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# Study of Ultra-precision Finishing Techniques for Brittle Materials

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***Abstract—***

***Wide application of hard and brittle advanced ceramics, glasses and semiconductors in Mechanical, Optical and Electronic industry has led to the development of new ultra-precision finishing processes. With an increase in the applications of these materials, the need of finishing these materials has also become a great challenge. Dimensional and finish accuracies are the parameters that needs to be focused and improved with minimum time and cost. Another crucial parameter is the subsurface damages that are quiet common with these materials during finishing process. New processes have been developed to overcome the drawbacks of the existing processes for Nano finishing. These processes can be classified as Conventional, Precision and Ultra-precision finishing based on the degree of dimensional accuracy and final surface finish. Both loose and bonded abrasives have been used for these processes. This paper deals with the study of some of the significant advances in ultra-precision finishing processes of hard and brittle materials.***

***Keywords**— Ultra-precision Finishing, Ceramics, Semi-conductor, Optical Glass*

## I. INTRODUCTION

The demand of highly precise, accurate and good surface finish of products has led to the development of ultra-precision systems which include ultra-precision machines, tools and instruments for the measurement of accuracy. Based on the requirement, the process may be termed as polishing, finishing, lapping and honing. As we talk about term polishing, the image of smooth surface emerges. Similarly, in lapping, the main focus is on the form or shape, and Honing generates the required topography to trap lubricant. The process finishing is used to describe either one or all of the above terms which includes dimensional accuracy and surface finish. The geometrical accuracies required in ultra-precision are of the order 0.001 µm. Surface roughness of the order nanometer is obtained on different surface geometries such as planar, round or parabolic. For the finishing of brittle materials, it is very important that material removal remains at micro level so that subsurface defects can be avoided.

## II. WORK MATERIALS

Finishing of brittle and hard materials has always been a challenging task as compared to ductile materials. The favourable features such as high symmetry in crystal structure, high thermal conductivity, low density, high purity, high toughness and large strain to fracture ratio makes metals more suitable for precision finishing. An extensive movement of dislocations in metals at low stresses is because of non-directional metallic bonding. Whereas, ionic or covalent bonding, low symmetry, low slip system for plastic deformation, low thermal conductivity and low fracture toughness in brittle materials makes finishing of these materials tedious. Low mobility of dislocations is another major factor behind difficult finishing of brittle materials. But the properties like high hardness, high thermal and chemical stability, low density, high Young's modulus, high stiffness, good fatigue life, low friction, and high wear resistance make these materials suitable for many optical, mechanical and electronics applications. The paper discusses the finishing of ceramics, glasses and semiconductors.

### *A. Advanced Ceramics*

These are made from extremely pure microscopic powders and consolidated at high temperatures resulting in dense and durable structure. Advanced ceramics have superior wear resistance, high thermal and chemical stability as compared to metals. The lower value of electrical and thermal conductivity makes them suitable for many mechanical and electrical applications. However, low fracture toughness of ceramics is the major cause behind their sudden failure which occurs when applied stress is sufficient to propagate cracks that originate at flaws in materials. Several methods have been developed to avoid sudden failures which include incorporation of ceramic particulate, whiskers or continuous fibres in ceramic matrix. Thin coatings of ceramics has also been used on metals leading to the manufacture of composite materials with high toughness provided by base metal along with excellent wear properties of ceramics. Grinding or finishing of these materials in ductile mode also helps in reducing the flaws. While designing the ceramic products, a good knowledge of brittle materials is very important. Local stress concentration may result in micro-cracks which lead to the failure of the product. So, it is important that micro-cracks do not occur while manufacturing.

### *B. Optical Glasses*

In Optical glasses, the surface flaws in relation to regions under stress governs the strength of glass. Factors such as size, orientation and location determine the strength of glass. These flaws usually occur when glass undergoes manufacturing and finishing operations. Under loading conditions, these cracks propagate to a critical value where uncontrolled crack growth starts leading to fractures. So it is very important to minimize surface flaws during manufacturing processes, as they directly control the strength of glass. The main focus while machining is to remove the material to a depth which is equal to or greater than maximum flaw depth. Lot of improvement has been done in grinding and polishing processes where the depth of flaws has been reduced to 0.001". However, conventional processes fail to reduce the flaw depth beyond this value. Thus, non-conventional processes have been developed. Material strength testing is very important to characterize the strength of glass. The rate at which cracks propagate is determined using statistical data provided during testing. Fracture toughness or critical stress intensity factor KIC is the resistance to flaw growth. The value of KIC determines the ease with which glass can be finished with minimum flaws. Higher the fracture toughness, lesser will be the chances of flaws. Stress intensity factor KI is the concentration of stress distribution on the verge of crack tip. Failure occurs when KI exceeds KIC. Crack geometry and lack of plastic deformation are the major causes of stress concentration. KI can be determined using Griffith's law which is given below

$KI=Y\sigma\sqrt{a}$

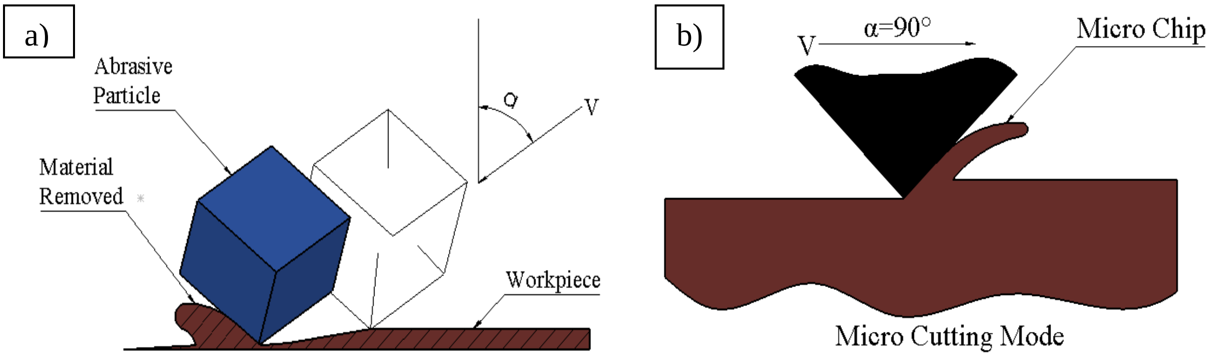
Where Y is crack geometry factor, σ is the nominal and a is the flaw size.

