Technological Advances in Super Fine Finishing

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Abstract

Focusing short wavelength radiations such as Extreme Ultra-Violet (EUV) and X-rays can be accomplished by assemblies of reflective aspheric optics. Application of such systems ranges from research in X-ray astronomy and microscopy, to semi-conductors production by EUV lithography. But such optical surfaces require finishing to very low levels of micro-roughness, in proportion to the wavelength of incoming radiation. In this paper, recent advances in super fine finishing technologies (capable of achieving micro-roughness below 0.5 nm rms) for aspheric and freeform optical surfaces are presented. The paper deals with both ultra-precision grinding and polishing technologies, with the performance and advantages/disadvantages of each method being discussed, and examples of applications provided.

1 Introduction

The ability to fabricate complex optical surfaces (aspheric and freeform) with high shape accuracy and super fine surface finish is increasingly becoming a critical enabler for a range of state-of-the-art technology and scientific research. Application ranges from next generation Extreme Ultra-Violet (EUV) lithography [1] to astrophysical observations using X-ray telescopes [2]. Indeed, the performance in reflectivity for ever shorter radiation wavelengths is directly linked to the ability to produce ever smoother optical surfaces. In the past, incremental refinements to traditional fabrication methods such as grinding, lapping and polishing using semi-automated machinery have usually provided much of the necessary improvements in the fabrication chain. As was thoroughly reported by Evans et al [3], these refinements were often achieved through a deeper understanding of the chemical and mechanical relationship in material removal conditions, for various categories of material. However, it is now becoming routine for alternative finishing technologies to be employed in the final fabrication stages.

For instance, the production of photomask blanks for lithography application has long relied on the use of conventional lapping and polishing. But as the international specification for next generation EUV photomask blanks [4] now requires flatness between 30 and 100 nm Peak-to-Valley together with surface roughness below 0.15 nm rms (for spatial wavelength below 15 µm), the limits of conventional fabrication methods are clearly being reached. This has led blank manufacturers to seek alternative post-finishing methods to reliably attain the EUV specification.

In this paper, a survey including some of the most recent developments in super fine finishing technologies is provided, together with the range of applications these methods can best be applied to. The full list of technologies and their acronyms is shown in Table 1. A distinction has been made between "grinding processes" (fixed abrasive cutting in ductile regime) and "polishing processes" (loose abrasives acting mechanically and/or chemically). The summary provides comparisons of the finishing vs. productivity potential of these processes, information on the finishing of very large (beyond metre scale) and structured surfaces, and finally some additional information regarding non-conventional processes

Table 1: List of technologies reviewed in the paper.

Acronym	Full Name
Super-fine grinding	
SSUPG	Super-Stiff Ultra-Precision Grinding
ELID	Electrolytic In-Process Dressing
SAG	Shape Adaptive Grinding
Super-fine polishing	
FP	Float Polishing
FJP	Fluid Jet Polishing
EEM	Elastic Emission Machining
CPP	Continuously Precessed Polishing
MRF	Magneto-Rheological Fluid Finishing
MAF	Magnetic field Assisted Finishing

2 Super fine grinding

Super fine grinding can also be described as the ability to attain ductile regime removal [5,6,7] with fine fixed abrasives (usually diamonds around 1 μm grit size or less). In this mode, it is possible to generate surfaces with grinding marks that are extremely shallow, without any break-up of the underlying substrate material. Three ductile mode grinding technologies are presented in this section, which differ greatly in the stiffness properties of the associated apparatus. At one end, Super-Stiff Ultra-Precision Grinding (SSUPG) relies on expensive machinery to produce a very stiff grinding loop, while at the other end Shape Adaptive Grinding (SAG) relies on a very soft "semi-elastic" tool.

2.1 Super-stiff ultra-precision grinding (SSUPG)

Super-Stiff Ultra-Precision Grinding (SSUPG) is a grinding method in which the overall stiffness of the machining loop is given prime consideration. Namba et al [8] produced experimental machinery, the principle of which is shown in Fig. 1. The machine consists of only two off-axis hydrostatic spindles, in which the lower spindle slowly feeds the workpiece across a grinding spindle rotating above. Large resinoid bonded diamond wheels are used, of diameter 125 mm or more. To increase stiffness and the thermal stability of the system, the shaft inside the grinding spindle is made entirely from zero expansion glass-ceramic, while the Z-travel of the upper spindle is mechanically locked into position before initiating the process cycle. The machine is then operated within a temperature controlled environment.

