and wheel. The wheel radius error was reduced by adjusting the wheel axis alignment.

5 Grinding fluids

Many problems are identified with grinding and cutting fluids, such as health and environment hazards. There is strong demand for better adequacy of industrial grinding processes to meet the present requirements of safety and protection to the environment. New combinations of fluids and grinding wheels have been tested. The application of CBN grinding wheels is a strong tendency. An environmentally friendly fluid accomplishes main requirements, such as biodegradable, low emissions and non-toxic. An ideal fluid offers good process performance and low costs. A proposed fluid [39] is based on a sulfonate vegetable oil with high concentration in water for CBN grinding at a high speed. The new fluid is non-toxic and has easy biodegradability.

Environmentally friendly water-based fluids have been offered recently by many suppliers. But the G ratio values obtained for CBN grinding with water-based coolants are much lower than with neat oil. A new water-based grinding fluid formulation able to meet the performance and environmental requirements for CBN grinding is presented by Oliveira and Alves [40]. The reaction between CBN grains and water is not significant compared to the measured volumetric wheel wear. A new fluid concept consisting of a high concentration of sulfonate vegetable oil in water is tested. It is possible to combine high lubricity, better heat conductivity and good environmental properties in one fluid.

Conventionally applied fluid only provides cooling but cannot penetrate the chip-tool interface. Major problems are requirements for filtration, pumping, local storage, recycling and large space, environmental pollution because of chemical break-down of the fluid at high temperature, soil contamination and water pollution during final disposal, and biological hazard to operators because of bacterial growth and inhalation of toxins. High production grinding enhances productivity, but increases the grinding zone temperature, which increases tool wear and impairs the product quality [1]. Historically grinding fluids are applied to control high temperature. They are perceived as a major source of pollution. The drastic cooling action of liquid nitrogen jets provides desirable temperature control. Cryogenic cooling with liquid nitrogen jets can be an efficient, effective, environmentally conscious and economic technology for controlling thermal problems in high production grinding and enhancing productivity and quality. It would be very interesting to follow the research direction in this area with future possible applications.

Grinding of ductile materials implies particular conditions such as maintaining the cutting ability of the wheel and wheel cleaning. The distance from the nozzle to the wheel should be small and several nozzles should be used if the wheel width is large. The flow rate needs to be high and the cleaning pressure needs to be low. The effect of the boundary layer of air is significant. The fluid temperature is not influential on the cleaning efficiency [2]. An active cooling approach for ductile material grinding is also examined by Gao and Lai [41] to enhance surface quality and productivity. A prototype is developed using forced convection of the heat generated during grinding. It improves the average surface roughness up to 36.7% [42].

A new cutting fluid application method is developed by Irani et al. for creep-feed grinding with Al_2O_3 grinding wheels. The fluid delivery system incorporates several concepts including coherent jets, high-speed fluid application, air scrapers and concentration effects associated with synthetic cutting fluids. The system results in an 83%

increase in MRR [43]. An experimentation method is also developed by Catai et al. [44] to evaluate the performance of the deflectors in the cutting region and minimize the air layer effect of the high speed of the grinding wheel. An optimized nozzle is used to compare the results with those obtained using the conventional fluid-application method (without baffles or deflectors). The results indicate the high efficiency of the deflectors or baffles for good finish.

An FEA model is developed and its predictions are verified with experiments by Salonitis and Chryssolouris. The grinding-hardening process uses the heat dissipation in the grinding area for inducing metallurgical transformation on the ground surface. The quenching must be assisted with coolant fluid for grinding-hardening of thin workpieces or cylindrical workpieces with small diameters [45]. FEA is also performed by Li and Li [46] to simulate the transient heat transfer process. For a brass-bonded diamond tool sliding over a glass substrate, 2.2% and 3.4% of the friction heat enters the substrate for water cooling and air cooling, respectively.

6 Grinding of mirrors and vibration-assisted grinding

The design of a six-axis machining system and its application in fabricating large off-axis aspherical mirrors is reported by Cheng et al. [47]. The system is developed using a computer-controlled optical surfacing technique for a large aperture on- and off-axis aspheric with micron precision. Grinding experiments involving an off-axis oblate ellipsoid mirror with a rectangular aperture of 770 mm×210 mm were conducted on the machining system. The final form error of the ellipsoid mirror with an initial error of 17.648 μm reached to 0.728 μm after 100 h of grinding and 100 h of fine grinding.

