Advances and Processes in Precision Glass Polishing Techniques

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1. **Introduction:** Advanced optical designs require shapes and materials that are challenging to finish. As designs become more intricate, new fabrication tools and techniques are needed. We discuss a general overview of some precision polishing methods and advanced surface-finishing methods that enables precision fabrication of flats and spheres as well as increasingly complex optics, such as aspheric and freeform shapes.

2. **Classification of glass:** We start with a basic classification of the most commonly used optical glass with the precision and advanced applications.

2.1 **Fused Silica** is the purest form of Silicon Dioxide (SiO_2). This glass has superior transmission in both the UV and IR spectra, a very low dielectric coefficient and excellent properties where fluorescence or solarization are an issue. Unlike sapphire (a crystalline structure, not amorphous) fused silica can be shaped to many forms and sizes. It has excellent resistance to non-fluorinated acids, solvents and plasmas. Heraeus and Nikon both produce extremely high grade (pure) Fused Silica glasses that exhibit excellent ultraviolet and infrared performance. Where purity, a non-reactive, durable substrate and homogeneity between melts (uniform optical properties) are needed, this high quality material is the likely choice.

2.2 **Bk7** is a barium borosilicate glass known for its high transmission and clean, clear appearance. It is by far the most common material for many optical glass applications, because it offers good optical properties and a reasonable price. It's used often as a standard of comparison for other glass materials.

2.3 **Borofloat** is a particular Schott Borosilicate Glass. It is characterized by excellent flatness and better resistance to heat. These characteristics make Borofloat more costly than float glass, but borosilicates retain shape and handle thermal shock better than other, less expensive glasses.

2.4 **B270** or **Crown Glass** or 'water white' has good optical transmission, and appears crystal clear as a result of fewer impurities. It can be polished and readily accepts all types of coatings.

2.5 **GE 124 & NSG OZ** are **Fused Quartz** glasses. Fused quartz is used in applications where good ultraviolet light transmission, very good thermal stability and chemical inertness (resistance to stains) are required. Fused Quartz is harder and more difficult to polish than borosilicate, so the cost is higher. For applications where prolonged or periodic temperatures are more extreme or there is a need for higher purity, fused quartz is an appropriate choice.

2.6 **Soda Lime**, also called **'Float Glass'** is a common, inexpensive substrate. Float glass is a sheet of glass made by floating molten glass on a bed of molten tin. This method gives the sheet uniform thickness and very flat surfaces. The oldest glass, float glass can appear with a slight greenish or blue tint, depending upon the amount of iron and other elements. It is easily tempered to increase strength.

2.7 **Zreodur** is a glass-ceramic made by Schott AG. It has both an amorphous (vitreous) component and a crystalline component. It is mainly used in many optical devices such as telescopes and optical cavities require a substrate material with a near-zero coefficient of thermal expansion ($\sim 0.02 \times 10^{-6}$/K at 0-50°C) and/or excellent thermal shock resistance.

3 **Classification of Glass Polishing Methods:** A small classification table here gives an idea of basic procedures that are used for precision polishing of glass.