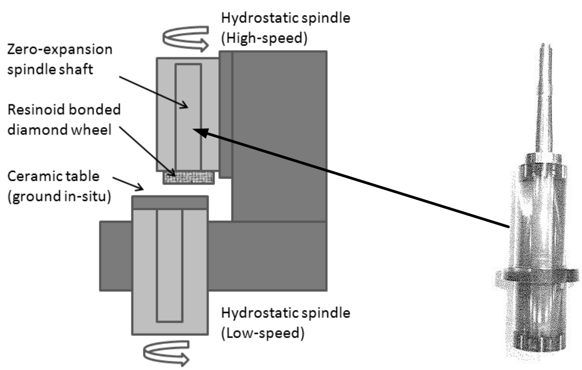


Figure 1: SSUPG machine (left) and photo of glass-ceramic spindle shaft (right) [8].

In order to achieve a high degree of flatness, the machine is first used to grind the sample bearing table in-situ. In the SSUPG process, it was found that the final surface finish is independent from depth of cut (as much as 50 µm of material depth can be removed in a single pass while maintaining ductile mode removal with stable surface finish). Final surface roughness below 0.1 nm rms has been achieved on a wide range of materials including glass, ceramics, and single crystals [8,9,10].

Though the system configuration is limited to only processing plano surfaces, its scope for application ranges from superior piezo electric substrates [10] to high power laser windows [11], and potentially the fabrication of photomask blanks for EUV lithography. Future improvement to the SSUPG machine would consist of building the entire frame from zero expansion glass-ceramic. This would further increase the thermal stability of the grinding loop, though the very high cost of realizing such a setup has prevented its implementation up-till now.

2.2 Electrolytic in-process dressing (ELID)

In conventional fixed abrasive grinding, the wheel requires dressing prior to initiating grinding of the actual sample. The aim of this dressing is to ensure that new sharp grit is protruding from the wheel surface. Ohmori et al. [12] introduced Electrolytic In-process Dressing (ELID) as a major improvement on this traditional method, whereby continuous dressing of the wheel occurs during the grinding cycle. Fig. 2 shows a diagram of the ELID principle: the axis of a metal bonded abrasive wheel is connected to a power supply with a brush. One side of the wheel performs grinding on the workpiece, while the other side undergoes electro-chemical dressing inside a small gap (usually around 0.1 mm) filled with alkaline liquids. These liquids usually serve both as electrolyte and coolant. The electrolytic reaction causes stripping of the metal bond, thus continuously revealing fresh and sharp grit that can perform in ductile regime.

One of the main challenges of this process is form control, since the wheel diameter is continuously reducing during the process. Nevertheless, ELID grinding has been tested with a wide variety of materials and shapes (including freeform).

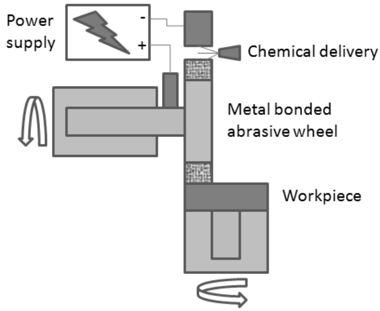


Figure 2: Principle of ELID grinding process.

Some notable applications include ultra-precise grinding of silicon wafers, synchrotron mirrors, and Wolter type mandrels for X-ray mirrors forming [13]. A variant of the process named “ELID lapping” has been shown to deliver micro-roughness finishes below 0.5 nm rms on mono-crystalline silicon, using extremely fine abrasive grit sizes (down to #3000000) bound with a metal-resinoid hybrid [13].

2.3 Shape adaptive grinding (SAG)

Shape Adaptive Grinding (SAG) was developed very recently, and consists of linking small hard grinding pellets to an elastically compliant tool. Beaucamp et al [14] have described the principle and deployment of such tool, which is shown in Fig. 3. A pressurized reinforced rubber membrane is covered with intertwined textile and metallic fabrics above which nickel pellets are electro-deposited. Diamond abrasives, of grit size ranging down to a few microns, are embedded inside these pellets. The grinding force is controlled by air pressure, while the grinding spot area is controlled by the geometrical position of the tool.