### *C. Semi-Conductors*

A major technological revolution in Electronic Industry is observed with the invention of semiconductors which have rapidly exploded into Computer Industry. Semiconductor is a non-metallic crystal held together by ionic or covalent bond with no free electrons. The electrical properties of semiconductors can be altered by doping. The quantum confinement effect and interfacial properties depend on the structure, thickness, composition, surface roughness and crystalline shape of semiconductors. A major role is played by surface coarseness in determination of optical scattering and absorption. The interfacial properties often deviate from their ideal behaviour because they like optical scattering and absorption are also influenced by surface structure. The roughness has also affected Raman scattering experiment. The surface phonon intensity increases with increasing surface roughness. Thus, the Raman yield is evaluated by surface roughness contribution and the contribution due to excitation energy. The roughness of surface is proportional to the thickness of film. The sample preparation procedure does not affect their relation. Similarly, the scanning length and roughness are also proportionate to each other; with increasing scanning length, the surface roughness increases. The procedure of high-quality polishing of the surface of semiconductor wafers is an essential stage in technologies, aimed at production of micro-electronics objects. Structurally destructed surface layer of a definite depth appear in operations for cutting the ingot of semiconductor material into wafers. Removing these destructed layers is complex technological task and applying the operations of polishing requires developed optimal technological regimes and compositions of polishing media. The mechanism of material removal is discussed in the next section.

## III. MECHANISM OF MATERIAL REMOVAL

For the finishing of brittle materials, it is very important that material removal remains at micro level to prevent subsurface defects. Bifano et al. (1991) have suggested that extremely low depth of cut (DOC) and fine abrasives can minimize or eliminate brittle cracking [1]. Ghatu and Micheal (2007) have performed scratch test on alumina ceramics to prove that ductile mode can give damage free surface. They reported that extent of induced damage is function of depth of groove generated by abrasives. Smaller particle size, low forces will generate lower depth of groove and hence minimum brittle fracture indicating ductile mode [2]. Brinksmeier et al. (2010) have also concluded that achieving ductile mode is very important to get best surface finish without subsurface damages. The most prominent condition for this mode is use of fine abrasives and lower depth of cut. Results show when grain of smaller size 4-6µm is used, grinding mode changes from fracture to ductile [3]. Another important factor is use of lubricant. Lubricants help in achieving smaller ratio of grit penetration to grit diameter during abrasive action. It results in rapid micro-cutting form of abrasive wear.



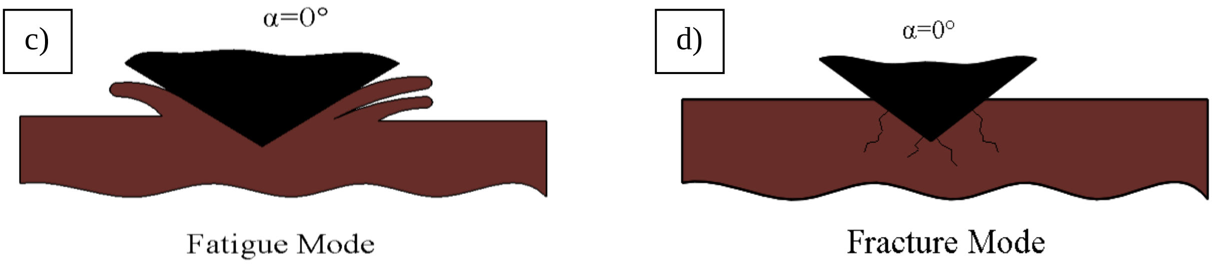


Fig. 1 (a) Kinematics of the grain, (b–d) different modes of the interference between abrasive grain and workpiece surface.

Hashimoto et al. (2016) has explained the mechanism of material removal of brittle materials using loose abrasive [4]. Figure 1 (a) shows kinematics of the grains. The particles or grits may remove material by micro-cutting, micro-fracture or accelerated fatigue by repeated deformations as illustrated in Figure 1 (b-d). The mode depends on the angle of impingement (α) of abrasive particle, momentum or velocity v of the grain (measured from the normal of the workpiece surface) and on its rotation ω. Small impact angle leads to vertical indentation. Repeated attacks of abrasive grains remove material from the surface and are termed as fatigue. Large impact angles with constrained grain rotation leads to micro cutting and makes scratches. The grains with large angle and free rotation hit the surface and roll over resulting in smoothed surface. In the case of loose grains the passive force is obtained from inverting the direction of the vertical momentum component, while the reduction of the tangential momentum component during work contact gives the cutting force. Sliding or rubbing occur instead of cutting when the grain depth of cut becomes very small leading high level surface finish without damaging surface.

## IV. ULTRA-PRECISION FINISHING (UPF)

Ultra-precision finishing can be represented as a system (fig. 2) rather than just ultra-precision Machine. The system consists of inputs (ultra-precision tools, abrasives and clean environment), constraints (hard and brittle material) and the outputs (surface/sub-surface damage, nano level surface finish and minimum geometric tolerance). The ultra-precision finishing processes with fine abrasives are placed at the centre.

