## ADVANCED FINISHING PROCESSES (AFPs)

There are many advances taking place in the finishing of materials with fine abrasives, including the processes, the abrasives and their bonding, making them capable of obtaining nanometer order surface finish. Earlier there has been a limit on the fine size of abrasives (~a few µm) but today, new advances in materials syntheses have enabled production of ultra fine abrasives in the nanometer range. Abrasives are used in a variety of forms including loose abrasives (polishing, lapping), bonded abrasives (grinding wheels), and coated abrasives for producing components of various shapes, sizes, accuracy, finish and surface integrity.

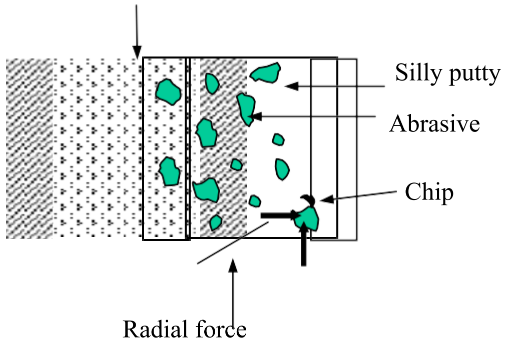
The electronics and computer industries are always in demand of higher and higher precision for large devices and high data packing densities. The ultimate precision obtainable through finishing is when chip size approaches atomic size (~ 0.3 nm) [2]. To finish surfaces in nanometer range, it is required to remove material in the form of atoms or molecules individually or in the groups. Some processes like Elastic Emission Machining (EEM) and Ion beam Machining (IBM) work directly by removing atoms and molecules from the surface. Other processes based on abrasive wear remove them in clusters. On the basis of energy used, the advanced finishing processes (AFPs) can be broadly categorized into mechanical, thermoelectric, electrochemical and chemical processes [5]. The performance and use of certain specific process depend on workpiece material properties and functional requirement of the component. In mechanical AFPs, very precise control over finishing forces is required. Many newly developed AFPs make use of magnetic/electric field to externally control finishing forces on abrasive particles. To name a few, these magnetic field assisted finishing processes include Magnetic Abrasive Finishing (MAF), Magnetic Float Polishing (MFP), Magnetorheological Finishing (MRF), and Magnetorheological Abrasive Flow Finishing (MRAFF). Chemo Mechanical polishing (CMP) utilizes both mechanical wear and chemical etching to achieve surface finish of nanometer and planarization. CMP is the most preferred process used in semiconductor industry for silicon wafer finishing and planarization. Since the material removal in fine abrasive finishing processes is extremely small, they can be used successfully to obtain nanometer surface finish, and very low value of dimensional tolerances. Advanced abrasive finishing processes belong to a subset of ultra precision finishing processes which are developed for obtaining nanometer order surface finish. A comparison of surface finish obtainable from different finishing process is given in Table 1. This chapter discusses about the principles of working and potential applications of such processes in following paragraphs.

Table 1: Comparison of surface finish obtainable by different finishing processes

| S.No. | Finishing Process | Workpiece | Ra value (nm) |
|---|---|---|---|
| 1. | Grinding | - | 25 - 6250 |
| 2. | Honing | - | 25 - 1500 |
| 3. | Lapping | - | 13 - 750 |
| 4. | Abrasive Flow Machining (AFM) with SiC abrasives | Hardened steel | 50 |
| 5. | Magnetic Abrasive finishing (MAF) | Stainless steel | 7.6 |
| 6. | Magnetic Float Polishing (MFP) with $CeO_2$ | $Si_3N_4$ | 4.0 |
| 7. | Magnetorheological Finishing (MRF) with $CeO_2$ | Flat BK7 Glass | 0.8 |
| 8. | Elastic Emission Machining (EEM) with $ZrO_2$ abrasives | Silicon | <0.5 |
| 9. | Ion Beam Machining (IBM) | Cemented carbide | 0.1 |

### 1.1 Abrasive Flow Machining (AFM)

Abrasive Flow Machining (AFM) was identified in 1960s as a method to deburr, polish, and radius difficult to reach surfaces and edges by flowing an abrasive laden viscoplastic polymer over them. It uses two vertically opposed cylinders, which extrude an abrasive medium back and forth through passage formed by the workpiece and tooling. Abrasion occurs wherever the medium passes through the restrictive passages. The key components of AFM are the machine, the tooling, types of abrasives, medium composition and process settings [6]. Extrusion pressure, number of cycles, grit composition and type, and fixture design are the process parameters that have the largest impact on AFM results.




(a)


(b)

achining, (a) forces acting on abrasive particle in AFM
rocess, (b) Experimental setup

es by change in the rheological properties of the medium
through the restrictive passages [6]. The viscosity of
important role in finishing operation [7]. This allows it to
brade surfaces that it flows across. The work piece held by
medium cylinders which are clamped together to seal so
uring finishing process. The three major elements of the

fines and directs the abrasive medium flow to the areas
g and surface improvements are desired.
he process variables like extrusion pressure, medium flow
volume, and flow rate.

(c) The abrasive laden **Polymeric Medium** whose rheological properties determine the pattern and aggressiveness of the abrasive action. To formulate the AFM medium, the abrasive particles are blended into special viscoelastic polymer, which show change in viscosity when forced to flow through restrictive passages.

AFM can process many selected passages on a single workpiece or multiple parts simultaneously. Inaccessible areas and complex internal passages can be finished economically and productively. It reduces surface roughness by 75 to 90% on cast, machined or EDM'd surfaces [8]. The same AFM set up can be used to do a variety of jobs just by changing tooling, process settings and if necessary abrasive medium composition. Because of these unique capabilities and advantages, AFM can be applied to an impressive range of finishing operations that require uniform, repeatable and predictable results [8]. AFM offers precision, consistency, and flexibility. Its ability to process multiple parts simultaneously, and finishing inaccessible areas and complex internal passages economically and effectively led to its application in wide range of industries. Aerospace, aircraft, medical components, electronics, automotive parts, and precision dies and moulds manufacturing industries are extensively using abrasive flow machining process as a part of their manufacturing activities. Recently, AFM has been applied to the improvement in air and fluid flow for automotive engine components, which was proved as an effective method for lowering emissions as well as increasing performance. Some of these potential areas of AFM application are discussed below:

AFM process was originally identified for deburring and finishing critical hydraulic and fuel system components of aircraft in aerospace industries. With its unique advantages, the purview of its application has been expanded to include adjusting airflow resistance of blades, vanes, combustion liners, nozzles and diffusers; improving airfoil surface conditions on compressors and turbine section components following profile milling, casting, EDM or ECM operations; edge finishing of holes and attachments to improve the mechanical fatigue strength of blades, disks, hubs, and shafts with controlled polished, true radius edges; and finishing auxiliary parts such as fuel spray nozzles, fuel control bodies and bearing components.

The surface finish on the cast blades is improved from original 1.75 μm to 0.4 μm $R_a$ (Fig. 3a). Cooling air holes are deburred and radiused in one operation on turbine disks as large as 760 mm in diameter (Fig. 3b). It is also used to remove milling marks and improve finish on the complex airfoil profiles of impellers and blades. Intricate intersections can also be finished easily.

Since in the AFM process, abrading medium conforms to the passage geometry, complex shapes can be processed as easily as simple ones. Dies are the ideal workpiece for the AFM process as they provide the restriction for medium flow, typically eliminating fixturing requirements. AFM process has revolutionized the finishing of precision dies by polishing the die surfaces in the direction of material flow, producing a better quality and longer lasting dies with a uniform surface and gently radiused edges. The uniformity of stock removal permits accurate 'sizing' of undersized die passages. Precision dies are typically polished in 5 to 15 minutes unattended operation.

(b

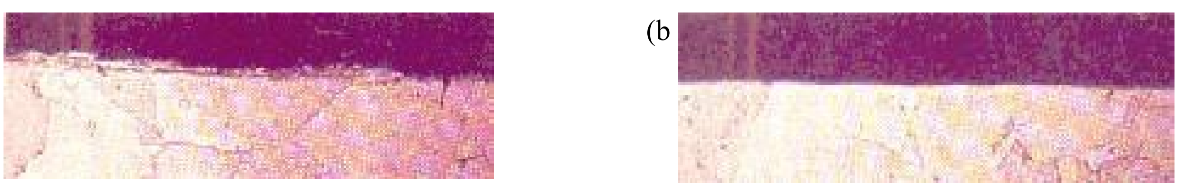


Fig. 3: 500X photomicrograph showing complete removal of EDM recast layer,
(a) before AFM, (b) after AFM [courtesy: Extrude Hone corporation, USA]

The original 2 μm $R_a$ EDM finish is improved to 0.2μm with a stock removal of 25 μm per surface. Fig. 3 shows the complete removal of EDM recast layer. In some cases, the tolerances have been achieved as 13 μm [9].