WC could be machined in the ductile mode by cutting, but the surface roughness R_a obtained was on the scale of 100–200 nm, which is not sufficient for optical applications. In addition, cutting of WC caused serious CBN tool wear. On the other hand, grinding with in-process dressing has been used to obtain mirror surfaces of engineering materials, but this technology requires the in-process dressing set-up for the expected function. Nanogrinding of a fine-grained WC-Co composite was performed by Yin et al. using a CNC grinding machine and a metal-bond diamond wheel to achieve an optical quality surface without polishing. Damage-free, planar mirror surfaces with a flatness at the submicron scale and surface roughness R_a<5 nm were obtained. The flatness increased linearly with an increase in the grinding contact length, with PV values ranging 0.245–0.79 μm. Different feed rates did not affect sample flatness. No effect of the grinding contact length on surface roughness was observed. Moderate feed rates gave the best surface finish [48]. Thermally sprayed WC-Co coatings are also machined by grinding and turning using diamond tools, and then characterized by Zhong and Peng [49]. Precision-machined WC-Co surfaces can be identified as self-affine fractals. The roughness of machined surfaces depends on the scale of cut-off length as a power law. It would not be suitable to compare roughness heights obtained using different cut-off lengths or scanning scales, because very small surface roughness readings can be obtained by scanning a very small area. However, it may be suitable to compare surfaces using roughness exponents.

A new centreless grinding technique, ultrasonic-shoe centreless grinding, is proposed by Wu et al. [50]. The method uses a plate-shaped ultrasonic shoe with a micro elliptic motion to support the workpiece and control its rotational motion. An apparatus capable of micro-scale fabrication was designed and tested by grinding of a WC test-piece, 0.6 mm in diameter and 15 mm in length, using a diamond grinding wheel. The result was a micro-scale cylindrical component, around 60 μm in diameter and 15 mm in length, with an aspect ratio of over 250.

Grinding of single-crystal silicon was performed by Zhong and Rui [51] using a diamond grinding wheel and a micro-vibration device. The grinding direction was parallel to the [110] direction of (100) silicon. The Si samples were ground under the same grinding conditions but with different vibration directions, frequencies, and/or amplitudes. Samples ground with vibrations had better surface finish than surfaces ground without vibrations. The best surface finish was achieved when (100) silicon was ground with horizontal vibrations at 70-Hz frequency and 6-μm amplitude perpendicular to the grinding direction.

7 Monitoring and control of grinding processes

There are not sufficient techniques for in-process monitoring of dressing diamond wear. Some existing methods are optics-based, but suffer from a high sensitivity to the harsh environment from the coolant. They are not suitable for online operation and are also expensive compared with intelligent methods based on signal feature extraction. The problems can be solved by processing characteristic signals related to the dressing process. Monitoring diamond wear makes possible autonomous determination of acceptable wheel dressing and the need for changing the dressing diamond. Integrating intelligent algorithms into monitoring and control of machining processes can help manufacturers towards higher product quality, cheaper costs and greater production flexibility [52]. Technical solutions based on effective parameters such as AE signals in dressing and advance signal processing algorithms such as wavelets can extract the required features for machining processes. With machine learning, machine tools can be capable of self-sensing.

Sensor equipped grinding wheels offer the possibility to gain information on the process status from direct measurements of physical quantities in the contact zone. This can be realized by the integration of small temperature and force sensors into segmented grinding wheels. A new thermocouple sensor was developed by Brinksmeier et al. [53] with the continuous contacting of the thermocouple by the grinding wheel wear. Tests were conducted using a piezoelectric sensor integrated into the grinding wheel, and forces in grinding and dressing processes were obtained. Tests in an industrial environment showed the reliability of the monitoring system.

Previous research using various sensors emphasizes the actual wear measurement and monitors variations on the grinding wheel, or obtains a local surface of the grinding wheel and then determines when a grinding wheel is trued/dressed. However, equipping every machine with sensors to monitor grinding wheels is expensive. Computing topography of the grinding wheel is very complicated and time consuming. Therefore, a more efficient and inexpensive solution is needed. A practical method that employs a specimen and has a grinding wheel grind a gap in it is presented by Su and Tarng. Grinding wheel contours were measured using machine vision. Measuring the image of the specimen with a gap substitute directly captures the image of the actual grinding wheel. This method converts the 3D topography of the grinding wheel into the 2D contour of the wheel. Back lighting enables a clear image to be acquired. This enables the coordinates of the contours obtained through edge detection to achieve a repeatable accuracy of ±3 μm [54]. A vision system is also used and a new multi-class classification system is developed by Zhang et al. [55] for identifying defects on the workpiece surface in grinding and polishing processes. The system has the highest right classification rate when combining the Gabor filter bank features and the statistical parameters. The system can label all defects into 15 predefined classes with an about 82% correct classification rate, which approaches the performance of a trained human operator.