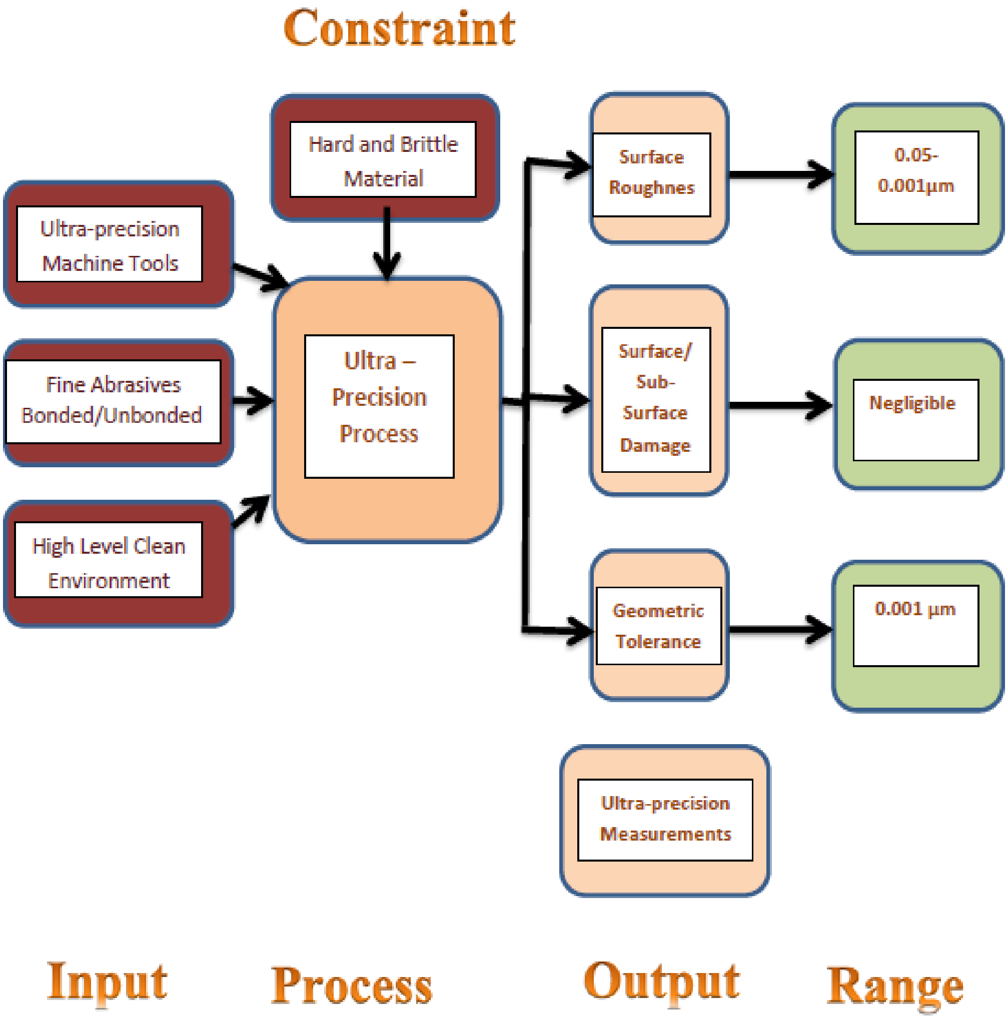


Fig.2 Diagrammatic representation of Ultra-precision Process for Hard and Brittle Materials

For precision and high quality work, the system should be rigid and highly precise along with high motion accuracy and feedback control. Uniform grain size of abrasives is very important for these processes, when used as loose or bonded. Ultra-precision metrology system should be used for assessment which is measured in terms of dimensional accuracy, surface finish and surface integrity. Clean environment is essential along with temperature, vibration and humidity control. The product should be free from surface and subsurface defects such as micro cracks, residual stresses etc. As these defects are the most common cause of failure at later stage.

Various precision material removal processes using fine abrasives are evolved. In most of the processes, the material removal is done through mechanical action. Chemical action may be induced in these processes by using proper abrasive-work material environment to promote chemo-mechanical finishing.

The processes of ultra-precision finishing have been classified based on the abrasives used, which can be bonded and unbounded. The bonded abrasive type processes include grinding, honing etc. In these processes, abrasives are fixed and the forces can be controlled externally. The second type of processes uses loose abrasives and the processes include polishing, lapping, magnetic assisted finishing etc. The forces acting on the abrasives in polishing and lapping processes cannot be controlled externally whereas these can be controlled in magnetic assisted finishing processes. These processes have following characteristics:

- Many more cutting edges.
- Distribution of rake angles: $+45^o$ to - $60^o$ .
- The grains undergo much larger deformations than cutting tools
- Only 2 to 5% of grain surface area is operative at any time
- Depth of cut for an individual grain w.r.t grain diameter is very small

This helps in obtaining better results without surface / subsurface damage on brittle materials. The advancements in these processes are also discussed in detail.

### *A. Ultra-precision Grinding*

The advancements in grinding system include new abrasives, new bonding methods and lubricants. The mechanism of material removal is at the borderline of brittle to ductile transition. For the better quality of the product, it is very important that the ultra-precision machines should be precise, smooth, vibration and backlash free, with low levels of synchronous and asynchronous spindle errors. Diamond and CBN are the two most commonly used abrasives. Different shapes of wheels with different bonding materials like metals, resins and vitrified have been used. Pre-process and in-process tool conditioning is also very important to avoid wheel loading and to maintain sharpness and protrusion over bonding layer of the fine grains. Conventional trueing and dressing has been replaced with new methods such as Electrolytic in-process dressing and EDM as pre-process dresser. Water based grinding fluids have been most commonly used to reduce friction and conduct heat out of the grinding zone.

The process has been successfully used for finishing glass lenses in digital cameras, scanners, projectors, telescopes etc. Ceramic plates and rollers have also been finished with different grinding tools. Silicon wafers used in IC manufacturing have been finished to the desired levels with minimum subsurface damages. Most of the research focuses on the improvement in machine tools, the advancements in grinding wheels and the dressing of wheels which are discussed below.

*1) Machine Tools:* Brinksmeier et al. (2010) have stressed predictability and reliability of ultra-precision grinding processes [3]. The stability, reproducibility and rigidity of the machine tools and grinding tools are very important. Alao and Konneh (2012) have finished mono crystalline silicon samples on a high speed jig grinding unit attached on the numerically controlled vertical milling machine. They reported that input parameters depth of cut, feed and spindle speed have significant effect on results [5].