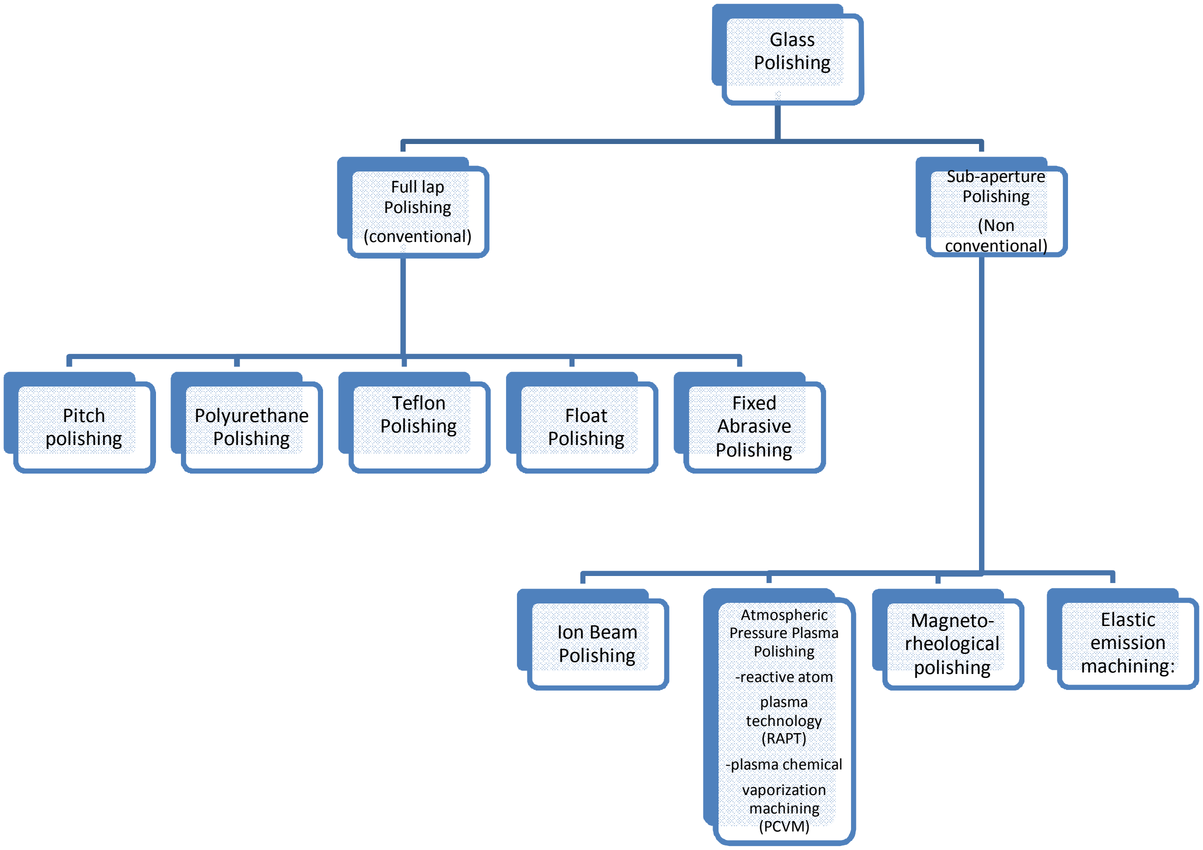


Table 1. Classification of polishing methods

3.1 Full Lap Polishing Processes (Conventional Methods)

Principle: There are three popular theories of glass polishing. Hooke, Newton and Rayleigh proposed the 'wear theory', which says that the polishing takes place by the mechanical wear of the abrasives and the surface of glass. In short it is an extension of grinding. This is also called the 'hypothesis of abrasion'. The other theory is 'flow theory' or 'flow hypothesis', which says that the polishing compounds can be used to form amorphous layer of glass that can be smeared to fill the voids of the glass surface was proposed by Beilby . Finally, Preston and Grebenshchikov advanced the 'chemical theory' or 'chemical hypothesis. The actual material removal rate in the glass depends on chemical durability of glass rather than micro-hardness or softening point of glass. As stated by Izumitani, there is no bulk material removal but just the soft hydrated layer is removed instead. There is a chemical reactivity between glasses, sometimes the lap and always with the polishing compounds that is a mix of water, polishing powder and additives. But as the wear on the polishing pads takes place, the amount of energy put in is reduced and hence the material removal rate. The SiO_2 film surface is first reacted with Cerium Oxide (CeO_2) particles and bonding of Si-O-Ce is formed. Then there is mechanical tearing of those bonds leading to SiO_2 removal instead of removal of lumps of Silicon Hydroxide ($Si(OH)_4$). [2]

3.1.1 Pitch Polishing:

It is one of the most historic processes and has been used since ages. Pitch is a very complex material. There is limited information in the literature regarding the composition and properties of optical polishing pitch. Compositions are mostly proprietary. It is generally understood that the material consists of various amounts of the following: residues distilled from tar, oil, or wood; rosin, a derivative of turpentine which comes from sap of pine trees or stumps, to increase melting point and tackiness; beeswax or linseed oil to lower melting point; asphalt; flake shellac; paraffin wax; wood flour; or walnut shell flour. Properties of importance are viscosity (stated to be in the range of 10^7 to 10^9 Pa·s), softening point, (55-70 °C), penetration hardness (60-80 by Shore D), coefficient of friction (tackiness), and groove pattern. After the glass is ground, it is fitted into an already spherical visco-plastic pitch lap. Now any tangential force that will be applied to the workpiece will cause it to slide on the lap surface which also wetted with a slurry containing abrasive. Here the high spots are under more pressure and hence they are removed preferentially and hence the spherical surface is obtained almost automatically. The abrasives could be Silicon Carbide (SiC) (rough grinding) or Aluminium oxide (Al_2O_3) (fine grinding) and compounds like cerium oxide (CeO_2), zirconium oxide, barnesite or red rouge for polishing. The surface roughness that can be obtained is 5.7Å RMS for BK7 with Al_2O_3 and 2.6Å with CeO_2, 8Å for flint glass with Al_2O_3 and 0.8Å with CeO_2.[2]

Advantages: High metal removal rate, lap can be produced in hours.
Disadvantages: Lap has to be frequently checked and corrected, pitch is volatile and sometimes acts as a fluid, the abrasive media used can sometimes be reactive with the surface.