An in-process evaluation method is proposed by Xie and Tamaki [56] for the grit protrusion feature on the wheel surface by monitoring the discharge current during electro-contact discharge dressing of the metal-bonded diamond grinding wheel. The grit protrusion feature is sensitive to the discharge parameters with reference to the mean diamond grit size. There are good correlations between discharge removal and discharge parameters for impulse discharge machining of the metal bond.

A micro-positioning table driven by three piezoelectric actuators was developed by Tian et al. to improve the machining precision of precision grinders [57–60]. The inverse model of the table was developed for numerical control. The modal synthesis method and Lagrange's equation were used to establish the dynamic equation of an intelligent grinding machine system. The simulation results show that the machining accuracy of the workpiece can be effectively improved by using the micro-positioning table to implement dynamic compensation [61]. Experimental tests were also conducted, and the waviness of the workpiece could be reduced from 0.46 μm to 0.10 μm [62]. The maximum displacement in the Z direction is 12 μm and the maximum angle is 130 μrad [63].

8 Optimization of grinding

Optimization is needed for any process to achieve good product quality, high productivity and low cost. Efficient grinding of SiC involves the optimal selection of operating parameters to maximize the MRR, achieve the required surface finish and minimize surface damage. Optimization is performed by Lee et al. [64] using particle swarm optimization (PSO), and results indicate that PSO is a stable, convergent algorithm.

Wheel and work speeds and depth of cut are the major parameters affecting the quality of the ground surface. Determination of optimal parameters depends on the proper design of experiments (DOE). To conduct DOE at the earliest stage of a process development cycle is the key to overall success. The factorial design and/or Taguchi methods were used by Alagumurthi et al. to obtain optimal grinding cycle time and conditions [3], and for optimization of the amount of heat generation and modelling of the temperature rise between the wheel and work contact zone for a cylindrical grinding process to achieve better surface integrity of steel materials [65].

Several conventional optimisation techniques have been applied to grinding optimisation, but their application is often limited due to the complexity involved in grinding optimisation and the possibility of reaching local optimal points. A scatter search (SS)-based optimization approach is developed by Krishna and Rao [66] to optimize wheel and work speeds, depth of dressing and lead of dressing using a multi-objective function model for the surface grinding process. The production cost and rate are evaluated for the optimal grinding conditions. The results are compared with the results obtained by the ants-colony algorithm, genetic algorithm and quadratic programming techniques. SS search mechanisms result in optimization procedures with the ability to escape local optimum points. SS is a generalized optimization method for machining optimization problems because it has no restrictive assumptions regarding the objective function and constraint set.

A supervision system developed by Kruszynski and Lajmert [67] uses techniques of artificial intelligence to monitor, control and optimize the traverse grinding operation. The system consists of two levels which act in parallel to produce parts satisfying the geometrical and surface finish requirements with maximum possible productivity. The first optimization level maximizes the material removal rate, simultaneously satisfying restrictions on surface roughness, out-of-roundness and waviness errors and on grinding temperature. The geometrical control level is responsible for the removal of the initial shape error by stabilizing the motion trajectory of the grinding wheel in relation to the ground part.

Experimental research is performed by Liu et al. [68] on Ni-based alloy grinding using super-abrasive and Al_2O_3 wheels. With on-line monitoring and off-line inspection, grinding performance and cost are evaluated based on statistical analysis. Using multi-objective optimization, the models of performance and cost assessment are established to evaluate the grinding performance and cost under different grinding conditions. The performance index of diamond wheels are considerably higher than that of Al_2O_3 wheels.

9 Modelling and simulation of grinding

Abrasive grains with random shapes are randomly and three-dimensionally distributed in a grinding wheel. Modelling and quantitative monitoring are said to be impossible, and prediction of grinding phenomena has limitations. Good grinding operations depend on skilled operators. Against this, Sakakura et al. [69] presented a skill-formation model, which repeated learning with the total grinding stock and initial infeed rate given, changing infeed rate, and evaluating the size and the removal rate in the process end. Simulations exhibited that the model could generate desirable infeed processes such as multi-stage, spark-out and accelerated spark-out processes. The model demonstrated a skill-formation process similar to that of an operator. In another study, modelling of the kinematics of precision contour grinding is performed by Heinzel and Grimme [70]. Changes in feed speeds and rotational speed ratios are examined and their effects on generated surfaces are simulated and compared with ground surfaces.

Molecular dynamics (MD) simulations have been attractive to achieve deeper understanding of microscopic material behaviour. Most of the MD material removal process simulations focus on the material removal mechanisms, chip and surface generation. Rentsch and Inasaki [71] presented an extension of the state-of-the-art MD material removal process modelling to investigate the tribological contact conditions and the impact of coolant on the surface generation.