*2) Properties of Work Material:* The properties of material to be grinded also plays very important role. Zhao et al. (2007) found that fracture toughness is very crucial parameter which can help in predicting optical glass's machinability before grinding process. Experiments conducted on quartz and fused silica have proved that material with higher value of fracture toughness has better surface finish (Ra 5.2 nm for fused quartz and Ra 8.2nm for fused silica). The result also shows that high fracture toughness results in lower amplitude and RMS value, thus gives better finish [6].

*3) Grinding Wheels:* New methods have been developed for manufacturing grinding wheels with higher bonding strength and coarse grains. Guo et al. (2014) have found that the depth of damage reduced from 5 µm to 1.5 µm with 150 µm grit size single layer electroplated diamond grinding wheel in comparison to conventional coarse grained diamond wheel [7]. Zhao and Guo et al. (2015) have reported that coarse grained wheels can be reduced to constant wheel peripheral envelope surface exhibiting flattened diamond grains. Optical glasses have been ground using five axis ultra-precision grinding machine. Surface finish of the order Ra 1nm with minimum subsurface damage less than 3 µm is reported which is better than fine grain grinding wheels. Precision conditioned coarse grained diamond wheels have machined brittle materials successfully with low wear rate, better dimensional accuracy and low machining cost [8]. The scope of grinding large jobs seems possible with this technique.

*4) Dressing:* The use of fine abrasives lead to fast abrasive wear, clogging and loading of wheel which can be overcome by dressing. But dressing of fine abrasive wheels is a tedious task. Different processes have been developed for dressing. ELID (Electrolytic in-process dressing) technique, developed by Murata et al (1985), uses metal bonded grinding wheels with higher rigidity and stability [9]. Kumar et al. (2002) have studied ELID technique in detail and performed certain experiments on borosilicate crown glass (BK7). The results show that average roughness of the ground surface with and without ELID are 0.1491 µm and 0.3795 µm, respectively. The instability of normal and tangential forces, observed during ELID, could be minimized with 50% or higher current duty ratios [10].

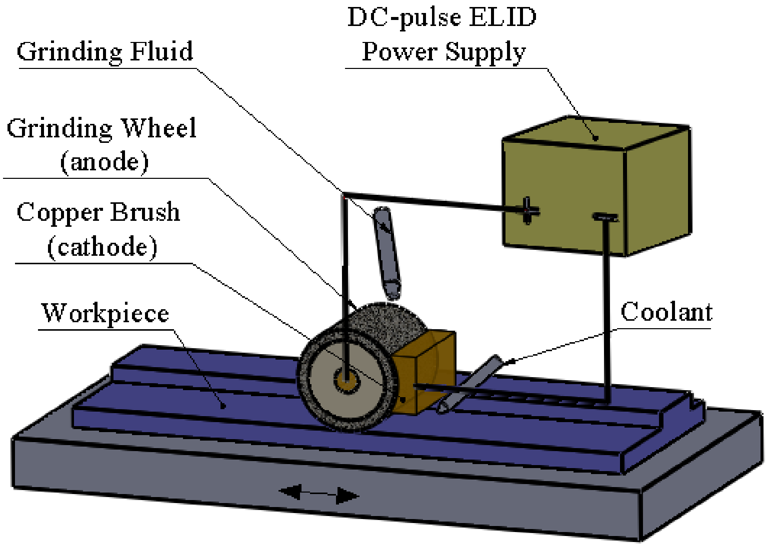


Fig. 3. Schematic illustration of ELID grinding

Yanyan et al. (2009) have used two dimensional ultrasonic assisted grinding machine (TDUAG) for finishing of Nano ZrO2 ceramics. Results show that better surface finish (Ra 0.081 µm) is possible with ultrasonic assisted grinding machine when compared to grinder without ultrasonic vibrations [11]. A novel conditioning technique has been attempted by Zhao and Guo et al. (2015) where copper bonded diamond wheels with grit size 15 µm and 91 µm have been dressed by ELID. These have been further used as conditioners for truing of mono layer nickel electroplated diamond wheels with grit size of 46 µm, 91 µm and 151 µm. They reported that coarse grained wheels can be reduced to constant wheel peripheral envelope surface exhibiting flattened diamond grains. The run out also reduced from 20 µm to 2.5 µm under optimum conditions of dressing [8].

### *B. Ultra-precision Polishing*

Polishing is the process in which fine abrasives are used with soft pads. The sliding friction between the work piece and the abrasives removes the material. The efficiency of the process is low because of micro action of abrasives. The micro action is taken advantageously as it prevents subsurface damage. The process of producing nano level finish with minimum subsurface damage is termed as Ultra-precision polishing. The removal may be mechanical or chemical in nature. The mechanical action may be abrasive or erosive involving plastic deformation or fracture. During chemical action either chemical reaction or dissolution of material takes place. Combined chemo- mechanical action may also be used for polishing.

Abrasive pads, speeds and pressure are the main factors which control the surface finish and subsurface damage. Different combinations have been developed by different organizations on proprietary basis.