AFM process is used to enhance the performance of high-speed automotive engines. It is a well-known fact in the automobile engineering that smoother and larger intake ports produce more horsepower with better fuel efficiency. But it's very difficult to obtain good surface finish on the internal passageway of intake ports because of its complex shape [10]. The demand for this process is increasing rapidly among car and two wheeler manufacturers as it abrades smoothes and polishes the surfaces of 2- stroke cylinders and 4- stroke engine heads for improved air flow and better performance. The AFM process can polish anywhere that air, liquid or fuel flows. Rough, power robbing cast surfaces are improved from 80-90% regardless of surface complexities

Advanced high-pressure injection system components in diesel engines are subjected to repeated pulses of very high pressure that can generate fatigue failures at high stressed areas. Smoothing and removing surface stress risers, cracks, as well as uniform radiusing of sharp edges by AFM process can significantly extend component life. Flow tuned spray orifices of fuel injector nozzles can reduce particulate emissions and improves the fuel efficiency of diesel powered engines.

### 1.2 Magnetic Abrasive Finishing (MAF)

Magnetic abrasives are emerging as important finishing methods for metals and ceramics. Magnetic Abrasive Finishing is one such unconventional finishing process developed recently to produce efficiently and economically good quality finish on the internal and external surfaces of tubes as well as flat surfaces made of magnetic or non-magnetic materials. In this process, usually ferromagnetic particles are sintered with fine abrasive particles ($Al_2O_3$, SiC, CBN or diamond) and such particles are called ferromagnetic abrasive particles (or magnetic abrasive particles). However, homogeneously mixed loose ferromagnetic and abrasive particles are also used in certain applications. Fig. 4 shows a Plane MAF process in which finishing action is generated by the application of magnetic field across the gap between workpiece surface and rotating electromagnet pole. The enlarged view of finishing zone in Fig. 4 shows the forces acting on the work surface to remove material in the form of chips. Force due to magnetic field is responsible for normal force causing abrasive penetration inside the workpiece while rotation of the magnetic abrasive brush (i.e. North pole) results in material removal in the form of chips.

The magnetic abrasive grains are combined to each other magnetically between magnetic poles along a line of magnetic force, forming a flexible magnetic abrasive brush. MAF uses this magneti . The
magnetic field retains the powde der to
be pressed against the surface t urved
shape can also be finished along ent of
the magnetic coil precisely cont es on
the work piece [12].

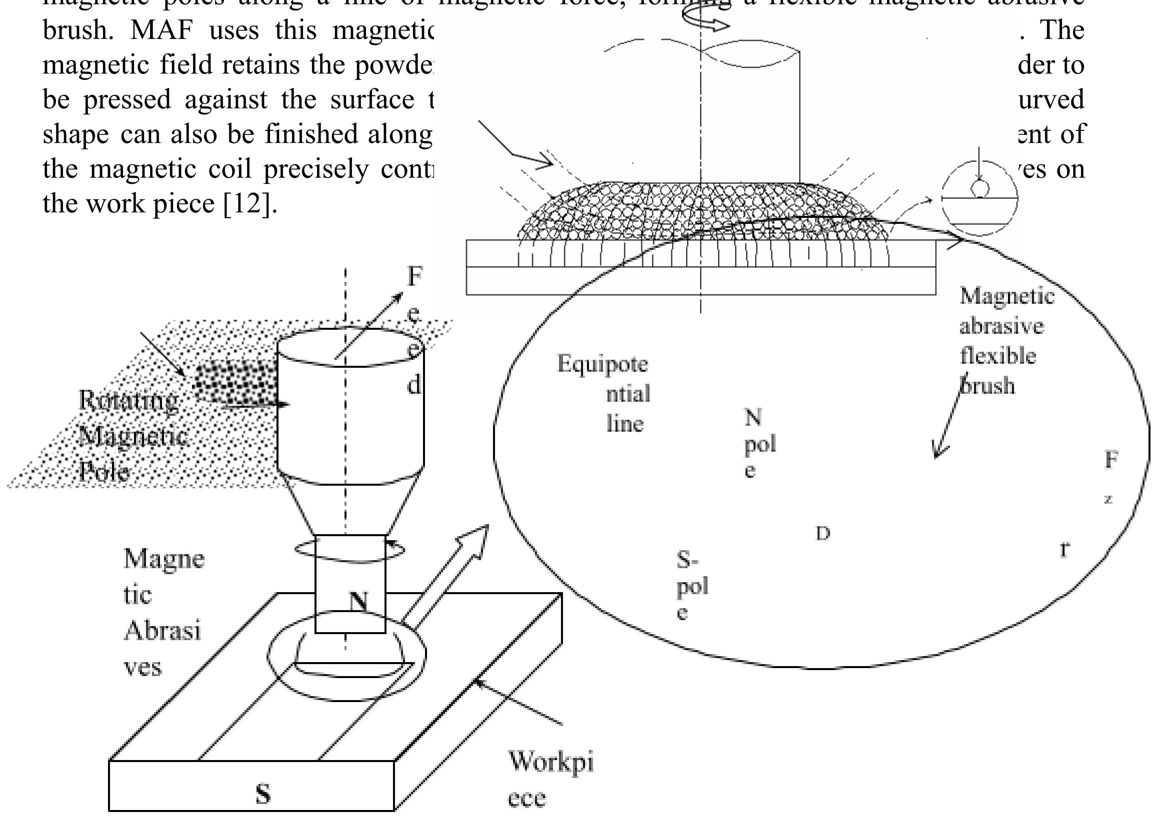



Fig. 4: Plane Magnetic abrasive finishing

Since the magnitude of machining force caused by the magnetic field is very low but controllable, a mirror like surface finish ($R_a$ value in the range of nano-meter) is obtained. In MAF, mirror finishing is realized and burrs are removed without lowering the accuracy of the shape. These fine finishing technologies using magnetic abrasives have a wide range of applications. The surface finishing, deburring and precision rounding off the workpiece can be done simultaneously. MAF can be used to perform operations as polishing and removal of thin oxide films from high speed rotating shafts. Shinmura et al [13] have applied MAF to the internal surface of work pieces such as vacuum tubes and sanitary tubes.

Fig. 5 shows the magnetic abrasive jet finishing of internal surface of a hollow cylindrical workpiece. It's a variant of MAF process in which working fluid mixed with magnetic abrasives is jetted into the internal surface of the tube, with magnetic poles being provided on the external surface of the tube [14]. The magnetic abrasives in the jet mixed with fluid are moved to the internal surface by magnetic force, where the magnetic abrasives finish the internal surface effectively and precisely.

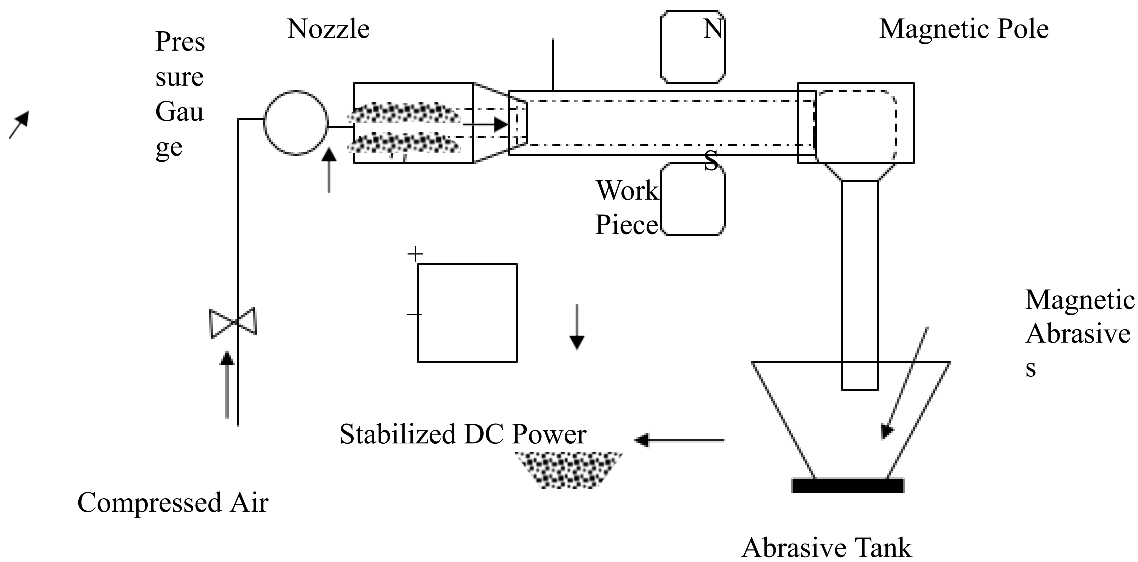
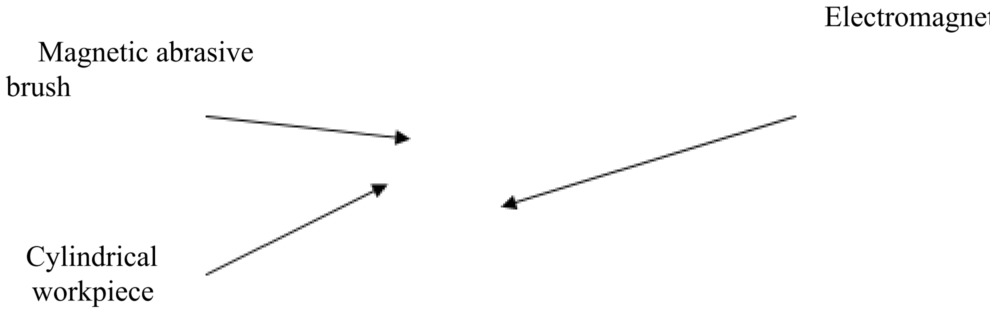
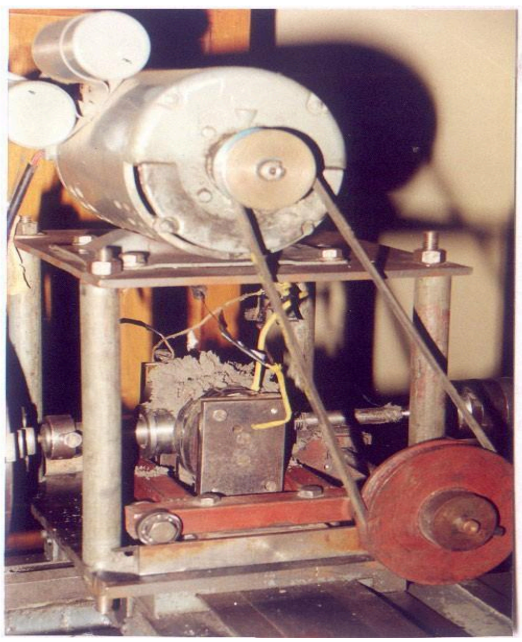