The grinding force of the creep feed grinding is modelled and forecasted by Wang and Wu [72] using an improved back propagation neural network. The grinding energy can be accurately predicted using the grinding force model. Workpiece burning occurs when the grinding energy is greater than the critical grinding energy. Conditions can be adjusted to avoid workpiece burning and maximize the metal removed rate. A lower wheel speed and a larger wheel size can be applied to have a better working efficiency.

The selection of machining parameters for glass mould fabrication in ophthalmic lens production requires a theoretical-empirical model of the ground surface to predict the overall geometry errors of the surface. The correspondence among theoretical hypotheses and experimental results allows realistic predictions of the attainable surface texture during a contour grinding operation and the adoption of preventive actions to compensate the geometrical errors [73]. Empirical modelling and optimization of the plunge centreless grinding process are also performed by Krajnik et al. [5]. The design of grinding factors is based on a response surface method, which integrates DOE, regression modelling and basic optimization. The single-objective optimization is solved by non-linear programming and genetic algorithm. The ground surface roughness is most significantly affected by the wheel dressing condition, and is also affected by the geometrical grinding gap set-up factor and the wheel speed.

An intelligent approach based on fuzzy basis function neural networks (FBF-NNs) is proposed by Nandi and Banerjee to model the cylindrical plunge grinding process. The results obtained using the FBF-NNs and empirical expressions are compared with experimental results, and the FBF-NN models give better predictions than mathematical models. The model developed based on FBF-NN using a GA can predict surface roughness and the corresponding power requirement [74]. A clustering method is proposed by Liao et al. [4] to monitor the grinding wheel condition in operations. The method first extracts features from acoustic emission signals based on discrete wavelet decomposition using a moving window approach, and then generates a distance matrix using a hidden Markov model. The results show that higher MRR produces more discriminatory features than lower MRR.

There is not a comprehensive model to predict roughness over wide ranges of operating conditions, which still relies on operator's experience and skills, because many variables affecting the process are interdependent, non-linear or difficult to quantify. The models available are not fully feasible, experimental investigations have limited applicability, and a complete understanding is not achieved. Empirical models have limited applicability, and can predict surface roughness only in a particular situation. The predicted roughness value using traditional methods is often smaller than the measured value. An analytical model for surface roughness prediction was developed by Agarwal and Venkateswara Rao [6]. A simple relationship between the surface roughness and the chip thickness was obtained, which was validated by experimental results of SiC grinding. The model considers the overlapping effect, the parameters of the abrasive wheel and process kinematics conditions.

An intelligent approach is introduced by Lizarralde et al. [75] to avoid centreless grinding process instabilities. Instead of using sensors, model-based algorithms were used to detect the configurations and the process conditions under which instabilities appear. A commercial software package is developed to guide technicians for the setup process configuration. Prediction of elastic deformation can be conducted by two methods. The first is to measure it directly, and the second is to estimate it from the static machine stiffness and the mechanical properties of the workpiece and wheels. The first method is more accurate, but it would not be practical to make measurements for all possible working configurations. The approach developed needs only one measurement and then deduces the elastic deformation value for the rest of the configurations from theoretical considerations.

In many cases, regression models developed using DOE could not predict an appropriate minimal response value. This is a serious limitation for on-line process control, where the predicted optimal values must be determined with high accuracy and are continuously compared with targets to maintain the desired output level. An approach was developed by Fredj and Amamou [76] with the combination of DOE method and artificial neural network (ANN). Data of the DOE were used to train ANNs, and the inputs of the ANNs were selected from the factors and the interactions between factors of the DOE according to their significance at different confidence levels. The ANNs show high sensibility to the inputs levels and low deviation from the training and testing data.

A model is developed by Maksoud to calculate the workpiece temperature in a creep-feed grinding process. Nucleate boiling or no boiling occurs in regions where the workpiece surface temperature is less than the film boiling temperature of the coolant used [77]. Predictive modelling of grinding force and power is also performed by Hecker et al. [78] based on the probabilistic distribution of undeformed chip thickness as a function of the kinematic conditions, wheel microstructure, material properties, and dynamic effects. The model also considers the wheel grain geometry and the static grain density.

10 Size effect

Although benefits of segmental grinding wheels were observed, little analytical work was performed to understand the mechanisms for the benefits. A force model is developed by Fan and Miller for grinding with segmental wheels. Experimental and analytical results show that the average grinding force decreases and the peak force increases using segmental wheels compared to conventional wheels. Larger spaces between segments further reduce the average force and increase the peak force. The reduction in average force is due to the size effect whereby the specific energy decreases at higher instantaneous MRRs. Severe segmentation leads to much rougher surfaces than conventional grinding. A good segment wheel design would balance the requirements for power, wheel wear and surface finish. The forces in the tangential and normal directions (F_x and F_z) are modelled as follows [79].

$$F_x = k_x(\mathrm{MRR})^{m_x} + F_{x0} \tag{4}$$

$$F_z = k_z(\mathrm{MRR})^{m_z} + F_{z0} \tag{5}$$

Where, m_x, m_z, k_x and k_z are empirical constants that depend on workpiece properties, grinding wheel characteristics and grinding conditions, and F_{x0} and F_{z0} are the rubbing components in the tangential and normal directions respectively. The model can predict grinding forces with segmental wheels, after the MRR and empirical constants are determined.