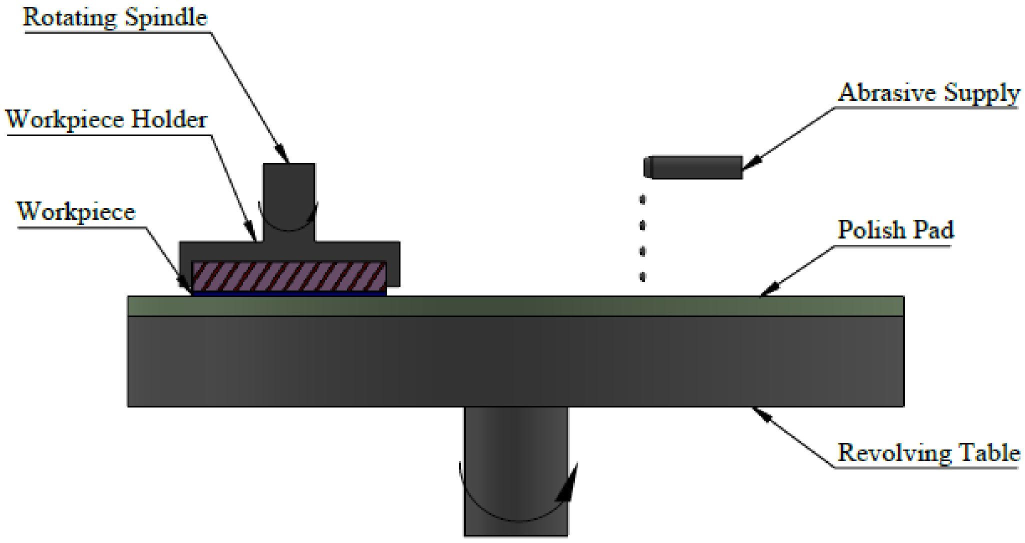


Fig. 4 Schematic of Polishing Setup

Meinel (1982) has reported the manufacturing of large telescope mirrors comprised of three phases. In the first phase, rough grinding was done using cylindrical grinder with fixed abrasive wheels of silicon carbide or diamond. In second phase, loose abrasives such as silicon carbide, aluminium oxide or diamond with spherical shaped segmented metal lap were used. Use of progressively fine abrasives leads to surface roughness of 1 µm to 3 µm. In final phase, soft pitch lap with very fine abrasives of 2 µm to 0.8 µm were used giving final surface roughness value 1-2 nm.

Contrary to lapping, soft pad is used in polishing which results in such a good quality surface. Lot of new materials such as polyurethane, foam, felt, Teflon, artificial leather etc. have been developed and used as polishing pad.

Brown (1986) used hard pitch for optical component polishing and obtained surface finish of 0.08 nm rms. Leinster (1993) polished BK7 glass using Teflon lap with $Al_2O_3$ abrasives resulting in surface roughness less than 1nm Ra. Ni plated optics were finished to surface roughness of less than 1 nm by Parks and Evans (1994) by using synthetic fabric faced laps.

Kasai et al. (1988) developed a fully automatic machine for semiconductor wafers. Flatness of less than 2 µm was reported over 80% of diameter and surface roughness less than 2 nm $R_{max}$. Bromine methanol solution with fluoro Carbon plastic pads was used.

Kuriyagawa et al. (2002) used electrorheological fluids for finishing three-dimensional optical micro aspherical lenses. The CCD microscope was used to observe the behaviour of electrorheological particles and abrasive particles in the area of the tip of the tool. The electric field strength, electrode shape, and type of abrasive particles were investigated. It was observed that the abrasive particles collect at the rotating tool tip because of the electrorheological effect. Micro-grinding and micro-polishing was done using electrorheological fluid-assisted micro-aspherical generator system.

Kim et al. (2003) used ER fluid assisted polishing for finishing borosilicate glass. The forces exerted by electric field on particles of ER fluid and abrasive particles were evaluated. The results show that with the increase of ER effect, the forces on abrasives also increase and hence, give greater material removal rate. ER fluid was prepared by dispersing $Al_2O_3$ abrasives of 0.5 µm in starch and silicone oil. The process was carried out for 10 minutes in the final surface finish 2.8 nm Ra was achieved.

Pal et al. (2016) reported that finishing of hard and brittle is a challenging task. Tight tolerances of surface figure and finish make polishing a more critical operation. Full aperture polishing process was used for polishing a substrate of Schott BK7 optical glass. Optical pitch polisher and cerium oxide (CeO2) slurry were used in the process. The experiments were designed using Taguchi’s L9 orthogonal array. Abrasive concentration, pressure and overarm speed were taken as variable process parameters. Polishing was carried out for duration of 120 minutes for each combination of parameters. The results show that one of the most significant parameters in the optical polishing process was abrasive slurry concentration. Both the material removal rate (MRR) and the surface roughness were affected. The MRR was also affected significantly by the pressure applied at the workpiece–polisher interface whereas variation of pressure does not have significant effect on the surface roughness. It was also found that both MRR (the larger the better) and Ra (the smaller the better) cannot be optimized simultaneously. Thus, there was a need of trade-off between the two. Hence, the optimized parameters reported were 8.25% abrasive concentration, 30 g/cm2 pressure and 25 rpm overarm speed leading to MRR of 9.86 nm/min and Ra of 13.4nm.

As mechanical and chemical actions, there are (a) mechanical removal by abrasion, (b) friction to disorder the atomic arrangement, (c) etching and dissolving, and (d) formation of a thin film. The combination of these actions at different ratios constitutes various polishing methods such as Elastic Emission Machining, Abrasive Jet Machining, Float Polishing and Chemical Mechanical polishing.

### C. *Magnetic Assisted Polishing*

A major limitation in finishing intricate shapes is predefined relative motion of the cutting edge with respect to the workpiece surface. To achieve the desired results, the multiple cutting edges in some loosely bonded form can be used for finishing the complex geometries. Precise control of finishing forces is another vital consideration for fine finishing with close tolerances and without subsurface damage. The incapability in controlling abrading forces is a major lag in the existing technologies. The extent of abrasion and quality of the finished surface are determined by the nature and strength of bonding material that holds the abrasive particles. Keeping in view these limitations, advanced fine finishing processes are developed namely Magnetic Abrasive Finishing, Magnetic Float Polishing, Magnetorheological Fluid Finishing and Magnetorheological Abrasive Flow Finishing. Magnetic Assisted Polishing is one of the super polishing processes involving extremely small amount of material removal even to the extent of an atomic cluster. This process uses magnetic force for material removal. The cutting forces of extremely small magnitude are applied on the workpiece surface. These forces are uniformly distributed on the work surface and are easily controllable. Hence there is negligible damage to the surface of workpiece. The process is capable of achieving surface roughness of the order of nanometric level.