Fig. 5: Magnetic abrasive jet finishing

Fig. 6 shows a schematic of a typical MAF process in which the workpiece to be machined is located between two magnetic poles. The gap between the workpiece and the pole is filled with a magnetic abrasive powder. The magnetic abrasive grains are linked to each other magnetically between the north and south magnetic poles along the lines of magnetic force, forming a flexible 2-5 mm long magnetic brush. MAF uses this magnetic abrasive brush for surface and edge finishing. The magnetic field retains the powder in gaps, and acts as a binder causing the powder to be pressed against the surface to be finished [15]. A rotary motion is provided to cylindrical workpiece, such as ceramic bearing rollers between magnetic poles. Also axial vibratory motion is introduced in the magnetic field by the oscillating motion of magnetic poles to accomplish surface and edge finishing at faster rate and better quality.

The process is highly efficient and the removal rate and finishing rate depends on the workpiece circumferential speed, magnetic flux density, working clearance, workpiece materials, and size, type and volume fraction of abrasives. The exciting current of the magnetic coil precisely controls the machining force transferred through magnetic abrasives on the work piece.



e Finishing of cylindrical surface

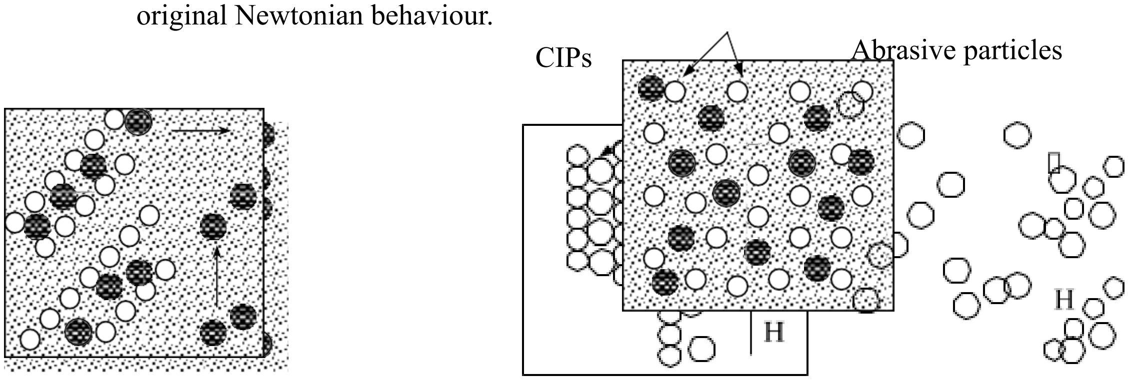
orce caused by the magnetic field is very low, a
e in the range of nano-meter) can be obtained.
re of finishing stainless steel rollers using MAF
initial Ra of 0.22 μm in 30 seconds [16].

**(MRF)**

hing high precision lenses, ceramics and
nsive and labor intensive. The primary obstacle
nses is that lenses are usually made of brittle
s to crack while it is machined. Even a single
nder a lens's performance, making it completely
ion. Every device that uses either lasers or fiber
ecision lens, increasing its demand higher than

ssified into two main processes: grinding and finishing. Grinding gets the lens close to the desired size, while finishing removes the cracks and tiny surface imperfections that the grinding process either overlooked or created. The lens manufacturer generally uses its in-house opticians for the finishing process, which makes it an arduous, labor-intensive process. Perhaps the biggest disadvantage to manual grinding and finishing is that it is non- deterministic. To overcome these difficulties, Center for Optics Manufacturing (COM) in Rochester, N.Y. has developed a technology to automate the lens finishing process known as Magnetorheological Finishing (MRF) [17].

The MRF process relies on a unique "smart fluid", known as Magnetorheological (MR) fluid. MR-Fluids are suspensions of micron sized magnetizable particles such as carbonyl iron, dispersed in a non-magnetic carrier medium like silicone oil, mineral oil or water. In the absence of a magnetic field, an ideal MR-fluid exhibits Newtonian behaviour. On the application of an external magnetic field to a MR-suspension, a phenomenon known as Magnetorheological effect, shown in Fig.7, is observed. Fig. 7a shows the random distribution of the particles in the absence of external magnetic field; In Fig. 7b, particles magnetize and form columns when external magnetic field is applied. The particles acquire dipole moments proportional to magnetic field strength and when the dipolar interaction between particles exceeds their thermal energy, the particles aggregate into chains of dipoles aligned in the field direction. Because energy is required to deform and rupture the chains, this micro-structural transition is responsible for the onset of a large "controllable" finite yield stress [18]. Fig. 7c shows an increasing resistance to an applied shear strain, $\gamma$ due to this yield stress. When the field is removed, the particles return to their random state and the fluid again exhibits its original Newtonian behaviour.




(a) (b) (c)

Fig. 7: Magnetorheological effect, (a) MRP-fluid at no magnetic field, (b) at magnetic field strength H, and (c) At magnetic field H & applied shear strain $\gamma$

Rheologically, the behaviour of MR-fluid in presence of magnetic field is described by Bingham Plastic model [19]:

$$\tau = \tau_o + \eta\dot{\gamma}$$

where, $\tau$ is the fluid shear stress, $\tau_o$ is magnetic field induced yield shear stress, $\eta$ is dynamic viscosity of MR-fluid and $\dot{\gamma}$ is Shear rate [$s^{-1}$]

The dynamic viscosity is mostly determined by the base fluid. The field induced shear stress $\tau_o$ depends on the magnetic field strength, H. The strength of the fluid (i.e. the value of static yield shear stress) increases as the applied magnetic field increases. However, this increase is non-linear since the particles are ferromagnetic and magnetizations in different parts of the particles occur non- uniformly [20]. MR-fluids exhibit dynamic field strength of 50-100 kPa for applied magnetic fields of 150-250 kA/m (~2-3 kOe) [21]. The ultimate strength of MR-fluid is limited by magnetic saturation.

The ability of electrically manipulating the rheological properties of MR-fluid attracts attention from wide range of industries and numerous applications are explored [22]. These applications are use of MR-fluid in shock absorbers and damping devices, clutch, brakes, actuators, and artificial joints. The magnetic field applied to the fluid creates a temporary finishing surface, which can be controlled in real time by varying the field's strength and direction. The standard MR fluid composition is effective for finishing optical glasses, glass ceramics, plastics and some non-magnetic metals [23]

In the Magnetorheological finishing process as shown in Fig. 8, a convex, flat, or concave workpiece is positioned above a reference surface. A MR fluid ribbon is deposited on the rotating wheel rim, Fig. 9. By applying magnetic field in the gap, the stiffened region forms a transient work zone or finishing spot. Surface smoothing, removal of sub-surface damage, and figure correction are accomplished by rotating the lens on a spindle at a constant speed while sweeping the lens about its radius of curvature through the stiffened finishing zone [24]. Material removal takes place through the shear stress created as the magnetorheological polishing ribbon is dragged into the converging gap between the part and carrier surface. The zone of contact is restricted to a spot, which conforms perfectly to the local topography of the part. Deterministic finishing of flats, spheres, and aspheres can be accomplished by mounting the part on rotating spindle and sweeping it through the spot under computer control, such that dwell time determines the amount of material removal.