3.1.2 Polyurethane Polishing:

Basically introduced in the 80s by Carl Zeiss optics, it was used due to the need of high speed and more and more accuracy needed in the advanced field of engineering. Pitch and cloth were replaced by highly wear resistant polyurethane polishing pads. The polyurethane lap is trued to the shape desired on the workpiece surface. Then during polishing this master shape is copied on the workpiece at high speeds. The rigid lap does not flow and so a fairly high number of workpieces can be machined by one lap before regrinding and there is no interruption due to necessary refurbishing of the instruments. Same slurry as the one used in pitch polishing is used here. Polyurethane may perform better than pitch from the viewpoint of the MRR (MRR, 10 µm/h for BK7 and 4 µm/h for fused silica; surface roughness, RMS less than 1 nm for both, 300 mesh size CeO_2. [3]. The basic setup of polyurethane polishing is shown in fig. 1. It is a PPS100 model, North Tiger Company, China. Polishing pad is the polyurethane pad and the slurry is the same as that for pitch polishing.

Advantages: Respectable MRR compared to pitch polishing, better surface obtained compared to pitch polishing.
Disadvantages: Occasionally small pits and depressions.

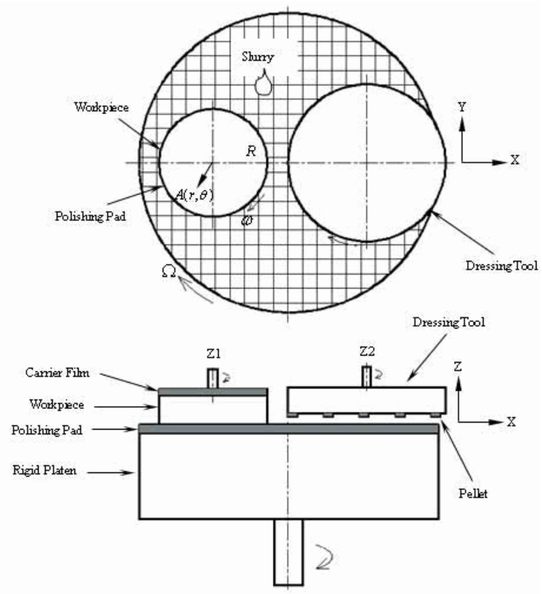


Fig 1. Schematic of PPS100 for Polyurethane Polishing [3]

3.1.3 Teflon Polishing:

This is a fine polishing technique which has a really low MRR. Before polishing a surface on Teflon, it must be polished using a pitch so that it will remove all the imperfections and all the grinding marks. If not done so, the residual roughness for the surface will abrade the Teflon. A typical Teflon lap is made on a Zerodur substrate by cutting two sets of parallel grooves at right angles to each other to produce facets approximately. A Teflon film, very thin, is built on top of the facets. After coating is completed, the existing residual thickness difference of the Teflon layer from facet to facet is eliminated by rubbing with a ground-glass (e.g., fused silica) conditioning plate. No abrasive is used for this operation; it is the roughness of the flat ground-glass plate that abrades the Teflon. A photograph of a Teflon lap and its setup with a workpiece in the holder is shown in fig. 2. This process is carried out in stages with the conditioning plate ground initially with a 70-µm abrasive and then with successively finer abrasives down to 15 µm. At the final stage, the conditioning plate will produce a specularly reflecting surface at normal incidence on the Teflon lap. Producing a flat Teflon surface before polishing commences is a most important part of the technique because Teflon, unlike pitch, does not flow; once the lap is flat it will remain flat for long periods (e.g., months). Here same abrasives are used as the ones for pitch polishing. The surface average roughness that can be achieved is 1.8Å for Zerodur with Al_2O_3 abrasive and 47.8 Å with CeO_2, 0.8 Å for BK7 with Al_2O_3. [2]

Advantages: Long life of lap (12-18 months between dressings), stable surface shape, no restriction on type of polishing agent, inert so does not enter polishing agent.
Disadvantages: Lap production takes days, Low MRR.