It is possible to use the size effect of the specific grinding energy for a controlled work-hardening surface layer of metal parts. A grinding process of abrasive material removal with plastic deformation is designed by Heinzel and Bleil for the investigation. To achieve high specific energy values and minimize thermal effects counteracting the work hardening can be achieved by low cutting speeds with low depths of cut. The method leads to an in-process work-hardening of the surface layer, resulting in a compressive residual stress, and higher wear resistance and hardness [80]. There is a good correlation between the specific grinding energy (the size effect) and compressive residual stresses [81].

Hard turning and grinding are competing finishing processes for precision components. Surface hardening is attributed to strain/strain rate hardening and size effect. Research found that mechanical deformation plays a larger role during hard turning than grinding [82, 83]. Hard turning induces a thicker plastically deformed zone than grinding, while grinding temperatures penetrate deeper into the subsurface. A hard turned surface may have a fatigue life more than 100% longer than a ground one with an equivalent surface finish because of the very different characteristics of surface integrity. The size effect is more prominent in grinding than turning, and produces higher surface hardness.

Nanoindentation can be used to determine the surface/subsurface mechanical properties, although the test results may be significantly affected by size effect, strain hardening, residual stresses and microstructures. Nanoindentation tests were performed by Warren et al. [84] on the samples machined by grinding, hard turning and honing. The residual stress nature can be determined by the slope at initial loading, residual depth, total depth, and the ratio of residual depth to total depth. Microstructure changes have a significant effect on the characteristics of a load-displacement curve.

11 Conclusions

Ductile mode grinding of brittle materials has been and will continue to be an intensive research area because of its increasing industrial applications and academic demands for fundamental understanding of the ductile mode grinding mechanism. Highly precision manufacturing of silicon substrates faces more and more new challenges. Grinding of silicon continues to be a popular research topic. Using lasers to true and dress grinding wheels has attracted great research interest, because it has significant advantages over mechanical processes. Environmentally friendly grinding fluids are increasingly highly demanded. Vibration-assisted grinding is promising. Monitoring, modelling and optimization of grinding processes help to understand grinding mechanisms and achieve better grinding performance. The size effect is more prominent in grinding than turning and can be used for obtaining a controlled work-hardening surface layer with higher wear resistance and hardness.

This general review paper attempts to provide brief introduction to recent developments in grinding of advanced materials. With the reference provided, readers may explore more deeply by reading a particular journal article for the detailed description of grinding kinematics and the explanation of the key outcomes.