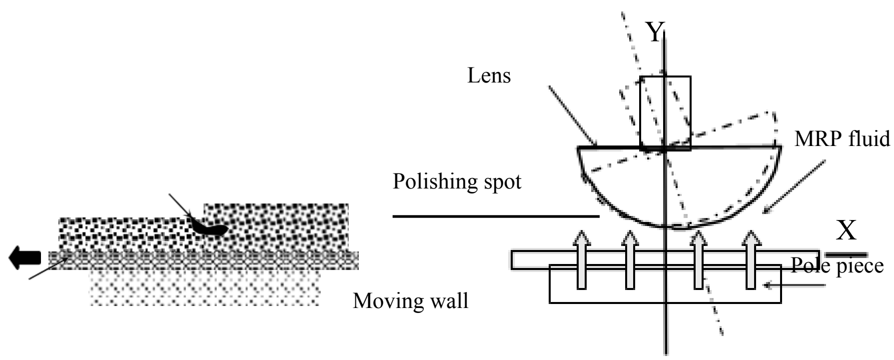



Fig. 8: Magnetorheological finishing process

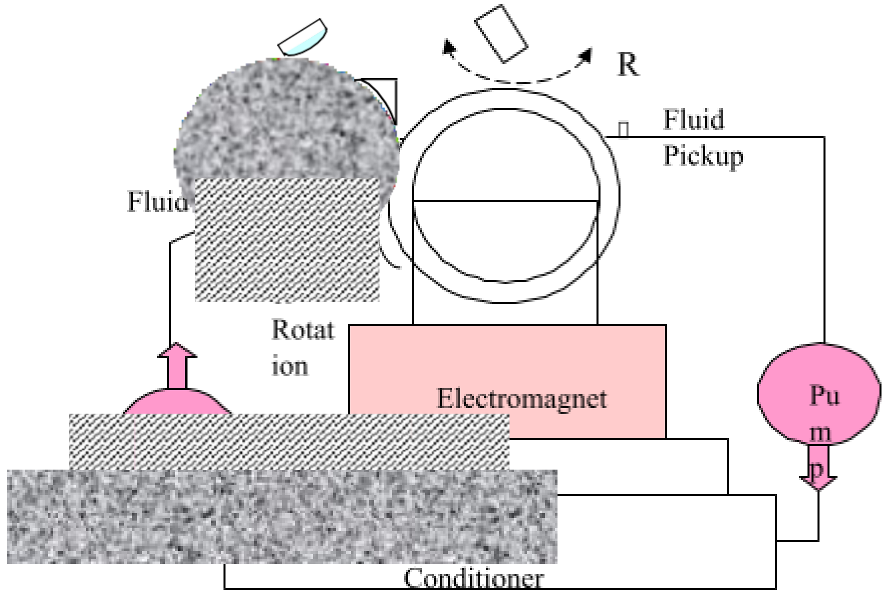



Fig. 9: A Vertical MRF Machine [24]

The MR-polishing fluid lap has following merits over traditional lap:-

1. Its compliance is adjustable through the magnetic field.
2. It carries heat and debris away from the polishing zone.
3. It does not load up as in grinding wheel.

4. It is flexible and adapts the shape of the part of the workpiece which is in its contact.

The computer controlled Magnetorheological finishing process has demonstrated the ability to produce the surface accuracy of order 10-100 nm peak to valley by overcoming many fundamental limitations inherent to traditional finishing techniques [17].These unique characteristics made Magnetorheological Finishing as the most efficient and able process for high precision finishing of optics. MRF makes finishing of free form shapes possible for first time.

Applications that use high precision lenses include medical equipment such as endoscopes, collision-avoidance devices for the transportation industry, scientific testing devices and military's night vision equipment like infrared binoculars. Missiles are equipped with a wide variety of high precision lenses for navigation, target location, and other functions. The nano diamond doped MR fluid removes edge chips, cracks, and scratches in sapphire bend bars.

## 1.4 Magnetorheological Abrasive Flow Finishing (MRAFF)

In AFM, the polishing medium acts as compliant lap and overcomes shape limitation inherent in almost all traditional finishing processes. As abrading forces in AFM process mainly depend on rheological behaviour of polymeric medium, which is least controllable by external means, hence lacks determinism. The process named as Magnetorheological finishing described above, uses magnetically stiffened ribbon to deterministically finish optical flats, spheres and aspheres. In order to maintain the versatility of Abrasive Flow Machining process and at the same time introducing determinism and controllability of rheological properties of abrasive laden medium, a new hybrid process termed as "*Magnetorheological Abrasive Flow Finishing (MRAFF)*" is used, Fig. 10 [25]. This process relies on smart behaviour of magnetorheological fluids whose rheological properties are controllable by means of external magnetic field.

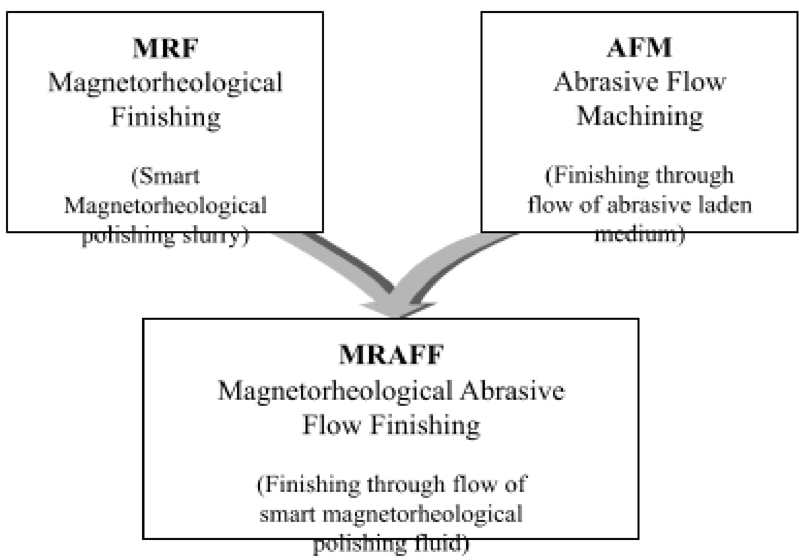
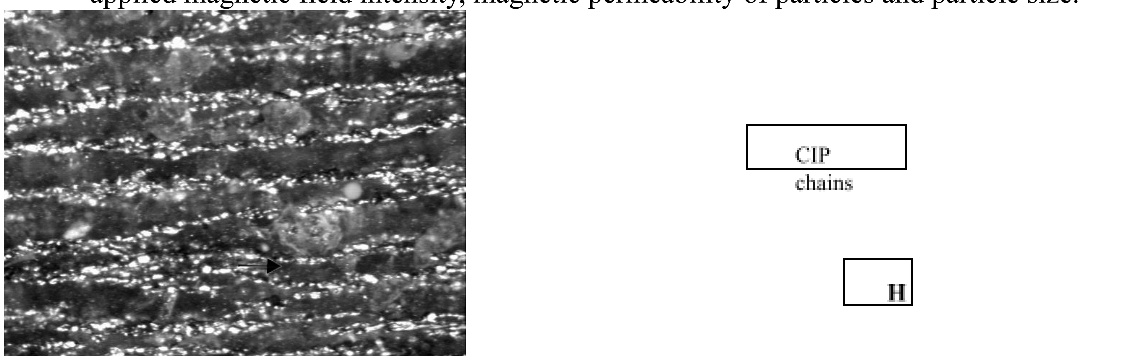



Fig. 10: Development of Magnetorheological Abrasive Flow Finishing process [25]

The use of magnetorheological polishing fluid with cerium oxide abrasives for finishing optical lenses up to the level of 0.8 nm R.M.S. (root mean square) value has already been demonstrated by MRF process [17]. MRAFF process has the capability of finishing complex internal geometries up to nanometer level. It imparts better control on the process performance as compared to AFM process due to in-process control over abrading medium’s rheological behaviour through magnetic field.

Magnetorheological (MR) fluids, invented by Rabinow [26] in late 1940s, belong to a class of smart controllable materials whose rheological behaviour can be manipulated externally by the application of some energy fields. The ability to electrically manipulate the rheological properties of MR-fluid attracts attention from a wide range of industries, and numerous applications are explored [27]. These applications include shock absorbers, damping devices, clutches, brakes, actuators, and artificial joints.