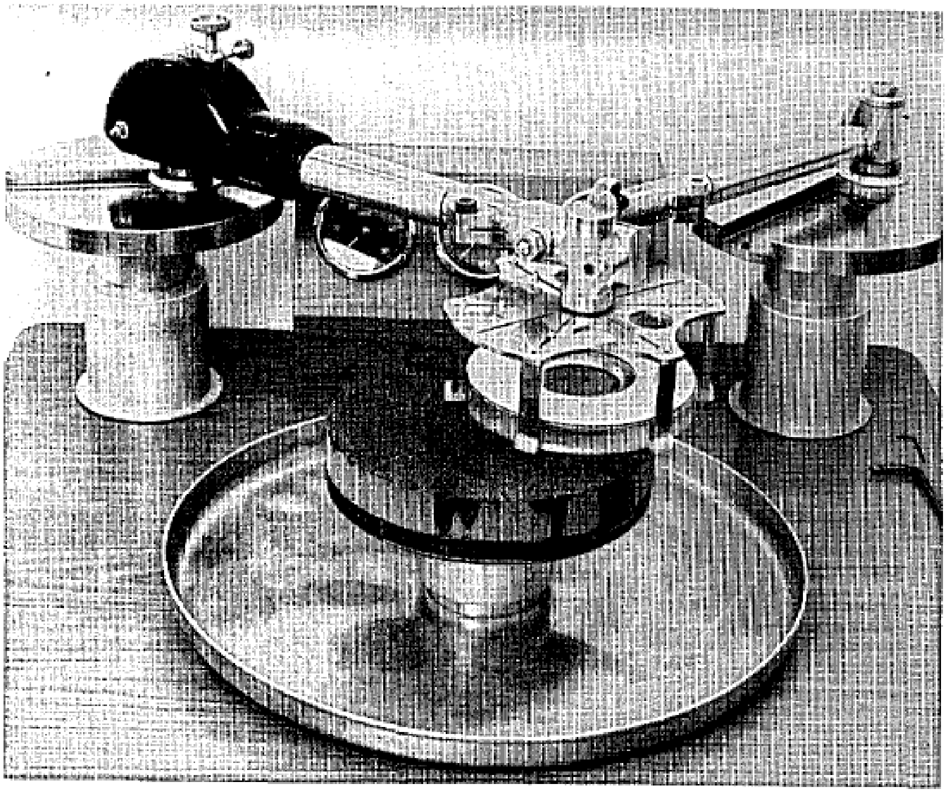


Fig 2. Photograph of the sample holder on a Teflon lap [2]

3.1.4 Float Polishing:

Float polishing uses a rapidly rotating tin lap with aqueous polishing slurry of colloidal silicon oxide. The key to successful float polishing is the 46-cm diam tin lap. Other materials have been tried with varying degrees of success. Copper, aluminum, glass, stainless steel, and several types of plastic laps have been used, but high-quality nonporous tin seems to work best. The size of these polishing particles is in the range of just 4-7nm, whereas the particles in conventional polishing are in the order of 1 µm. The removal mechanism is an elastic bombardment of the workpiece surface by the polishing grains, leading to contact bonding and removal of weakly bonded atoms from the surface. The essential parts and the setup for float polishing is as shown in fig.3. The tin lap with its slurry- retaining bowl is mounted on the spindle. The upper spindle has a splined driving shaft that engages the driving motor and couples the torque to the sample blocking plate. The blocking plate is mounted so that the parts can be separated and surface roughness measurement could made during the process itself. The average surface roughnesses that can be experimentally obtained for some glass are as follows: Zerodur-8.5Å, fused quartz – 11 Å, Cer-Vit – 3.2 Å. [4]

Advantages: Better surface generated, advantageous for mass production.
Disadvantages: Highly reactive with some surfaces.

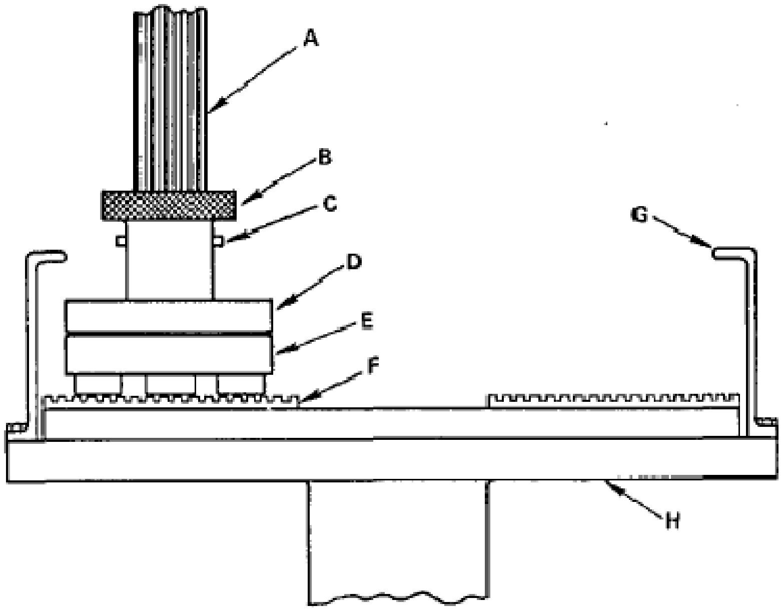


Fig 3. Schematic of float-polishing machine: A, upper spindledriving spline; *B,* knurled retaining ring; C, driving pin; D, steel holding and driving fixture; E, glass blocking plate with samples; *F,* tin lap bonded to stainless steel backing plate; G, bowl for retaining slurry; *H,* lower spindle-driving plate.[4]

3.1.5 Bound Abrasive Polishing:

This are especially suitable for the high volume production of lower quality lenses with diameters up to about 20 mm. Plastic laps, highly charged with sub-micron ceria abrasive, are used with pure water as a lubricant. Beside the higher removal rate, the advantage of this system over polyurethane polishing is that no chemically unreliable slurry is needed. A successful bound-abrasive polisher consists of (in weight percent) 60-90% (w/w) polishing agent, 5-25% (w/w) binder, and 5-15% (w/w) erosion promoter. Because of its high polishing efficiency for many soft and moderately hard glasses, CeO_2 is the polishing abrasive of choice. An impure CeO_2–

rare-earth oxide blend, known as Polirit, is used in the Aquapol media. The average RMS that can be achieved is 2 nm [11].