1) *Magnetic Abrasive Finishing:* In MAF operation, workpiece is kept between the two magnets. The air gap between the workpiece and the magnet is filled with magnetic abrasive particles (MAPs). MAPs are made up of iron powder and abrasive powder. MAPs can be used as unbonded, loosely bonded or bonded. Bonded MAPs are prepared by sintering of ferromagnetic powder and abrasive powder at a very high pressure and temperature in inert gas atmosphere. Loosely bonded MAPs are prepared by mechanical mixing of ferromagnetic powder and abrasive powder with a small amount of lubricant to give some holding strength between the abrasive and ferromagnetic particles. Unbounded MAPs are mechanical mixture of ferromagnetic and abrasive particles without any lubricant. Singh et al. (2010) studied that amongst all the available varieties of magnetic abrasives, the sintered magnetic abrasives provides highest surface finish on most of the work materials. The MAPs join each other along the lines of magnetic force and form a flexible magnetic abrasive brush between each magnetic pole and the workpiece. The pressure is generated by magnetic field. The normal

component of magnetic force is responsible for abrasive action. Cylindrical and flat surfaces have been polished using this process. The main parameters which affect the performance of this process include speed of the workpiece, magnetic flux density and working gap, in addition to size, type and concentration of abrasives. Different researchers have performed experiments by varying these parameters.

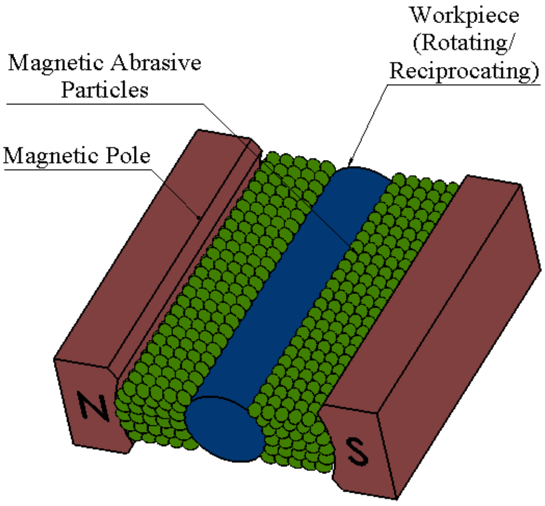


Fig.5 Schematic view of the Magnetic Abrasive Finishing.

Yamaguchi and Shinmura (2004) used the technique for polishing inner surface of alumina tubes. The value of surface finish was reduced to 0.02 µm by using 0-1 µm diamond abrasives. The results show that abrasive size plays a very important role in surface finish.

Magnetic abrasive finishing (MAF) gives superior surface finish over conventional finishing processes. It can give fine polishing to different geometrical shapes and advanced engineering materials at low cost. Its gentle tool does not impact the workpiece surface. Houshi (2016) studied advanced finishing processes and the limitations of MAF. He found that no mathematical model is comprehensive of the effect of all machining parameters on MRR and surface roughness. MRR and surface finish have not been modelled and optimized together; automation of the magnetic pole path to finish of neither plane surfaces nor free form surfaces is lacking.

*2) Magnetic Float Polishing:* This MFP technique is governed by magneto-hydrodynamic behaviour of a magnetic fluid. Figure shows a schematic of the magnetic float polishing apparatus. A colloidal distribution of extremely fine (100 to 150 Å) sub-domain ferromagnetic particles, usually magnetite ($Fe_3O_4$) is used in a carrier fluid, such as water or kerosene to make magnetic fluid. The fluid can levitate all non-magnetic materials suspended in it. Surfactants are added to stabilize Ferro fluids against particle gathering. On the application of magnetic field, $Fe_3O_4$ particles get pulled down towards the higher magnetic field whereas the non-magnetic particles i. e. the abrasive grains, balls and acrylic float are lifted towards the lower magnetic field. The drive shaft is pushed down to exert the required force on the balls. The balls come in contact with the shaft at the top, chamber on the side and float at the bottom. The abrasives work under the action of magnetic buoyancy force, on the rotation of the spindle. Low loads, high speeds and abrasives such as boron carbide, silicon carbide, and cerium oxide are used in MFP.

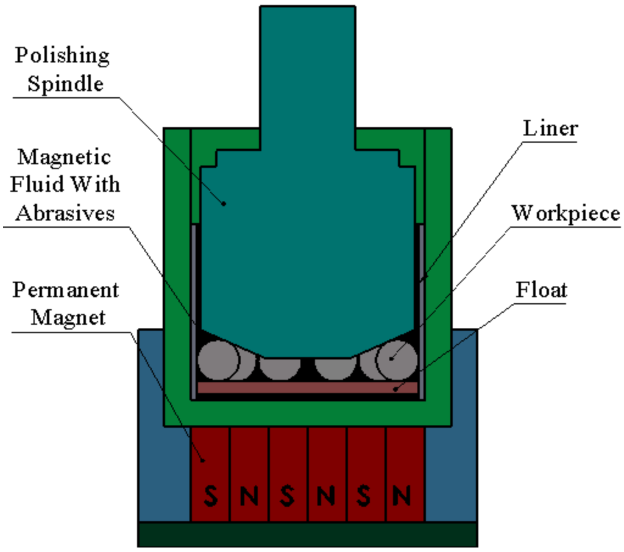


Fig.6 Schematic of the Magnetic Float Polishing apparatus

In order to improve existing ball finishing methods and to minimize surface damages and improve surface finish, Tani and Kawata (1984) has developed Magnetic Fluid Grinding (MFG), also called Magnetic Float Polishing (MFP). Kato and Umehara (1988) have improved this technique significantly using a float. Umehara and Kato (1996) have used MFP for finishing a wide range of products to a high level accuracy and excellent surface finish. Childs et al. (1995) has focused on design and mechanics of magnetic fluid grinding cell. Jiang and Komanduri, (1998) has developed a systematic, efficient, and repeatable methodology of MFP process of finishing $Si_3N_4$ ball bearings.