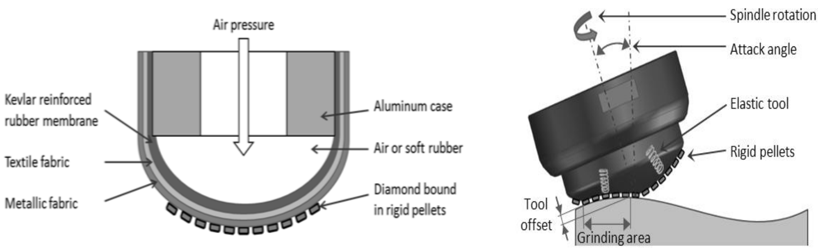


Figure 3: Multi-layer design of SAG tool (left) and principle of operation (right) [14].

The principle of shape adaptive grinding is also shown in Fig. 3 (right). Due to the elasticity of the rubber membrane and deformability of the fabrics, the tool is able to comply with freeform surfaces of any type (either convex or concave). General compliance between the SAG tool and freeform surface is thus maintained over a sub-aperture contact area of the workpiece. However, at the smaller scale of the pellets the tool is rigid. This hard contact allows for grinding to take place (rather than a soft contact resulting in polishing). The first application of this novel grinding method to Chemical Vapour Deposited (CVD) silicon carbide has yielded ductile mode grinding results, with surface finish as low as 0.4 nm rms [14]. Further investigation regarding the application of this method will include other ceramic materials (such as tungsten carbide), moulding steels, and single crystal materials.

3 Super fine polishing

Super fine polishing processes can be split into two separate categories. In the first category, which includes Float Polishing (FP), Fluid Jet Polishing (FJP) and Elastic Emission Polishing (EEM), the abrasives are contacting the surface freely, without embedding into a support system or viscous fluid. In the second category, which includes Continuously Precessed Polishing (CPP), Magneto-Rheological Finishing (MRF) and Magnetic Abrasive Finishing (MAF) the abrasives are contacting the surface under direct influence from the support system or fluid.

3.1 Float polishing (FP)

Float Polishing (FP) is an ultrafine finishing technique used in the fabrication of optical, electronic, and magnetic components requiring damage-free surfaces. The equipment developed by Namba et al. [15] is shown in Fig. 4: a weighted sample and tin lap are submerged in slurry composed of de-ionized water and a measure of nano-sized abrasives. The sample and lap are rotated in the same direction, and usually at the same rate. Prior to operation, the tin lap is diamond turned on-machine, to achieve perfect alignment with the axis of the hydro-static spindle underneath. Under equilibrium conditions, the sample floats on a fluid layer a few microns above the lap, thus getting skimmed by the microscopic polishing particles suspended in the slurry.

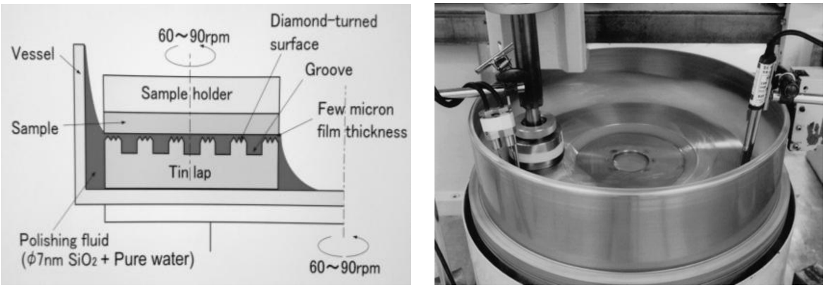


Figure 4: Principle (left) and photograph (right) of float polishing machine.

Comparisons by AFM with mica surfaces have shown that it is possible to obtain almost atomically smooth surfaces by FP. In recent years, surface texture around or below 0.1 nm rms was achieved by this method on materials such as nickel and calcium fluoride [16,17]. Some drawbacks of this method include extremely low material removal rates (the start condition is thus required to already have a high degree of flatness), and applicability only to plano surfaces.

3.2 Fluid jet polishing (FJP)

Fluid Jet Polishing (FJP) is a finishing method that was described and implemented by Fähnle et al [18,19]. It offers some attractive advantages that include the ability to generate sub-millimetre polishing footprints, a wide range of material removal rates through variation of the abrasive grit size and inlet pressure, a propensity for removing machining marks from prior processes without introducing another tool signature, as well as the absence of tool wear. A mixture of water and abrasive particles is delivered by a pump to a converging nozzle of outlet diameter usually between 0.1 and 2.0 mm. The jet impinges the workpiece, thus generating a polishing spot (see Fig. 5, right). The typical pressure range for the slurry inlet is between 1 and 20 bar, while abrasive grit size may range from 0.1 to 50 µm. The applicability of this process has been verified on glass, metals, and ceramics.