Advantages: Polishing efficiency (high MRR per stroke of polisher), temperature stability, low cost of consumables, compatibility with computer controlled machines reduces overall production times when employed in mass production.
Disadvantages: The tool has to be dressed frequently (tool life is in hours), tool has to be checked for shape accuracy frequently.

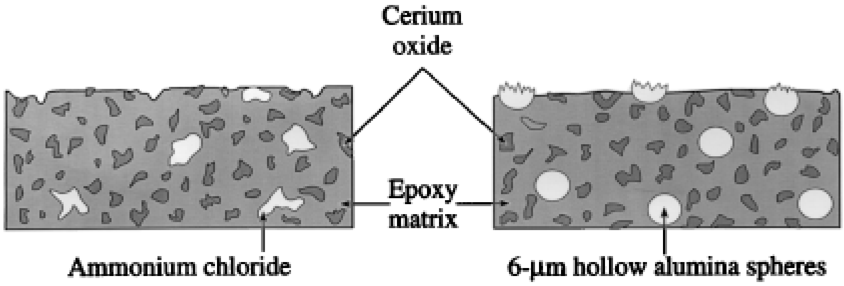


Fig 4. Ammonium chloride and hollow alumina spheres help to promote erosion of the binder to expose fresh cerium oxide grains. [5]

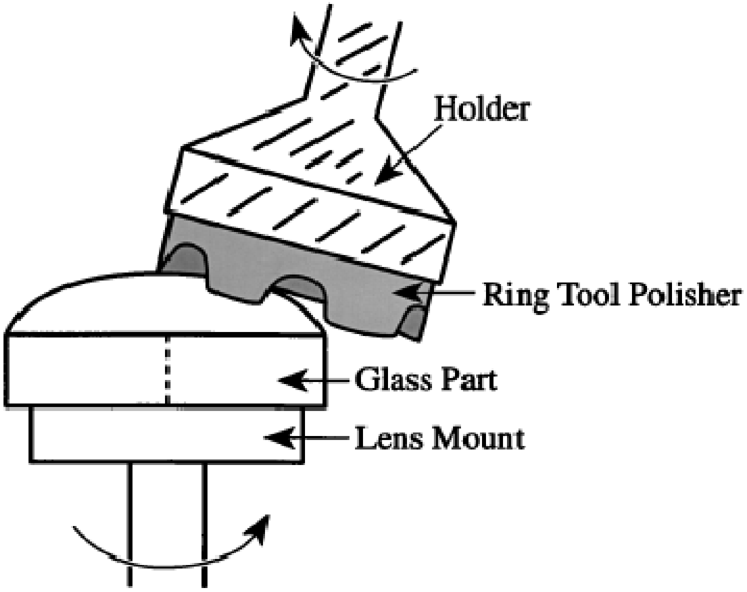


Fig 5. Bound-abrasive ring tool polisher schematic. [5]

3.2 Sub Aperture Polishing (Non-conventional Methods):

With the advances in the technology and new inventions in the space technology, there was a need to develop optic surfaces of free forms. This was not possible with the conventional full aperture polishing methods and computer control was necessary to generate aspheric and freeform surfaces. This led to the development of non-conventional processes.

3.2.1 Ion Beam Polishing:

Principle: Low-energy ion-beam sputtering, i.e. the removal of atoms from a surface due to the impact of energetic ions or atoms.

The facility used for Ion beam polishing has some of the following common parts; a) Pumping system (for generating vacuum); b) gas system for supplying sputter gases; c) loading dock for workpiece; d) cooling system; e) broad beam ion source. The distance between the ion source and the workpiece holder is smaller than the mean free path length of ions so that the extracted ions will reach the workpiece without collision. A typical system may have a vacuum of 2×10^{-6} Torr or lower. The workpiece holder can be made with all the possible advances in mechanisms and with all the possible degrees of freedom. All the given ion incidence angles refer to the angle spanned by the surface normal and the axis of the ion-beam source, i.e. 0° ion incidence corresponds to normal ion incidence onto the macroscopic plane surface. There are various criteria for selecting the ion source. Some basic parameters are given here.

This source selection process should identify the following:

- What type and size of Ion Beam Source required
  - Gridless - End Hall or Anode Layer Source (ALS)
  - Gridded – Radio Frequency (RF) or Direct Current (DC)
    - What grid type is needed

- How the ion source should be mounted
  - Internal or on an external flange to your vacuum system