References

1. Paul S, Chattopadhyay AB (2006) Environmentally conscious machining and grinding with cryogenic cooling. Mach Sci Technol 10(1):87–131
2. Sinot O, Chevrier P, Padilla P (2006) Experimental simulation of the efficiency of high speed grinding wheel cleaning. Int J Mach Tools Manuf 46(2):170–175
3. Alagumurthi N, Palaniradja K, Soundararajan V (2006) Optimization of grinding process through design of experiment (DOE) - A comparative study. Mater Manuf Process 21(1):19–21
4. Liao TW, Hua G, Qu J, Blau PJ (2006) Grinding wheel condition monitoring with Hidden Markov model-based clustering methods. Mach Sci Technol 10(4):511–538
5. Krajnik P, Kopac J, Sluga A (2005) Design of grinding factors based on response surface methodology. J Mater Process Technol 162–163(SPEC. ISS.):629–636
6. Agarwal S, Venkateswara Rao P (2005) A new surface roughness prediction model for ceramic grinding. Proc Inst Mech Eng, B J Eng Manuf 219(11):811–821
7. Young HT, Liao HT, Huang HY (2006) Surface integrity of silicon wafers in ultra precision machining. Int J Adv Manuf Technol 29(3–4):372–378
8. Young HT, Chen DJ (2006) Online dressing of profile grinding wheels. Int J Adv Manuf Technol 27(9–10):883–888
9. Sahu P, Sagar R (2006) Development of abrasive cut-off wheel having side grooves. Int J Adv Manuf Technol 31(1–2):37–40
10. Ma Y, Lou ZF (2005) Abrasive technology of single-crystal diamond by diamond abrasive wheel. Key Eng Mater 291–292:21–26
11. Kim JD, Lee DH, Lee KB (2005) The effects of dynamic characteristics on the surface texture in mirror grinding. Int J Adv Manuf Technol 27(3–4):274–280
12. Sanchez JA, Ortega N, Lopez De Lacalle LN, Lamikiz A, Maranon JA (2006) Analysis of the electro discharge dressing (EDD) process of large-grit size cBN grinding wheels. Int J Adv Manuf Technol 29(7–8):688–694
13. Sun X, Stephenson DJ, Ohnishi O, Baldwin A (2006) An investigation into parallel and cross grinding of BK7 glass. Precis Eng 30(2):145–153
14. Min S, Dornfeld D, Inasaki I, Ohmori H, Lee D, Deichmueller M, Yasuda T, Niwa K (2006) Variation in machinability of single crystal materials in micromachining. CIRP Annals - Manufacturing Technology 55(1):103–106
15. Venkatesh VC, Izman S, Vichare PS, Mon TT, Murugan S (2005) The novel bondless wheel, spherical glass chips and a new method of aspheric generation. J Mater Process Technol 167(2–3):184–190
16. Koshy P, Zhou Y, Guo C, Chand R, Malkin S (2005) Novel kinematics for cylindrical grinding of brittle materials. CIRP Annals - Manufacturing Technology 54(1):289–292
17. Tong S, Gracewski SM, Funkenbusch PD (2006) Measurement of the Preston coefficient of resin and bronze bond tools for deterministic microgrinding of glass. Precis Eng 30(2):115–122
18. Izman S, Venkatesh VC (2007) Gelling of chips during vertical surface diamond grinding of BK7 glass. J Mater Process Technol 185(1–3):178–183
19. Chen M, Zhao Q, Dong S, Li D (2005) The critical conditions of brittle-ductile transition and the factors influencing the surface quality of brittle materials in ultra-precision grinding. J Mater Process Technol 168(1):75–82
20. Jirapattarasilp K, Rukijkanpanich J (2007) The experiment of high-speed grinding of a gemstone: Cubic zirconia. Int J Adv Manuf Technol 33(11–12):1136–1142
21. Sun W, Pei ZJ, Fisher G (2006) A grinding-based manufacturing method for silicon wafers: Generation mechanisms of central bumps on ground wafers. Mach Sci Technol 10(2):219–233
22. Sun W, Pei ZJ, Fisher GR (2005) Fine grinding of silicon wafers: effects of chuck shape on grinding marks. Int J Mach Tools Manuf 45(6):673–686
23. Narasimhan A (2005) Thermal analysis of a silicon wafer processing combination bake-chill station used in microlithography. Mater Manuf Process 20(2):273–286
24. Young HT, Lin CC, Liao HT, Yang M (2008) Precision wafer thinning and its surface conditioning technique. Int J Mater Prod Technol 31(1):36–45
25. Paehler D, Schneider D, Herben M (2007) Nondestructive characterization of sub-surface damage in rotational ground silicon wafers by laser acoustics. Microelectron Eng 84(2):340–354
26. Zimmermann S, Zhao QT, Trui B, Wiemer M, Kaufmann C, Mantl S, Dudek V, Gessner T (2005) Fabrication and character-