Magnetorheological polishing fluid comprises of MR-fluid with fine abrasive particles dispersed in it. On the application of magnetic field the carbonyl iron particles (CIP) form a chain like columnar structure with abrasives embedded in between. Figs. 11a & 11b show actual photographs taken by optical microscope for the case when no magnetic field is applied and the structure formed in the presence of magnetic field respectively. The magnetic force between iron particles encompassing abrasive grain provides bonding strength to it and its magnitude is a function of iron concentration, applied magnetic field intensity, magnetic permeability of particles and particle size.




(a) (b)

Fig. 11: Chain formation in Magnetorheological polishing fluid, (a) abrasives & carbonyl iron particles at zero magnetic field, (b) abrasive particles embedded in carbonyl iron particle chains on application of external magnetic field

In MRAFF process, a magnetically stiffened slug of magnetorheological polishing fluid is extruded back and forth through or across the passage formed by workpiece and fixture. Abrasion occurs selectively only where the magnetic field is applied across the workpiece surface, keeping the other areas unaffected. The mechanism of the process is shown in Fig 12. The rheological behaviour of polishing fluid changes from nearly Newtonian to Bingham plastic upon entering and Bingham to Newtonian upon exiting the finishing zone. The abrasive (cutting edges) held by carbonyl iron chains rub the workpiece surface and shear the peaks from it, Fig. 13. The amount of material sheared from the peaks of the workpiece surface by abrasive grains depends on the bonding strength provided by field-induced structure of MR-polishing fluid and the extrusion pressure applied through piston. In this way magnetic field strength controls the extent of abrasion of peaks by abrasives.

The viscosity of smart magnetorheological polishing fluid (MRPF) is a function of applied magnetic field strength, and it is varied according to the desired finishing characteristics. The shearing of the Bingham plastic polishing fluid near the workpiece surface contributes to the material removal and hence finishing. Extrusion of the MRP-fluid through the passage formed in the workpiece fixture is accomplished by driving two opposed pistons in MRPF cylinders using hydraulic actuators operated in desired manner with the help of designed hydraulic circuit, Fig. 14.

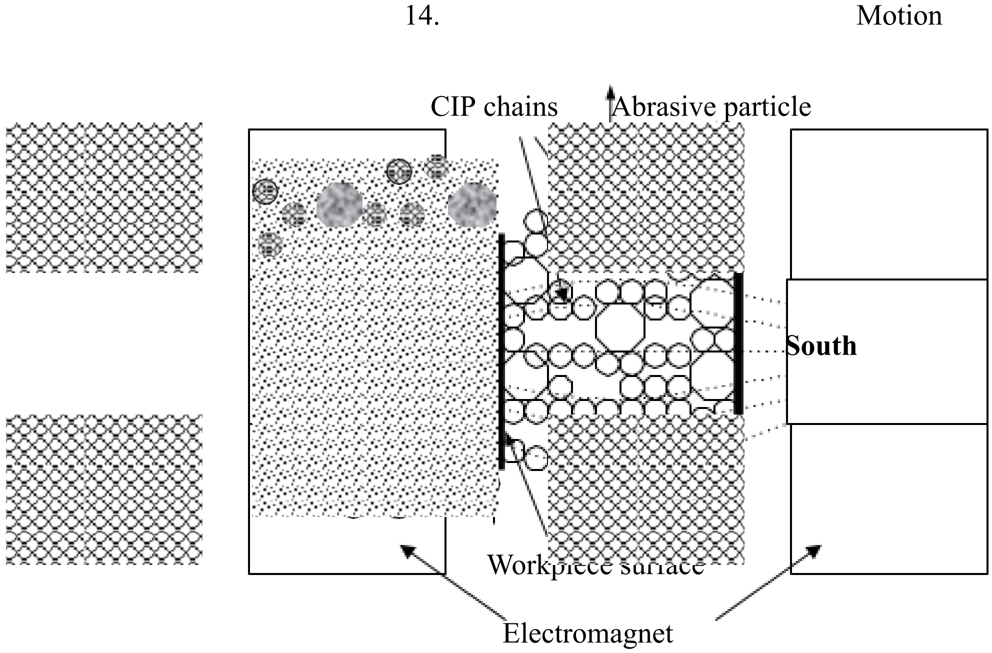



Fig. 12: Mechanism of MRAFF process [25]

The role of magnetic field strength in MRAFF process is clearly distinguished in Fig.15, as at no field conditions no improvement in surface finish is observed and the improvement is significant at high magnetic field strength. This is because, in the absence of magnetic field the carbonyl iron particles and abrasive particles flow over the workpiece surface without any finishing action due to absence of bonding strength of CIPs. As the magnetic field strength increased by increasing magnetizing current, carbonyl iron particles chains keep on holding abrasives more firmly and thereby result in increased finishing action. Even 0.1521 Tesla field is capable of removing to some extent, loosely held ploughed material left after grinding process and expose the actual grinding marks made by abrasives.

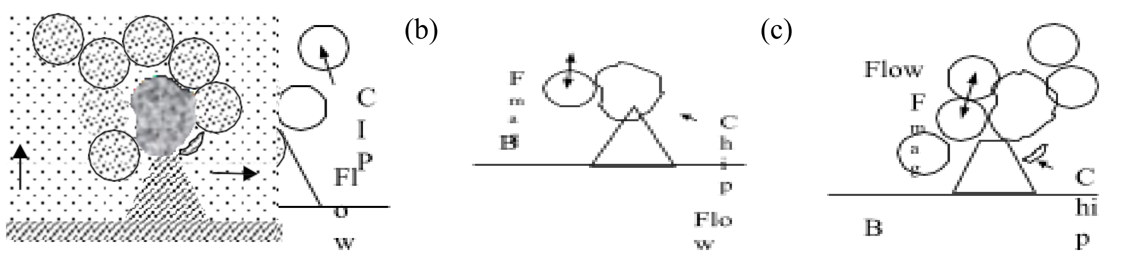



Fig.13: Finishing action on a single profile in presence of external magnetic field
(a) Abrasive grain along with CIP chains approaching roughness peak, (b) Abrasive grain takes a small cut on roughness peak in presence of bonding forces, (c) Abrasive grain crossing the roughness peak after removing a microchip during cutting action.

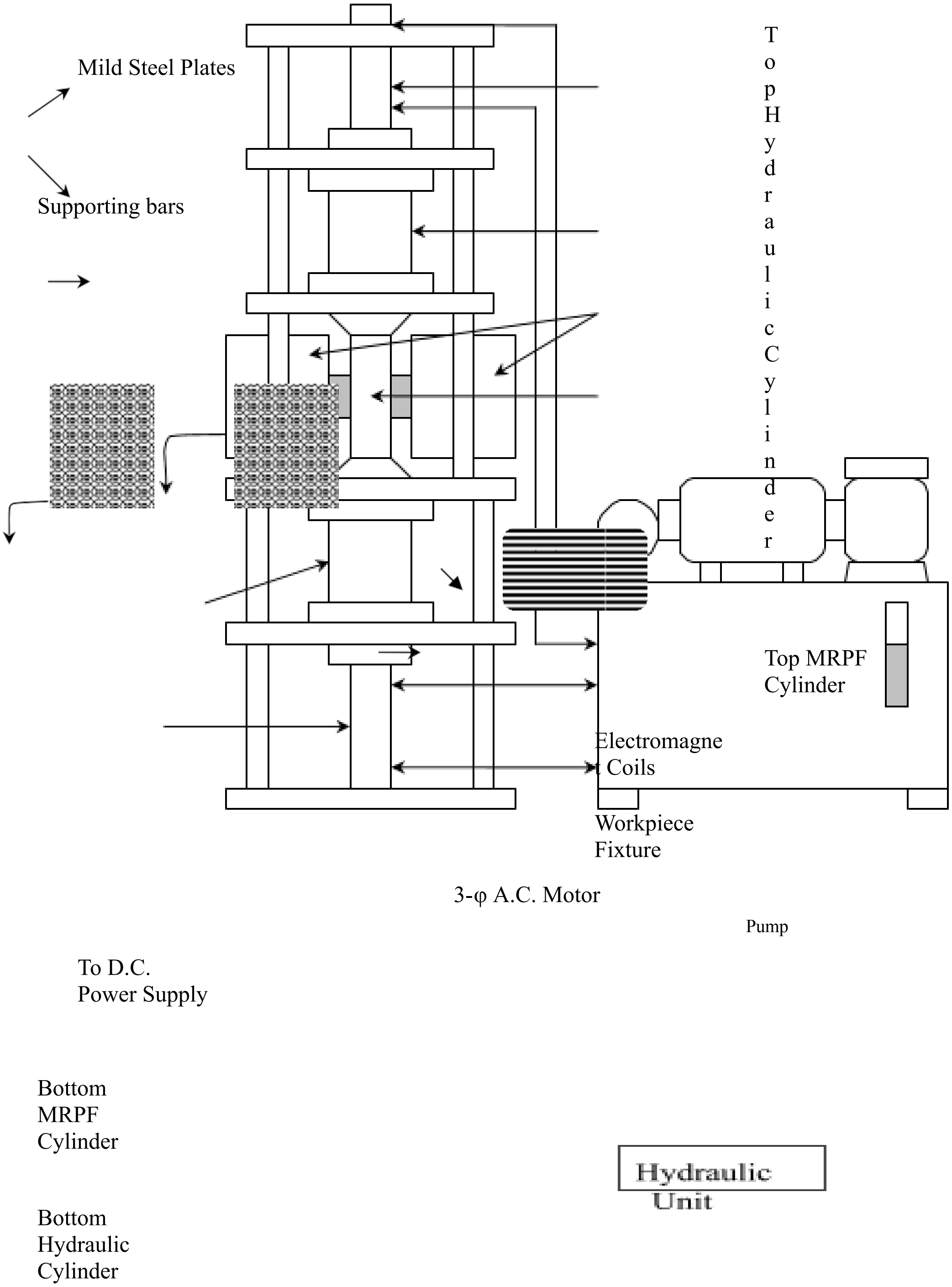
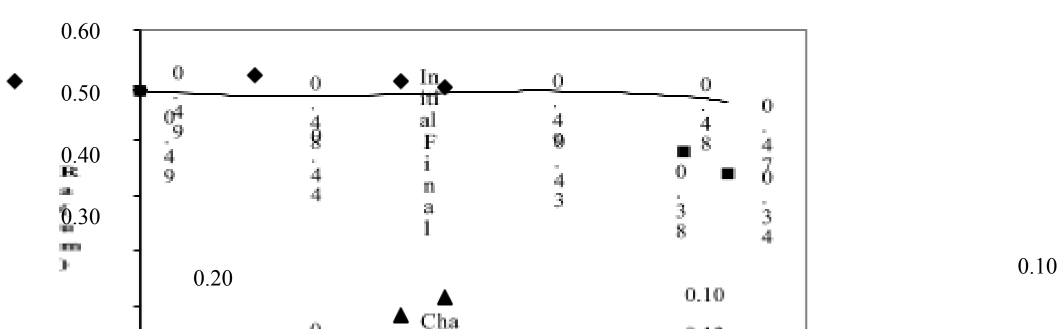