The ion-beam divergence and angular distribution of the ions within the beam are called secondary ion beam parameters are inherent to all broad-beam ion sources, typically used for low-energy ion-beam sputtering, resulting in a non-ideally parallel ion beam, i.e. all ions forming the beam feature an angular distribution which is also reflected in the angular distribution of ions arriving at the surface. For some of the presented pattern, these parameters play a crucial role in the evolution of the surface topography. During the sputtering polishing, ions bombard the substrate and cascade collides with atoms. The cascade collision performs best when the ion beam incidence angle between 45^{o} and 60^{o}. But if the incidence degree is too big, most of the ions were reflected. Only few ions implant into the substrate, the polishing effects were not obvious. When the incidence angle access 90^{o}, no energy transmission occurs, due to ion beam almost parallel with the substrate and no sputtering occurs on the substrate surface. With this we get the average surface roughness of 0.2 nm. The beam diameters can be 5 nm to 0.5 µm. The MRR can reach 1.050 $\mu m^3/s$. [7]

Advantages: Suitable for special purpose application

Disadvantages: Expensive, limited availability and long polishing cycles

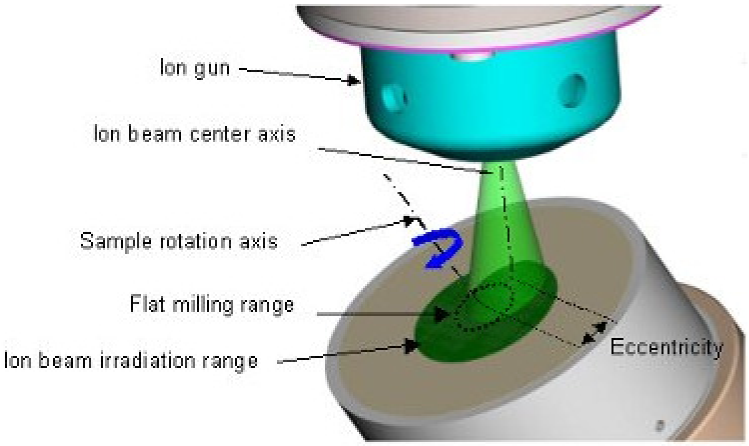


Fig. 6 Schematic of Ion beam polishing [6]

3.2.2 Atmospheric Pressure Plasma Polishing:

Principle: It utilizes chemical reactions between reactive plasma and surface atoms to perform atom-scale material removal.

Since the process is chemical in nature, APPP avoids various surface/subsurface defects which usually appear in conventional machining processes. Uniform low temperature plasma can be generated over a large surface at low cost and more extensive application range. Also due to the presence of more active and multifarious species than those generated from chemical reactions, it easily reacts with materials. The reaction gas and plasma gas with optimum ratio is sufficiently mixed and then input into the plasma torch. Then, ionized by the radiofrequency (RF) power, the reaction gas is excited in the plasma to generate high density and high energy reactive radicals. Then the generated reactive radicals cause chemical reactions with the surface atoms of the work-piece, which performs the effective atom-scale material removal. For different materials, different combinations of plasma and reactive gas are used. Like for silicon, Helium is used as plasma and carbon tetraflouride (CF_4) is used as reactive gas. This gives a radical F* and SiF_4 both of which are volatile and machined surface is left with no contaminant. The principle of APPP is shown in fig. 7. It shows how the reactive radicles combine with the workpiece surface atoms and volatile products are formed. The APPP method uses low temperature plasma to avoid local high temperature on the part surface. The temperature is just 90^0C as compared to 800-900 ^{0}C in ion beam polishing.

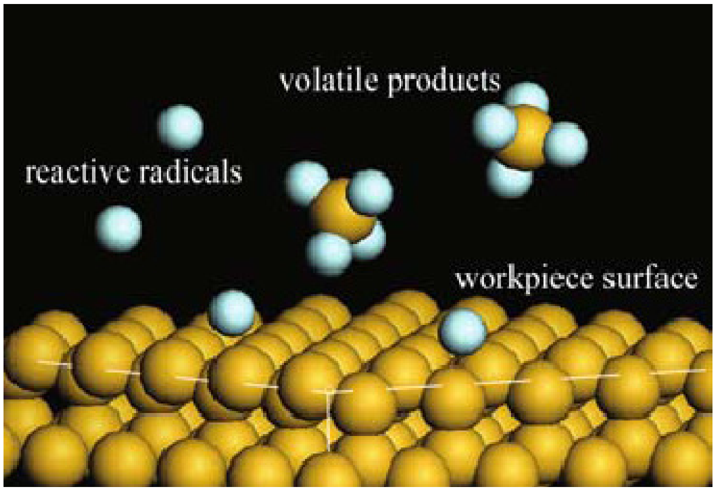


Fig.7 Principle of APPP [8]

The main components of the system are gas supply system, Radio Frequency (RF) power supply and impedance matching system, multi-axes worktable and relevant motion control system, hermetic chamber, and residual gas recovery system. But the main component is a plasma torch. The plasma torch is where the plasma and reactive radicals are generated. The plasma torch used is a capacitance coupled RF plasma torch. A simple torch and its setup is shown in fig. 8.