But obtaining super-fine finished surfaces by FJP has required a number of process optimizations. The use of Computational Fluid Dynamics (CFD) to optimize the operating conditions of an advanced slurry deliver system to the nozzle inlet, shown in Fig. 5 (left), has been reported [20]. By operating under well optimized conditions, it is possible to obtain surface finish as low as 1.0 nm rms. This optimized process has been applied to removal of diamond turning marks on electroless nickel plated mandrels for X-ray mirror replications.

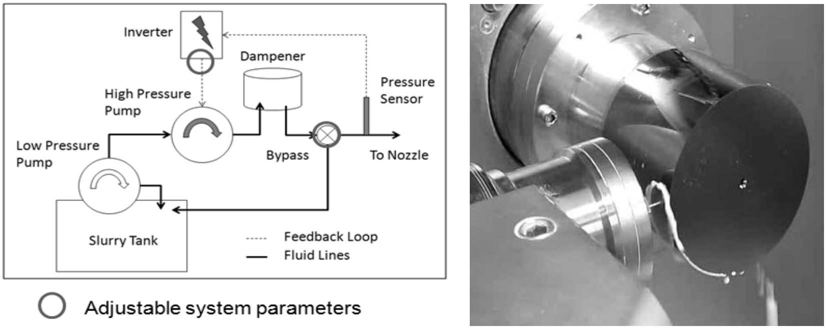


Figure 5: Advanced slurry delivery system with adjustable parameters optimized by CFD [20] (left), FJP polishing of mandrel for X-ray mirror replication [20] (right).

Very recently, some theoretical and experimental research has been carried out into the possibility of hybridizing FP and FJP into a single process [21,22]. Super smooth surfaces down to 0.1nm rms are achievable through this novel approach, with the important advantage that FJP is applicable to freeform shapes.

3.3 Elastic emission machining (EEM)

Elastic emission machining is a finishing process that was introduced by Mori et al. [23], in which ultra-fine abrasives are suspended in pure water and made to flow at high speed across the workpiece surface by a rotating elastic spherical tool. After initial contact the tool stays clear from the workpiece, being lubricated by a small fluid gap. It is reckoned that this fluid gap induces particles to contact the work surface and create chemical bonds with the substrate material. These bonded atoms are then removed from the surface as the particles flow by (see Fig 6). Since rough surfaces have increased surface area at the microscopic level, rough areas are preferentially machined which leads to a reduction in surface roughness.

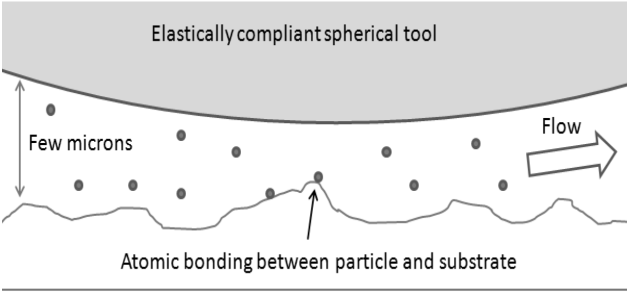


Figure 6: Principle of elastic emission machining.

The EEM process has been shown to produce super-smooth surfaces with micro-roughness down to 0.2 nm rms on various materials such as optical glass, silicon, and ceramics [23,24,25]. But similarly to the FP process, the low removal rates observed in the EEM process generally requires a highly polished surface to start with.

While originally employed preferentially on shallow surfaces, the EEM process was more recently demonstrated on curved surfaces such as small mandrels for hard X-ray microscopy, leading to a landmark breakthrough in focusing of radiations down to a 10 nm wide spot [26].

3.4 Continuously precessed polishing (CPP)

Precessed bonnet polishing is a sub-aperture finishing process that mimics characteristics of conventional full-aperture polishing methods. Walker et al. [27] have described the operation of the process, which is shown in Fig. 7 (left): the position and orientation (precess angle) of a spinning, inflated, membrane-tool are actively controlled as it traverses the surface of a workpiece. The workpiece may have any general shape, including concave, flat, or convex, aspheric or free-form.