Fig. 14: Schematic of MRAFF Machine [25]



0.00

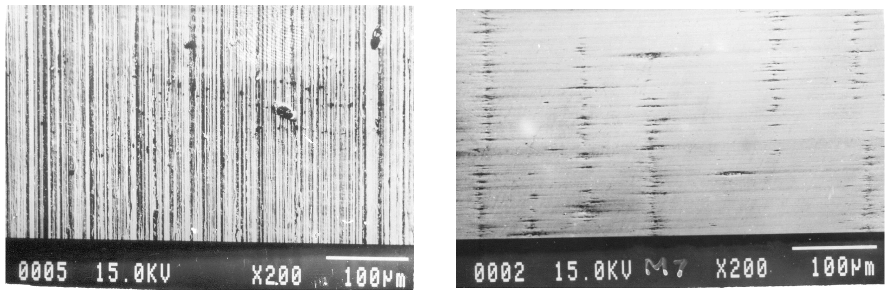
0 0.05 0.1

0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65

**Magnetic Flux Density, B (Tesla)**

Fig. 15: Effect of magnetic flux density on Ra value [25]

Depths of initial grinding marks were reduced progressively as the experiments were performed at higher flux density, reducing asperities. Fig. 16(a) shows the initial closely spaced grinding marks before MRAFF, which were sparsely located as shown in Fig. 16(b) after finishing for 200 cycles at 0.574 Tesla [25]. The other process variables that affect performance of MRAFF are number of finishing cycles, extrusion pressure and MRP-fluid composition. The relative particle size of abrasives and CIP plays an important role in finishing action.




(a) (b)

Fig. 16: Comparison of surface before and after MRAFF, (a) Initial surface before MRAFF, (b) Final surface after MRAFF for 200 cycles at B = 0.574 T [25]

### 3.4 Magnetic Float Polishing (MFP)

The applications of advanced ceramics are limited because of their poor machinability and difficulties involved in processing them into useful shapes. Ceramics are extremely sensitive to surface defects resulting from grinding and polishing processes. Since fatigue failure of ceramics is driven by surface imperfections, it is of utmost importance that the quality and finish of the elements of ceramic bearings be superior with minimal defects. For this gentle and flexible polishing conditions like low level of controlled forces and use of abrasives softer than workmaterial are required.

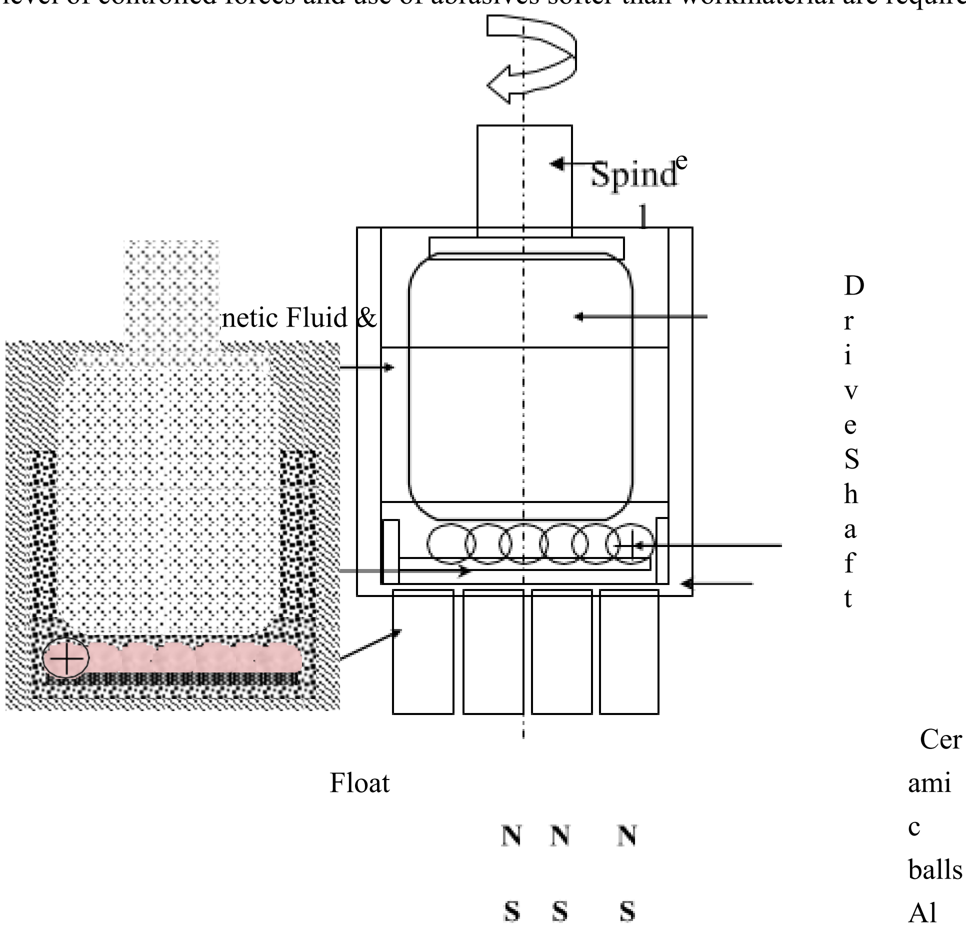


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Fig. 17: Schematic diagram of the magnetic float polishing apparatus [30]

A recent advancement in fine abrasive finishing processes involves the use of magnetic field to support abrasive slurries in finishing ceramic balls and bearing rollers, and the process is known as Magnetic Float Polishing (MFP). The magnetic float polishing technique is based on the ferro-hydrodynamic behaviour of a magnetic fluid that can levitate a non-magnetic float and abrasives suspended in it by magnetic field. The levitation force applied by the abrasives is proportional to the field gradients and are extremely small and highly controllable. It can be a very cost- effective and viable method for superfinishing of brittle materials with flat and spherical shapes. The schematic diagram of the magnetic float polishing apparatus used for finishing advanced ceramic balls is shown in Fig. 17. A magnetic fluid containing fine abrasive grains and extremely fine ferromagnetic particles in a carrier fluid such as water or kerosene fills the aluminium chamber. A bank of strong electromagnets is arranged alternately north and south below the chamber. On the application of magnetic field the ferro fluid is attracted downward towards the area of higher magnetic field and an upward buoyant force is exerted on non-magnetic material to push them to the area of lower magnetic field [28].