ization of buried silicide layers on SOI substrates for BICMOS-applications. Microelectron Eng 82(3–4):454–459
27. Pietsch GJ, Kerstan M (2005) Understanding simultaneous double-disk grinding: operation principle and material removal kinematics in silicon wafer planarization. Precis Eng 29(2):189–196
28. Schoenfelder S, Ebert M, Landesberger C, Bock K, Bagdahn J (2007) Investigations of the influence of dicing techniques on the strength properties of thin silicon. Microelectron Reliab 47 (2–3):168–178
29. Venkatesh VC, Izman S (2007) Development of a novel binderless diamond grinding wheel for machining IC chips for failure analysis. J Mater Process Technol 185(1–3):31–37
30. Tani Y, Okuyama T, Murai S, Kamimura Y, Sato H (2007) Development of Silica Polyvinyl Alcohol Wheels for Wet Mirror Grinding of Silicon Wafer. CIRP Annals - Manufacturing Technology 56(1):361–364
31. Touge M, Watanabe J (2006) Ultra-thinning processing of dielectric substrates by precision abrasive machining. CIRP Annals - Manufacturing Technology 55(1):317–320
32. Jackson MJ, Khangar A, Chen X, Robinson GM, Venkatesh VC, Dahotre NB (2007) Laser cleaning and dressing of vitrified grinding wheels. J Mater Process Technol 185(1–3):17–23
33. Hosokawa A, Ueda T, Yunoki T (2006) Laser dressing of metal bonded diamond wheel. CIRP Annals - Manufacturing Technology 55(1):329–332
34. Wang XY, Wu YB, Wang J, Xu WJ, Kato M (2005) Absorbed energy in laser truing of a small vitrified CBN grinding wheel. J Mater Process Technol 164–165:1128–1133
35. Harimkar SP, Dahotre NB (2006) Evolution of surface morphology in laser-dressed alumina grinding wheel material. International Journal of Applied Ceramic Technology 3(5):375–381
36. Khangar AA, Kenik EA, Dahotre NB (2005) Microstructure and microtexture in laser-dressed alumina grinding wheel material. Ceram Int 31(4):621–629
37. Chen WK, Kuriyagawa T, Huang H, Yosihara N (2005) Machining of micro aspherical mould inserts. Precis Eng 29 (3):315–323
38. Hwang Y, Kuriyagawa T, Lee SK (2006) Wheel curve generation error of aspheric microgrinding in parallel grinding method. Int J Mach Tools Manuf 46(15):1929–1933
39. Alves SM, de Oliveira JFG (2006) Development of new cutting fluid for grinding process adjusting mechanical performance and environmental impact. J Mater Process Technol 179(1–3):185–189
40. Oliveira JFG, Alves SM (2006) Development of environmentally friendly fluid for CBN grinding. CIRP Annals - Manufacturing Technology 55(1):343–346
41. Gao Y, Lai H (2007) Effects of actively cooled coolant for grinding ductile materials. Key Eng Mater 339:427–433
42. Gao Y, Lai H (2008) Use of actively cooled and activated coolant for surface quality improvement in ductile material grinding. Int J Mater Prod Technol 31(1):14–26
43. Irani RA, Bauer RJ, Warkentin A (2007) Development of a new cutting fluid delivery system for creepfeed grinding. Int J Manuf Technol Manag 12(1–3):108–126
44. Catai RE, Bianchi EC, Zilio FM, De Valarelli ID, Alves MCDS, Silva LR, De Aguiar PR (2006) Global analysis of aerodynamics deflectors efficiency in the grinding process. Journal of the Brazilian Society of Mechanical Sciences and Engineering 28 (2):140–145
45. Salonitis K, Chryssolouris G (2007) Cooling in grind-hardening operations. Int J Adv Manuf Technol 33(3–4):285–297
46. Li J, Li JCM (2005) Temperature distribution in workpiece during scratching and grinding. Materials Science and Engineering A 409 (1–2):108–119
47. Cheng HB, Feng ZJ, Cheng K, Wang YW (2005) Design of a six-axis high precision machine tool and its application in machining aspherical optical mirrors. Int J Mach Tools Manuf 45(9):1085–1094
48. Yin L, Pickering JP, Ramesh K, Huang H, Spowage AC, Vancoille EYJ (2005) Planar nanogrinding of a fine grained WC-Co composite for an optical surface finish. Int J Adv Manuf Technol 26(7–8):766–773
49. Zhong ZW, Peng ZF (2007) Fractal roughness structures of precision-machined WC-Co- and Inconel 625-coated steel rods. Int J Adv Manuf Technol 33(9–10):885–890
50. Wu Y, Fan Y, Kato M (2006) A feasibility study of microscale fabrication by ultrasonic-shoe centerless grinding. Precis Eng 30 (2):201–210
51. Zhong ZW, Rui ZY (2005) Grinding of single-crystal silicon using a microvibration device. Mater Manuf Process 20(4):687–696
52. Egana I, Mendikute A, Urionaguena X, Alberdi R (2006) Towards intelligent dressing. IEEE Instrum Meas Mag 9(3):38–43
53. Brinksmeier E, Heinzel C, Meyer L (2005) Development and application of a wheel based process monitoring system in grinding. CIRP Annals - Manufacturing Technology 54(1):301–304
54. Su JC, Tarng YS (2006) Measuring wear of the grinding wheel using machine vision. Int J Adv Manuf Technol 31(1–2):50–60
55. Zhang X, Krewet C, Kuhlenkötter B (2006) Automatic classification of defects on the product surface in grinding and polishing. Int J Mach Tools Manuf 46(1):59–69
56. Xie J, Tamaki J (2006) In-process evaluation of grit protrusion feature for fine diamond grinding wheel by means of electro-contact discharge dressing. J Mater Process Technol 180(1–3):83–90
57. Tian YL, Zhang DW, Yan B (2007) Static characteristic analysis of a 3-DOF micropositioning table for grinding. Key Eng Mater 339:177–182
58. Tian YL, Zhang DW, Chen HW (2006) Dynamic modeling of a novel 3-DOF micropositioning table for surface grinding control. Key Eng Mater 304–305:507–511
59. Zhang D, Chetwynd DG, Liu X, Tian Y (2006) Investigation of a 3-DOF micro-positioning table for surface grinding. Int J Mech Sci 48(12):1401–1408
60. Tian YL, Zhang DW, Yan B (2007) Performance investigation of a micropositioning table. Diffusion and Defect Data Pt.B: Solid State Phenomena 121–123:1285–1288
61. Tian Y, Zhang D, Chen H, Huang T (2005) Modeling of precision grinding process based on micro-positioning table and error compensation technology. Jixie Gongcheng Xuebao/Chinese Journal of Mechanical Engineering 41(4):168–173
62. Tian Y, Zhang D, Yan B (2006) Dynamics and control of grinding machine with micropositioning workpiece table. Trans Tianjin Univ 12(3):157–162
63. Tian YL, Zhang DW, Yan B (2006) Kinematic characteristics of a 3-DOF micropositioning table for precision grinding. Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/Journal of Tianjin University Science and Technology 39(7):777–782
64. Lee TS, Ting TO, Lin YJ, Htay T (2007) A particle swarm approach for grinding process optimization analysis. Int J Adv Manuf Technol 33(11–12):1128–1135
65. Alagumurthi N, Palaniradja K, Soundararajan V (2007) Heat generation and heat transfer in cylindrical grinding process - A numerical study. Int J Adv Manuf Technol 34(5–6):474–482
66. Krishna AG, Rao KM (2006) Multi-objective optimisation of surface grinding operations using scatter search approach. Int J Adv Manuf Technol 29(5):475–480
67. Kruszynski BW, Lajmert P (2005) An intelligent supervision system for cylindrical traverse grinding. CIRP Annals - Manufacturing Technology 54(1):305–308
68. Liu Q, Chen X, Gindy N (2007) Assessment of Al2O3 and superabrasive wheels in nickel-based alloy grinding. Int J Adv Manuf Technol 33(9–10):940–951