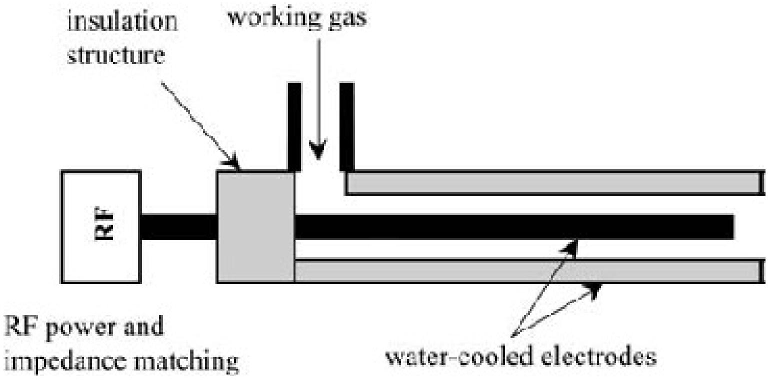


Fig. 8 Schematic of a Capacitance coupled radio frequency plasma torch [8]

The experimental value achieved till now is Ra of 0.631nm or 6.31Å [8]. This process is capable of achieving sub-nanometer average surface roughness. Also the MRR is 32 mm^3/min that is better than ion beam polishing.

Advantages: There are always certain defects on the final surfaces of the components formed in conventional contacting machining processes, such as micro-cracks, lattice disturbances, etc. It is especially serious for hard-brittle functional materials, such as crystals, glass and ceramics because of their special characteristics. To solve these problems, the atmospheric pressure plasma polishing (APPP) method is developed.
Disadvantages: Compared to Elastic Emission polishing, this is a costly method in terms of setup. The MRR is also low

3.2.3 Magneto Rheological (MR) polishing:

Principle: Basic principle is the same as traditional polishing method, but a non-traditional method of magnetic field is applied to achieve that.

MR fluids are smart materials such that they respond to applied magnetic field in their rheological behavior. A MR fluid (MRF) is a suspension of magnetically soft ferromagnetic particles in a carrier liquid. The magnetically soft media used to manufacture MR fluids, which are subsequently used in MRF, are carbonyl iron (CI) powders. Typically, the particles are of the order of a few microns in diameter, and their volume concentration is 30% to 40%.The MR effect has a direct effect on the mechanical properties of the MR fluids. The MRF carries suspended particles and those become aligned after being polarized and form chains. This chain formation restricts the movement of the MR fluids and thereby increases the yield stress of the fluid. This principle is used in MR polishing. Abrasive particles like CeO_2 provide additional contribution to the polishing kinetics due to chemical effects.

There is a moving wall and the workpiece is mounted underneath the moving wall and the distance between them is very short. There is a magnetic pole is under the moving wall. This creates the magnetic field in the fluid. As the fluid passes through the gap, it shows the behavior of a semi-solid and surface of workpiece under it is polished. We can think that the MR fluid creates some rigid “polishing spots” by the magnetic field and the rigidity of those “polishing spots” can be controlled by the strength of magnetic field. Because of the motion between those “polishing spots” and the part, the impurities on the part surface can be removed.

Parameters affecting the polishing are; velocity of MR fluid, air gap magnetic flux density and the gap between the wall and workpiece. Strength of flux is directly proportional to MRR. It is also directly proportional to velocity of MR fluid and inversely proportional to the gap between the wall and the workpiece. But the major parameter still being the strength of magnetic field supplied. A 1 nm smoothness with removal rates of 1 to 10 µm/min is routinely achieved.[10]

Advantages: Surface roughness obtained on the same scale of conventional processes, can create freeform surfaces.
Disadvantages: Costly than conventional processes as there is a need for dual pumping system for MR fluid as well as the slurry containing abrasive and the MR fluid itself being costly.

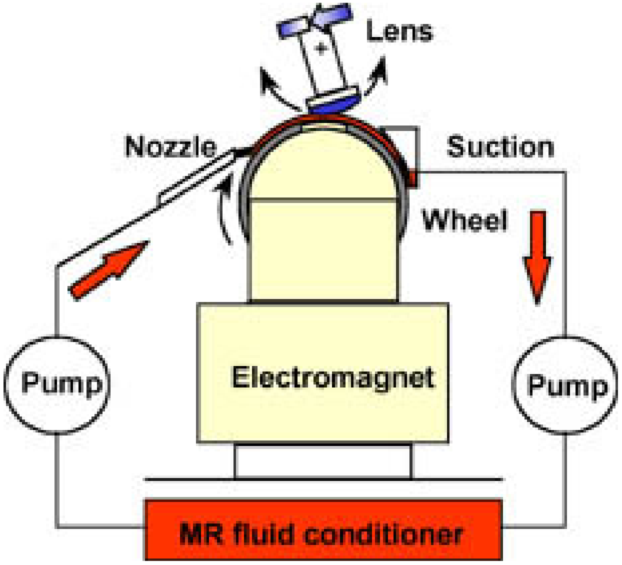


Fig. 10 A schematic of MR polishing. [11]

3.2.4 Elastic Emission Machining (EEM):

Principle: EEM is a noncontact machining process, differing from conventional polishing which uses an abrasive pad. Fine powder particles are brought to the workpiece surface in a flow of pure water, and the chemical reaction between the workpiece surface and the particles results in the removal of surface atoms from the workpiece.