Umehara et al. (2006) worked on large size/large batch silicon nitride ($Si_3N_4$) balls by magnetic float polishing (MFP) technology. Taguchi method was applied for the roughing stage to optimize parameters for the best material removal rate. Results show that a load of 1.5 N/ball, an abrasive concentration of 20%, and a speed of 400 rpm give high material removal rate using $B_4C$ (500 grit) abrasive. In the final finishing stage a batch of 46, 3/4 in. balls have been finished to a final diameter of 0.7500 in. The average sphericity of 0.25 µm and an average surface finish, Ra of 8 nm was achieved in 30 hours.

*3) Magnetorheological Fluid Finishing:* A Magnetorheological (MR) fluid consists of micron sized magnetisable particles dispersed in nonmagnetic carrier medium. The rheological behaviour of these materials can be handled externally with the help of energy fields. The particles in nonmagnetic carrier fluid develop dipole moment proportional to the magnetic field strength. The MR fluid becomes stiff under magnetic field. The carbonyl iron particles are attracted towards the magnet whereas the abrasives are pushed towards the workpiece due to levitation force. The abrasive particles are embedded in the chains formed by carbonyl iron particles. The bonding strength is provided by the magnetic interaction force between iron particles. Its magnitude depends upon the iron concentration, magnetic field intensity, particle size and magnetic permeability. The finishing is achieved by abrasion action between work piece and chains through relative motion.

CeO2 and nano diamond particles are the most commonly used abrasives. In general setup permanent magnet is supported on fixture which is nonmagnetic. The magnet can rotate and assembly is called wheel carrier.

Jung et al. (2009) reported that earlier developed MR processes does not yield satisfactory results for finishing hard materials because of the limitations of the wheel type MR finishing setup and use of conventional abrasives. The comparison was made, based on material removal rate and surface finish, between existing and modified conditions. Some preliminary experiments were performed on $Al_2O_3$-TiC hard disk slide and silicon based surfaces using wheel type MR finishing setup.

It was observed that material removal rate and surface finish tended to increase with rotational speed upto 500 rpm but decreased beyond this value. The centrifugal forces acting on carbonyl iron particles played adverse role leading to a weak bonding strength. To overcome these drawbacks the processing conditions were improved and new magnetisable hard abrasives were developed. The rectilinear velocity of workpiece was increased and newly developed iron-CNT (Carbon Nano Tubes) abrasives were used. It was reported that the surface finish was improved by 193% by increasing the relative speed between tool and workpiece. Compared to non-magnetisable abrasives, used in earlier experiments, magnetisable abrasives had better bonding strength even at higher speed.

Singh et al. (2011) observed that the magnetic assisted processes developed so far were capable for finishing concave, convex, flat and aspherical shapes due to relative movement of finishing medium and workpiece. The processes were not used for finishing 3D intricate shapes. To overcome this limitation, computer controlled 3D surface nano finishing technique using ball end MR finishing tool was developed. MR fluid was prepared by mixing carbonyl iron powder with silicon carbide dispersed in viscoelastic base of grease and heavy paraffin liquid. The liquid was made to pass through rotating tube which acts as tool. A stiffened ball end shape of MR fluid was formed at the open end of tube. The machine was capable of improving the surface finish of 3D groove surfaces but in less aggressive manner.

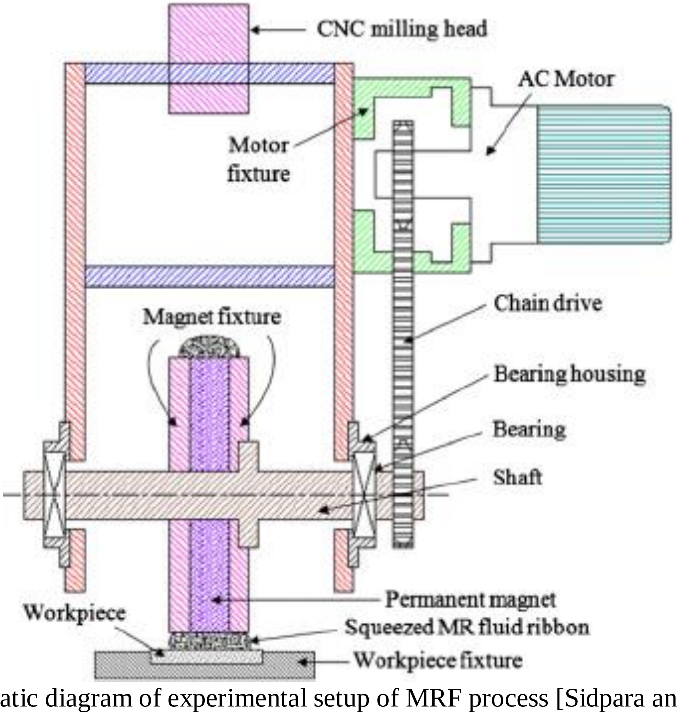


Fig.7 Schematic diagram of experimental setup of MRF process [Sidpara and Jain 2012].

Sidpara and Jain (2012) studied the effect of different process parameters of MR finishing on single crystal silicon blank. The main function of CIPs is to form dense chain structure and to hold abrasives firmly. It was reported that MRR increases as CIPs concentration increases while surface finish decreases. With increase in concentration of the CeO2, which is used as abrasive, the surface finish improves. The best surface finish of 12.5 nm was obtained at 40% CIPs, 5% abrasives and 300 rpm of the carrier wheel.

Wang et al. (2015) found that in the existing developments, the working area of stiffened MR fluid is relatively small. This makes process less efficient when dealing with planarization of large surfaces. In order to enlarge contact area between workpiece and magnetic ribbon, permanent magnetic yoke with straight air gap was used. FEM was used to simulate the magnetic performance of the developed set up. The experiments were performed on K9 glass using CeO2. Based on results of the preliminary experiments, final experiments were designed by varying trough speed, working gap and excitation gap. The FEM simulation demonstrated that new yoke produced large working area, hence improves the machining efficiency. The surface finish of 1 nm was obtained in 60 minutes with the excitation gap of 6 mm, work gap 1.5 mm, trough speed 40 rpm and workpiece speed of 80 rpm.