An improvement of this technology was recently proposed by Beaucamp et al. [28]: rather than rely on the usual “single precess” regime, whereby the tool is precessed in a given direction for each polishing pass, a novel tool path control method called Continuous Precess Polishing (CPP) was introduced. In this method, shown in Fig. 7 (right), the direction of the surface tangent used to compute the plane of precession of the spherical tool is allowed to spin around the centre of the polishing spot.

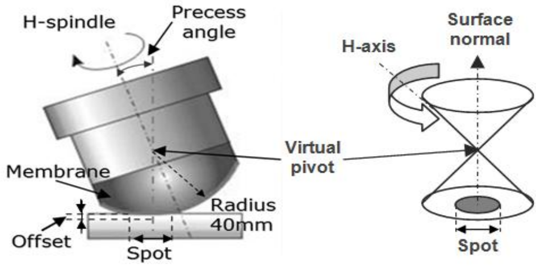


Figure 7: Principle of precess polishing (left) and continuous precessing (right) [28].

This motion may be compared to the wobbling of a spinning top: the H-axis describes a cone around the polishing spot, thereby allowing the polishing direction to change continuously as shown in Fig. 8.

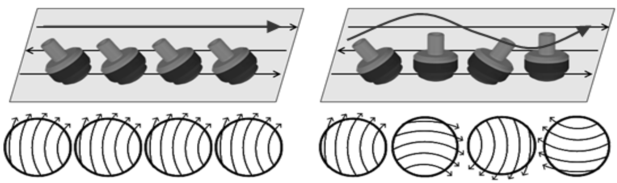


Figure 8: Single (left) and continuous precessing (right) across raster tool path, with associated polishing direction (bottom) [28].

This improved control version has been shown to produce anisotropic micro-roughness below 0.3 nm rms [28], and can be used to finish large electroless nickel plated mandrels employed in replication of thin mirrors for hard X-ray space telescopes. Another noteworthy application of this technology is the finishing of photomask blanks for EUV lithography [29].

Further improvements to sub-aperture pad finishing technologies are continuously being explored, such as recent research reported by Klocke et al regarding both modelling and experimentation of pad/substrate interaction [30,31]. Following a similar thought process as CPP (that is of a polishing pad continuously changing its machining direction), Brecher et al have also proposed a force controlled orbital polishing head for freeform surface finishing [32].

3.5 Magneto-rheological fluid finishing (MRF)

Magneto-rheological fluid (MRF) is composed of magnetic particles (typically carbonyl iron) mixed with abrasive particles in water and stabilizing agents. In the process described by Prokhorov et al [33], the fluid is ejected from a nozzle and applied to a rotating wheel by a collector. As the work-piece is then pressed against the wheel, a strong magnetic field hardens the fluid and causes material removal to take place in the contact zone, as shown in Fig. 9.

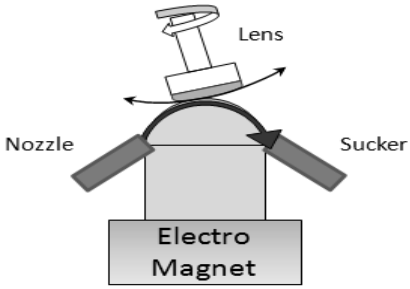


Figure 9: Principle of magneto-rheological fluid finishing.

MRF finishing can be used in the production of super-fine aspheric glass optics, with micro-roughness ranging between 0.5 ~ 1.0 nm rms [34]. The process has also been applied successfully to lithography for both silicon wafer finishing [35] and photomask blanks finishing [36]. Another development of the technology has involved funnelling of the magneto-rheological fluid through an electromagnetic nozzle to process steep concave shapes [37], with surface roughness around 0.6 nm rms being reported.

In more recent years, the process has been investigated within the context of chemo-mechanical finishing, for application to difficult CVD materials such as zinc sulphide [38], where grain boundaries and anisotropic material characteristics previously posed serious challenges.

3.6 Magnetic field assisted finishing (MAF)

In Magnetic field Assisted Finishing (MAF), very fine abrasive particles are mixed with ferro-magnetic particles of larger size and smeared as a spot on the workpiece surface. The process described by Shinmura et al. [39] involves a magnetic field that forces the mixture against the workpiece surface. Polishing is achieved by translation, oscillation and/or rotation of the magnetic field (see Fig. 10).