69. Sakakura M, Tsukamoto S, Fujiwara T, Inasaki I (2006) A skill-formation model for grinding operations. Mach Sci Technol 10 (4):457–470
70. Heinzel C, Grimme D (2006) Modeling of surface generation in contour grinding of optical molds. CIRP Annals - Manufacturing Technology 55(1):581–584
71. Rentsch R, Inasaki I (2006) Effects of fluids on the surface generation in material removal processes - Molecular dynamics simulation. CIRP Annals - Manufacturing Technology 55(1):601–604
72. Wang SB, Wu CF (2006) Selections of working conditions for creep feed grinding. Part(III): Avoidance of the workpiece burning by using improved BP neural network. Int J Adv Manuf Technol 28(1–2):31–37
73. Meneghello R, Concheri G, Savio G, Comelli D (2006) Surface and geometry error modeling in brittle mode grinding of ophthalmic lenses moulds. Int J Mach Tools Manuf 46(12–13):1662–1670
74. Nandi AK, Banerjee MK (2005) (655–664) FBF-NN-based modelling of cylindrical plunge grinding process using a GA. J Mater Process Technol 162–163(SPEC. ISS.):655–664
75. Lizarralde R, Montejo M, Barrenetxea D, Marquinez JI, Gallego I (2006) Intelligent grinding: Sensorless instabilities detection. IEEE Instrum Meas Mag 9(3):30–37
76. Fredj NB, Amamou R (2006) Ground surface roughness prediction based upon experimental design and neural network models. Int J Adv Manuf Technol 31(1–2):24–36
77. Maksoud TMA (2005) Heat transfer model for creep-feed grinding. J Mater Process Technol 168(3):448–463
78. Hecker RL, Liang SY, Wu XJ, Xia P, Jin DGW (2007) Grinding force and power modeling based on chip thickness analysis. Int J Adv Manuf Technol 33(5–6):449–459
79. Fan X, Miller MH (2006) Force analysis for grinding with segmental wheels. Mach Sci Technol 10(4):435–455
80. Heinzel C, Bleil N (2007) The use of the size effect in grinding for work-hardening. CIRP Annals - Manufacturing Technology 56 (1):327–330
81. Brinksmeier E, Bleil N (2007) Using the size effect of specific energy in grinding for work hardening. Int J Manuf Technol Manag 12(1–3):259–269
82. Warren AW, Guo YB (2006) On the clarification of surface hardening by hard turning and grinding. Trans North Am Manuf Res Inst SME 34:309–316
83. Hashimoto F, Guo YB, Warren AW (2006) Surface integrity difference between hard turned and ground surfaces and its impact on fatigue life. CIRP Annals - Manufacturing Technology 55 (1):81–84
84. Warren AW, Guo YB, Weaver ML (2006) The influence of machining induced residual stress and phase transformation on the measurement of subsurface mechanical behavior using nano-indentation. Surf Coat Technol 200(11):3459–3467