*4) Magnetorheological Abrasive Flow Finishing:* Jha and Jain 2004 investigated that in MAF, MRFF and MFP, the magnetic field is used to control the abrading forces, but the applications of these processes are limited to specific simple geometries. Internal intricate shapes and passages cannot be finished by these processes. Finishing of any complicated shapes can be done with AFM process by forcing abrasive-laden polymeric medium through the passage formed by the workpiece and fixture assembly but the forces to the abrasives cannot be controlled externally. For external finishing of optical lenses to the nanometer level MRF is used where forces can be controlled by external means (i.e. magnetic field). Keeping in view the advantages and limitations of AFM and MRF a new precision finishing process, magnetorheological abrasive flow finishing (MRAFF) was developed for nano-finishing of parts even with intricate shapes. Magnetorheological polishing fluid (MRPF) is used as the medium for finishing in this process. It is a homogeneous mixture of carbonyl iron particles (CIPs) and abrasive particles in a base medium of grease and paraffin liquid. CIPs in the fluid form a chain-like structure along the lines of magnetic field in between the two poles of an electromagnet. The embedded abrasive particles are strengthened by surrounding CIPs chains. These abrasive particles in contact with the workpiece surface perform cutting action by shearing off peaks of surface undulations from the workpiece surface when squeezed through the passage formed by workpiece and fixture. No improvement in surface finish was observed in absence of magnetic field.

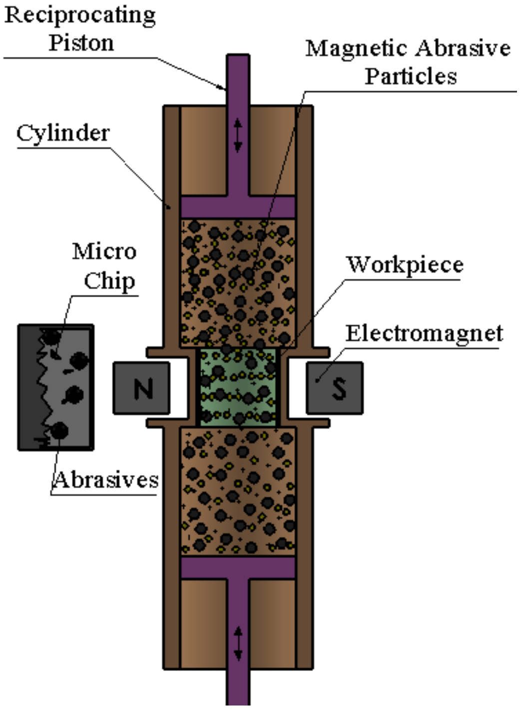


Fig. 8 Schematic and Mechanism of MRAFF Experimental Setup

Das et al. 2008 studied the effects of various process parameters. They analysed the medium flow through the fixture by finite difference method. The stresses established during the process were evaluated by assuming the medium as Bingham plastic. A capillary viscometer has been designed and fabricated to study the effect of magnetic field on the rheological properties of the medium. The normal force on the abrasive particles was evaluated from the applied magnetic field. It was found that with an increase in the magnetic field the viscosity of the fluid increases in a third-order logarithmic function and also yield stress of the fluid. The numerical simulation shows that at a given magnetic field higher axial pressure gives rise to smaller plug flow region. The fluid flow analysis reveal that for the same applied pressure a larger plug flow region of the flowing fluid is obtained with higher magnetic field. This is due to the development of strong structure of CIP chains. It was found that surface finish improves with increase in current and number of finishing cycles.

In order to enhance the finishing performance of MRAFF process Das et al 2012 proposed a new finishing process "rotational– magnetorheological abrasive flow finishing (R-MRAFF)". Rotatory motion was provided to the polishing medium by a rotating magnetic field in addition to reciprocating motion which was provided by hydraulic unit. It was found that R-MRAFF process is more effective in reducing surface roughness than MRAFF process under similar experimental conditions.

The process has various applications for complex shaped 3D components. Jha and Jain, 2006 conducted an experiment on silicon nitride using SiC, $B_4C$ and diamond abrasives. The experimental results show that MRAFF is capable in nano finishing of hard ceramics.

## V. CONCLUSION

The paper focuses on ultra-precision finishing techniques for brittle and hard materials. The techniques are classified according to abrasive state. Brief histories of these processes based on classification are presented. The paper discusses the processes which are capable of obtaining nanometric finish, sub-micrometric dimensional accuracy, and minimal subsurface/ subsurface damage. From the available experimental results and analysis, following conclusions can be drawn:

1. The features of hard and brittle material play vital role during the development of the ultra-precision finishing techniques. For example, ionic or covalent bonding, low symmetry, low slip system for plastic deformation, low thermal conductivity and low fracture toughness in brittle materials makes finishing of these materials tedious. Low mobility of dislocations is another major factor behind difficult finishing of brittle materials.
2. It is also observed that it is important to achieve ductile mode to obtain best possible surface finish without subsurface damages. These processes have characteristics such as many cutting edges, distribution of rake angles, larger deformations of grains, very small depth of cut etc. which make them capable of producing ultraprecise surfaces.
3. Unbounded abrasive finishing processes give higher surface finish in comparison to bonded abrasive finishing. They can also be used for different shape products.
4. The final performance is determined by factors like surface finish, geometric accuracy, and surface integrity and these requirements vary with applications. Ultra-precision grinding followed by polishing is preferable process for optics as finish and geometry are more important. In semiconductors flatness or subsurface damage is more important so magnetic assisted and chemical mechanical techniques can be used. The study shows that in ceramics, magnetic assisted techniques have shown very good results.
5. The study reveals that the effect of all machining factors simultaneously on response parameters are not described in a single model.
6. It is also seen that optimization in most of the ultra-precision processes has been done for individual response parameters. This document is a template. An electronic copy can be downloaded from the Journal website. For questions on paper guidelines, please contact the conference publications committee as indicated on the conference website. Information about final paper submission is available from the conference website.

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