The buoyant force acts on a non-magnetic body in magnetic fluid with magnetic field. The abrasive grains, the ceramic balls, and the acrylic float inside the chamber all being of non-magnetic materials, are levitated by the magnetic buoyant force. The drive shaft is fed down to contact the ball and presses them down to reach the desired force level. The balls are polished by the relative motion between the balls and the abrasives under the influence of levitation force and resistance [29].

Both higher material removal rate and smoother surface in this polishing method, are attained by stronger magnetic field and finer abrasives. Magnetic Float polishing is used to finish 9.5 mm diameter $Si_3N_4$ balls. $Si_3N_4$ is considered as a candidate material for high-speed hybrid bearing in ultra high-speed precision spindles of machine tools or in jet turbines of aircraft [31]. Conventional polishing of ceramic balls generally uses low polishing speeds (a few hundred rpm) and diamond abrasive as a polishing medium. In practice, it takes considerable time (some 12-15 weeks) to finish a batch of ceramic balls. The long processing time and use of expensive diamond abrasive result in high processing costs. Also, the use of diamond abrasive at high loads can result in deep pits, scratches, and micro cracks. To minimize the surface damage, 'gentle' polishing conditions are required, namely, low level of controlled force and abrasives not much harder than the work material. The magnetic float polishing (MFP) process easily accomplishes this. The surface finish obtained was 4 nm Ra and 40 nm Rmax. The best sphericity obtained of the $Si_3N_4$ balls was

0.15 to 0.2 μm. Finished surfaces relatively free of scratches, pits, etc. were obtained.

### 3.5 Elastic Emission Machining (EEM)

Though this process was developed as early as in 1976 [32], it attracts the attention because of its ability to remove material at the atomic level by mechanical methods and to give completely mirrored, crystallographically and physically undisturbed finished surface.

The material removal in conventional machining is in part due to the deformation or fracture based on migration or multiplication of pre-existing dislocations, or by the enlargement of cracks originating from pre-existing micro cracks. Consequently, the limit of the surface finish is determined by the distance between these defects. If the material removal can occur on atomic size units, then the finish generated can be close to the order of atomic dimensions (~0.2 nm to 0.4 nm). Using ultra fine particles to collide with the workpiece surface, it may be possible to finish the surface by the atomic scale elastic fracture without plastic deformation [33]. This new process is termed as Elastic Emission Machining (EEM). Mori et al. established theoretically and experimentally that atomic scale fracture can be induced elastically and the finished surface can be undisturbed crystallographically and physically [34]. The rotating sphere and workpiece interface in elastic emission machining is shown in Fig. 18.

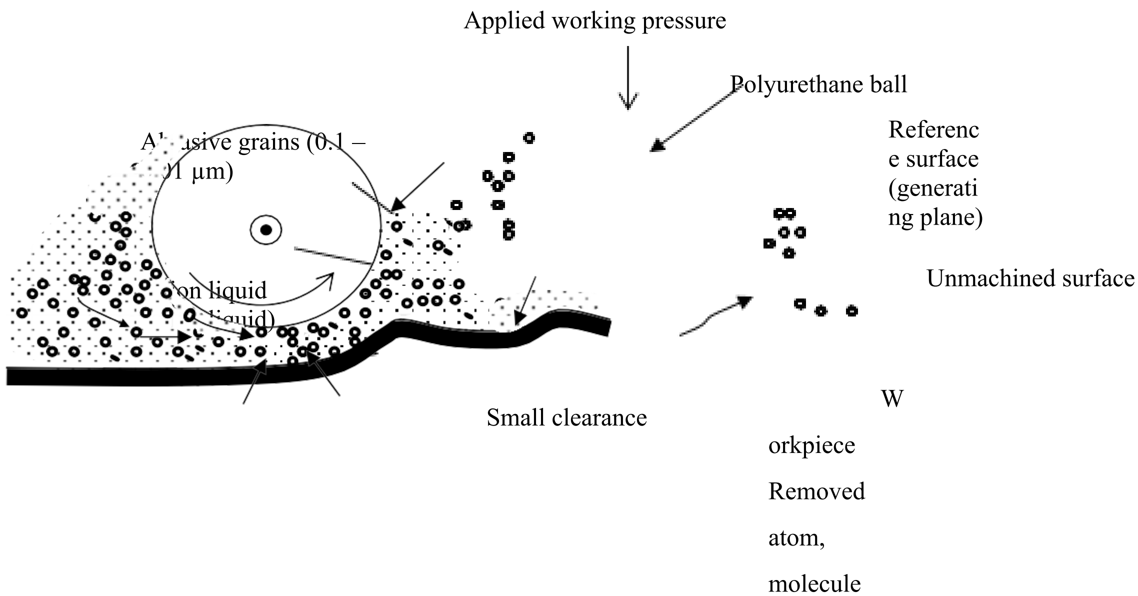



Fig. 18: Rotating sphere and workpiece interface in EEM [32]

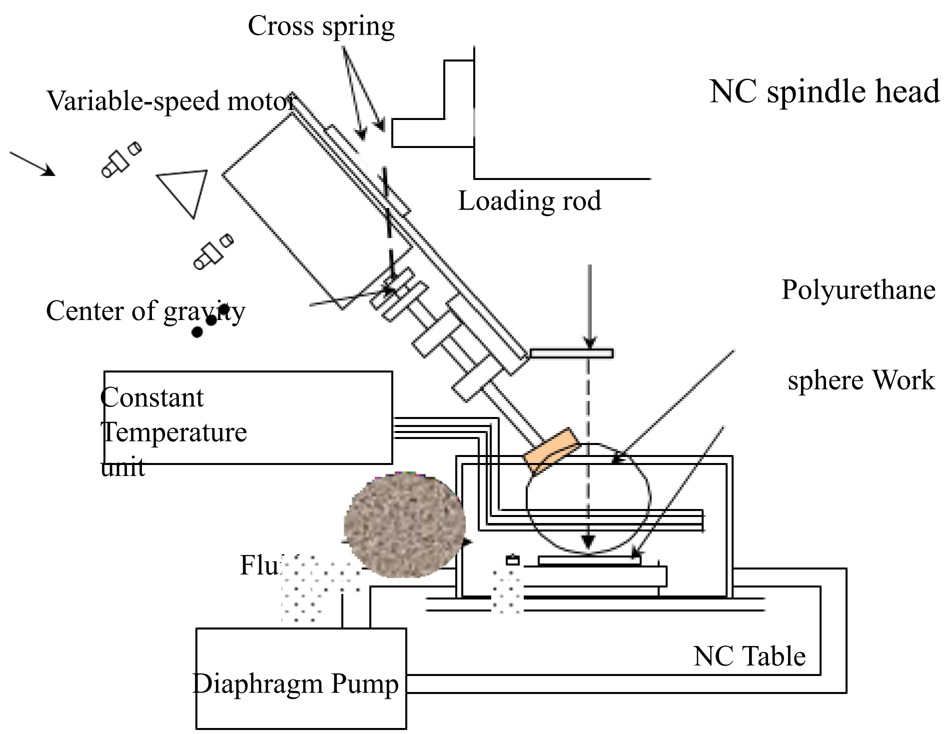


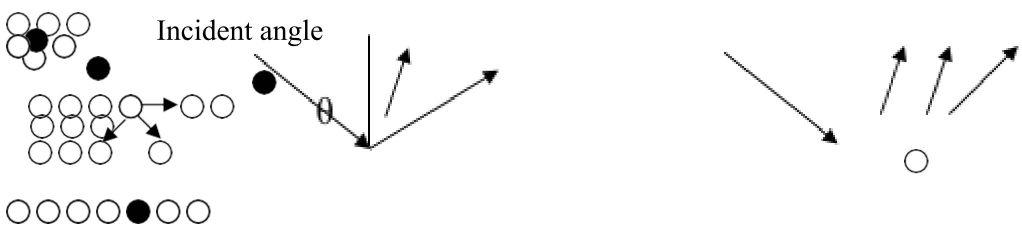
Fig. 19: Schematic of EEM assembly used on NC Machine [34]

In the EEM process a polyurethane ball, 56 mm in diameter, is mounted on a shaft driven by a variable speed motor (Fig 19). The axis of rotation is oriented at an angle of ~ 45º relative to the surface of the workpiece to be polished. The workpiece is submerged in slurry of $ZrO_2$ or $Al_2O_3$ abrasive particles and water. The material removal rate for the workpiece was found to be linear with dwell time at a particular location, allowing the total thickness of material removed to be controlled to within 20 nm. The removal rate, however, was found to vary non-linearly with concentration of abrasives in the slurry. The proposed mechanism of material removal due to slurry and workpiece interaction involves erosion of the surface atoms by the bombardment of abrasive particles without the introduction of dislocations. Surface roughness as low as 0.5 nm rms have been reported on glass and a surface roughness of ≤ 1nm rms was obtained when polishing single crystal Silicon. Mori et al. found out that the material removal process is a surface energy phenomenon in which each abrasive particle removes a number of atoms after coming into contact with the surface [35]. The type of abrasives used has been found to be critical to the removal efficiency.