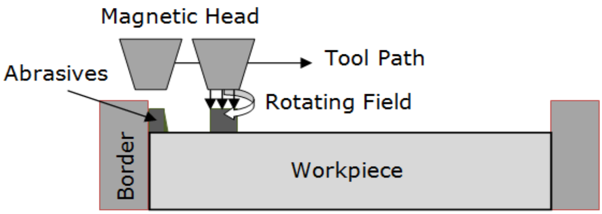


Figure 10: Principle of magnetic field assisted finishing.

MAF is a very flexible manufacturing method, that can be operated to finish surfaces inside cavities and pores, and can deliver ultra-sharp edges (by masking of the sides). It has been applied to wide range of materials, including high-speed steel and ceramics [40]. The process is applicable both to magnetic and non-magnetic substrates, through adjustments of the process conditions.

In recent years, finishing by MAF of microscopic sidewall surfaces in silicon micro-pore optics was achieved, with micro-roughness down to less than 0.2 nm rms being reported [41].

4 Summary

In conventional grinding, there exists a proportional relationship between removal rate and achievable surface roughness (the shallower the depth of cut per pass, the finer the resulting surface micro-topography). This principle extends to super-fine grinding, as shown in Fig. 11. The removal rate and micro-roughness relationships are compared for the various techniques reviewed in this paper. Generally speaking, the finest micro-roughness can be achieved by SSPUPG method, while optimal productivity (the best ratio of roughness to removal rate) seems to belong with the SAG method. ELID stands in between, providing the widest range of achievable removal rate and surface roughness.

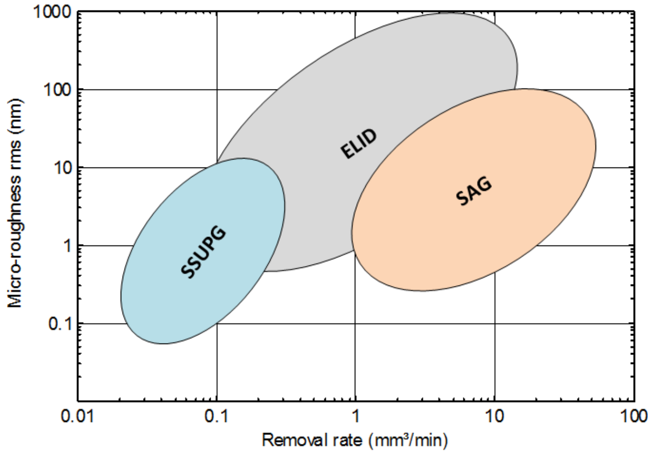


Fig. 11 – Comparison of super-fine grinding methods (roughness vs. removal rate).

A similar comparison chart is shown in Fig. 12 for super-fine polishing methods. Free flowing abrasive processes yield the finest surfaces (FP, EEM), while the pad based method (CPP) offers optimal productivity. The magnetic field assisted methods (MRF and MAF) are found between these two extremas, and FJP stands somewhat apart by spanning a very broad range of removal rate and surface roughness without attaining the ultra-low finishes of FP or the optimal productivity of CPP.

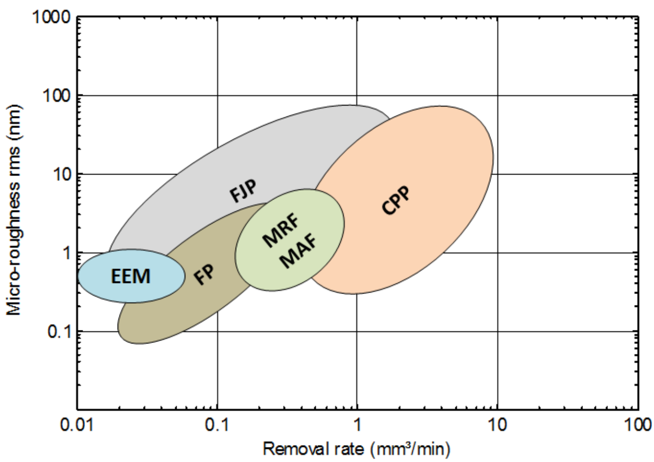


Fig. 12 – Comparison of super-fine polishing methods (roughness vs. removal rate).

Other comparative advantages of the various processes reviewed in this paper are shown in Table 2, including "potentially" achievable micro-roughness rms (this usually depends on the workpiece material), workpiece complexity, and applicable material types.