It has been found that the material removal process is a surface energy phenomenon in which each abrasive particle removes a number of atoms after coming in contact with the workpiece surface. It has been established theoretically and experimentally that atomic scale fracture can be induced elastically producing ultrafine surface finish without plastic deformation at atomic scale. Ability to remove material at the atomic level by mechanical means and to give completely mirrored, crystallographically and physically undisturbed finished surface is achieved by EEM. The ultra fine abrasive particles strike the individual atoms/group of atoms and separate them out from the parent surface. This is shown in Fig.11. In EEM, the material removal occurs at the atomic level, hence the surface finish obtained is close to the order of atomic dimensions (2–4 Å)[11]. The type of abrasive and size of abrasive grains used (in the nano-range) have been found to be critical to the material removal efficiency.

The particles supplied in a flow of pure water roll around on the processed surface along the streamlines, preferentially removing the topmost atoms on the surface as shown in fig. 12. Smoothing thus progresses automatically. EEM is known for its high smoothing performance. The surface roughness of single crystal silicon is reduced to 0.1 nm rms or less with EEM [11]

Advantages: No chemical reaction, material removal purely by mechanical means, surface finish obtained at the order of atomic dimensions.
Disadvantages: Practically no disadvantages.

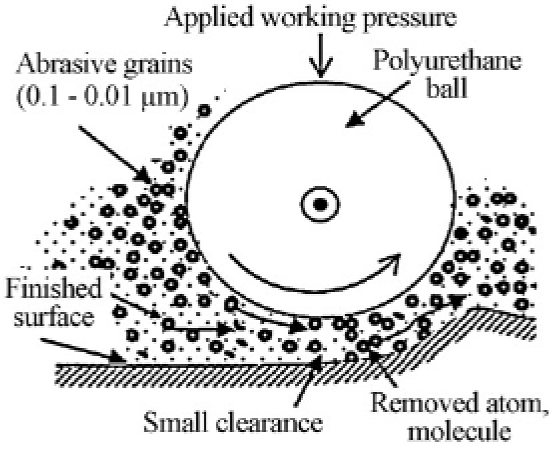
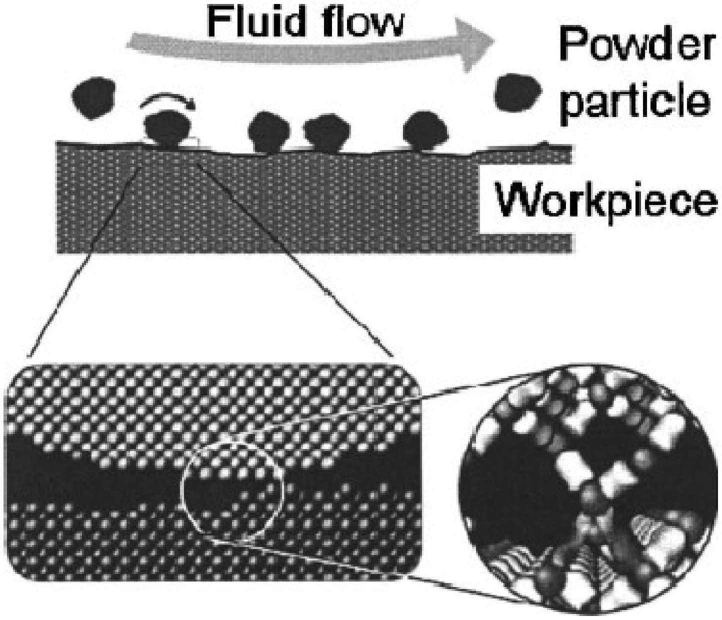


Fig. 11 EEM [11]



Schematic representation of atom removal process in EEM.

Fig. 12 [12]

4 **Conclusion:** The conventional full lap polishing processes have been there since a long time and some like pitch polishing have been used since historic times. The give really good surface qualities. The float polishing is specifically used to generate flat surfaces and float glass. By changing the laps from pitch to polyurethane and so on, the surface quality obtained and the material removal rate increases. The lap has to conform to the shape of the surface to be polished. They have to be checked for surface accuracy and reshaped over short periods. The nonconventional processes are free of laps. So there is no need to check the surface of the tool. The material removal rate of non conventional methods is low. But with the modern needs of aspherics, the conventional

processes are sometimes left incapable to polish such shapes, and even if they can, there is always a need to develop a tool that is specific to one workpiece. As in the case of non conventional methods, this major limitation is overcome. Even though the material removal rate is low, the capability of non conventional processes to be combined with numerical control to generate any type of contour is preferable for specialized manufacturing of precision optics. For mass manufacturing, there is rarely a need to generate such shapes and surfaces. So there is a need to focus more on the non-conventional processes which can be numerically controlled and can be especially used to polish freeform surfaces.

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