### 3.6 Ion Beam Machining (IBM)

Ion Beam Machining (IBM) is a molecular manufacturing process based on the sputtering off phenomenon of materials of the workpiece due to bombardment of energized ions of 1 to 10 keV and current density of $1mA/cm^2$. It removes atom or molecules at a time from the surface of the workpiece. The Ion beam machining is one of the most precise and fine machining method because of its basis of action on atomic size stock removal.

The sputtering off is basically a knocking out phenomenon of surface atom of the workpiece due to the kinetic momentum transfer from incident ions to target atoms. Removal of atoms will occur when the actual energy transferred exceeds the usual binding energy of 5-10 eV [36]




(a) Low energy Ideal case (b) High energy Ion implantation Fig. 20: Schematic illustration of the mechanism of material removal in IBM

Ions of higher energy may transfer enough momentum to more than one atom to cause a cascading effect in the layers near the surface, removing several atoms. At sufficiently high energy, cascading events will penetrate more deeply into the solid, several atoms, or molecules will be ejected out and the bombarding ion will become implanted deep within the material Fig. 20(b). Many microscopic damage centers will result from the energetic displacements of the atoms. Clearly it is not desirable from surface quality point of view. The low energy case is more likely a simulated sublimation of ions from the surface.

The sputtering yield is the most important machining characteristic of ion beam machining. The sputtering yield $S$ is defined as the mean number of atoms sputtered from the target surface per incident ion. The sputtering yield $S$ depends on the material being machined, the bombarding atoms and their energy, ion incidence angle to the target surface and the crystal face of the target. In order to describe the ion beam machining characteristic more practically, the concept of the specific sputter machine rate $V(\theta)$ [(µm/h)/(mA/cm²)] has been introduced. The relation between the sputtering yield $S$ and the sputter machine rate $V(\theta)$ is represented as [37]:

$$V(\theta) = 576\times10^{9}\,\frac{S(\theta)}{n}\times\cos\theta \quad (\mu m/h)/(mA/cm^2)$$

where, n is the atomic density of the target material in atoms/cm², and cosθ term accounts for the reduced current density at an angle θ to the normal, Fig. 20(a). Therefore if the sputter machine rate is obtained experimentally, the sputtering yield can be calculated.

Workpiece material, ion etching gas, angle of incidence, ion energy and current density are identified as the main factors affecting machining characteristics in IBM. Sputtering yield is a function of atomic number, binding energy, grain size, number of electron shell [38] etc. of the workpiece material and atomic weight of the incident ions. Ions having high atomic number will yield high MRR. Since the sputtering yield is related to the binding energy of the materials being etched it is possible to vary its value by introducing reactive gases. The reactive gases can react with the etched surface, vary binding energy and consequently vary the etch rate. The ion incidence angle at which the maximum sputtering yield occurs increases when the bombarding ion energy or its mass increases. The reason for this is that as the ion incidence angle increases, more atoms of the work piece can be knocked out or sputtered away easily from the two or three atomic layers of the surface of workpiece. However, when the ion incidence angle further increases, the machining rate begins to decrease because the ion current density for unit working area decreases by cosθ and the number of ions reflected from the surface of the workpiece without sputtering off atoms increases.

Success of ion beam polishing depends crucially on the grain size and initial morphology of the surface. With very small grain size, the machining rate of each grain will be almost the same, and therefore uniform machining over the surface will take place. For large grain size, the difference between the machining rates of the grains results in the increase in value of surface roughness [39]. The change in surface roughness with current density and energy behaves almost the same way as the machining depth.

Ion beam machining is ideal process for nano-finishing of high melting point and hard brittle materials such as ceramics, semiconductors, diamonds etc. As there is no load on the workpiece while finishing, it is suitable for finishing of very thin objects, optics and soft materials such as $CaF_2$. Diamond styli for profilometer were sharpened using Kaufman type ion source. Argon ion beam of an energy E=10keV and ion current density of 0.5 mA/cm² was used to sharpened the styli to the tip radius of 10 nm [40].

### 3.7 Chemical Mechanical polishing (CMP)

Chemical Mechanical Polishing (CMP) is the fastest growing process technology in the semiconductor manufacturing. CMP is a planarization process which involves a combination of chemical and mechanical actions. The importance of each contribution depends on the polished material. It was developed at IBM in the mid- 1980s as an enabling technology to planarize $SiO_2$ interlevel dielectric (ILD) layers so that three or more levels of metal could be integrated into a high-density interconnect process. This technology was adapted from silicon wafer polishing. By employing CMP, subsequent structures could he fabricated on a nearly planar surface. The initial application of CMP was ILD planarization, but its application to other areas in the overall semiconductor fabrication sequence followed quickly. A similar variant is Chemo-Mechanical polishing in which driving factor for material removal is chemical action between abrasives and the workmaterial under the polishing condition followed by mechanical action for the removal of reaction products [41]. In chemical mechanical polishing, the reaction is between the fluid and the workmaterial and the abrasive removes the reaction product by mechanical action [42] .

Chemo-mechanical polishing is expected to overcome many problems of surface damage associated with hard abrasives, including pitting due to brittle fracture, dislodgement of grains, scratching due to abrasion, etc. , resulting in smooth, damage free surfaces [43].

A schematic of CMP planarization process is shown in Fig. 21. The wafers are pressed face down by carriers and rotated agains a polishing pad covered with a layer of silica slurry.

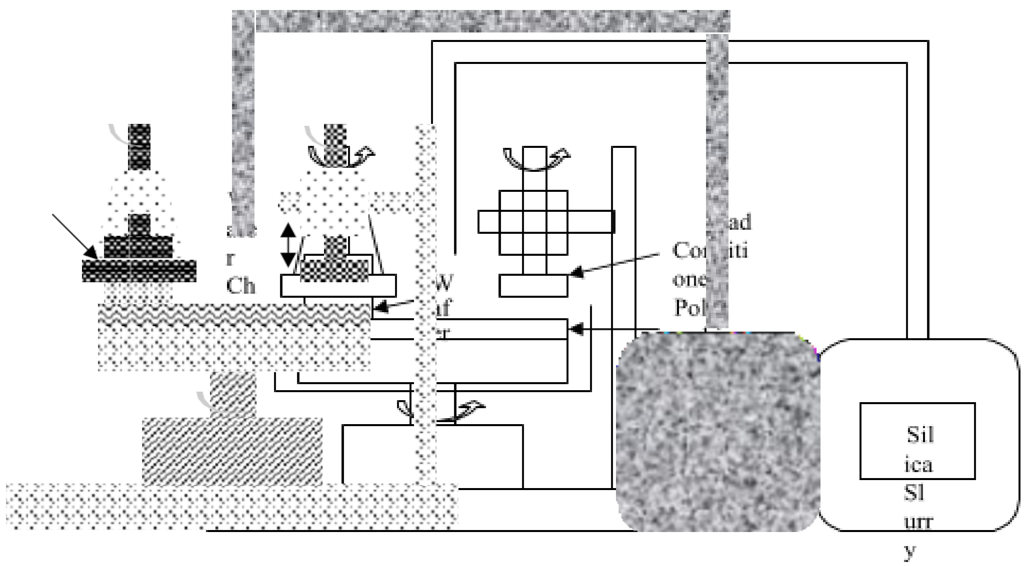



Fig. 21: Schematic of CMP planarization process equipment [44]

The polishing pad on rotating plate is used to hold the slurry particles, transmit load to the particle-wafer interface, and conform precisely to the wafer being polished. Aqueous colloidal silica suspension is widely used for polishing. Initial chemical reaction of silicon with the aqueous solution form a thin silica layer and this is then mechanically removed by the polishing slurry. The thin layer of silica reduces the friction force, provide uniform distribution of slurry particles and remove eroded material and heat generated. During CMP, the kinetic energy of the slurry particles moving between the wafer and the pad erode the surface of the wafer.

CMP has been used for a long time in manufacturing of silicon wafers. CMP results in defect free surfaces in contrast to mechanically polished surfaces [45]. From the most advanced 200 mm and 300 mm manufacturing processes simultaneous double side polishing is used [46]. Double side polishing gives a better parallelism compared to single side polishing and less adherence of particles since both sides are smooth. Another use of CMP substrate is in thin film transistor (TFT) technology [47]. In TFT, used for instance for making flat displays, polycrystalline silicon is deposited on glass substrates. To obtain more global planarization in contrast to local, CMP was introduced to planarize the deposited interlevel dielectric (ILD) oxide layers in metal interconnection layers. CMP for ILD planarization is used in the aluminum wiring – tungsten plug interconnection technology.