Table 2: Comparative advantages of various super-fine finishing methods.

Method	RMS	Workpiece complexity	Applicable Materials
Super-fine grinding			
SSUPG	<0.1 nm	Plano	Glass, ceramics
ELID	<0.5 nm	Freeforms	Glass, metals, ceramics
SAG	<0.5 nm	Steep freeforms	Metals, ceramics
Super-fine polishing			
FP	<0.1 nm	Plano	Glass, crystals, metals
FJP	<0.2 nm	Steep freeforms, cavities	Glass, metals
EEM	<0.2 nm	Freeforms	Glass, ceramics
CPP	<0.3 nm	Freeforms	Glass, metals, crystals, ceramics
MRF	<0.5 nm	Freeforms	Glass, crystals
MAF	<0.3 nm	Steep freeforms, cavities	Metals, ceramics

In the above considerations, workpiece size was generally assumed to be below the metre scale. Finishing surfaces beyond one metre size poses serious challenges when trying to scale up the equipment. Such difficulties were encountered in the prototyping of off-axis parabolic segments for the European Extremely Large Telescope (E-ELT), leading to innovations in grinding [42], polishing [43], and reactive plasma figuring technologies [44].

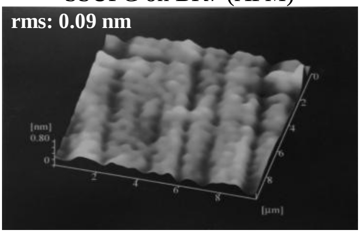
The treatment of structured surfaces is also worth mentioning, since it poses challenges of tool compliance that are not experienced in the case of continuous freeform surfaces. While achieving super-fine finish on such surfaces is very difficult, new polishing technologies are emerging such as the pin and grooved wheel type polyamide tools proposed by Brinksmeier et al [45].

A final comment is made on non-conventional finishing processes, which are offering alternative possibilities and strategies for super fine finishing. Ion beam figuring, first developed by Wilson et al [46], has found application to the production of super-smooth surfaces on optical glass and other materials such as single crystal silicon [47]. Another technology consists of irradiating the surface with ultraviolet to aid mechanical machining, as first proposed by Tanaka et al [48]. The method has since been applied to finishing of various metals, single crystal silicon carbide [49] and diamond [50]. Micro-roughness below 0.2 nm rms can be achieved by this method.

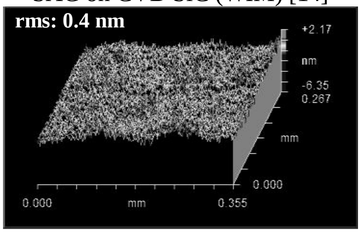
A few examples of surface finish attainable on selected materials are provided in Table 3, as measured by Whitelight Interferometric Microscope (WIM) and Atomic Force Microscope (AFM).

Table 3: Examples of attainable surface finish on selected materials.

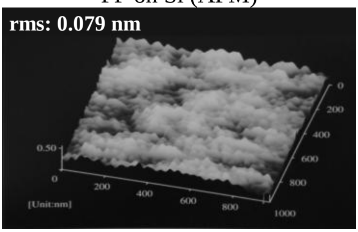
SSUPG on BK7 (AFM)



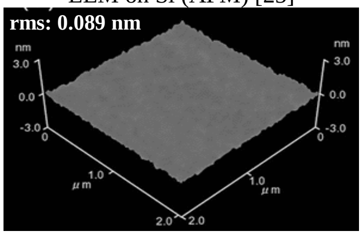
SAG on CVD SiC (WIM) [14]



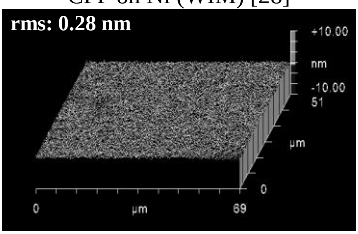
FP on Si (AFM)



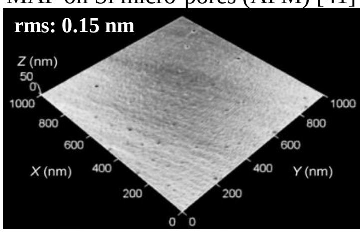
EEM on Si (AFM) [25]



CPP on Ni (WIM) [28]



MAF on Si micro-pores (AFM) [41]



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