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Introduction

1.1 Optical-Fabrication Processes

Optical fabrication is the manufacture of optical components such as passive optics – e.g. lenses, transmission flats, mirrors, and prisms – and active optics – e.g. laser-gain media, frequency converters, polarizers, and adaptive optics. These optics are produced in a myriad of shapes and sizes, using a variety of materials.

A typical optical-fabrication process starts from a block of bulk material, or a workpiece, which is processed through a series of grinding and polishing steps, as shown in Figure 1.1 to become an optic. A tremendous number of grinding and polishing steps exist, of many different types [1–17]. Nevertheless, the overall objective of all optical-fabrication process steps is to remove material from the workpiece in a controlled fashion to meet the specifications of the next or final process step. Generally, any surface damage caused by a given step is removed in the subsequent step, as depicted in Figure 1.2.

Optical-fabrication processes often require many iterations of a given process step (as suggested by the circular arrows in Figure 1.1), which are accompanied by metrology and process modifications to achieve a desired *surface figure* and *surface quality*. Early process steps tend to remove material much faster, with less geometric control and more surface damage to the workpiece. The final steps are typically the opposite: slower *material removal rates*, but greater control of geometry and little (or, ideally, no) surface damage to the workpiece.

The size of the abrasive or polishing particle is a dominant factor controlling the *material removal rate* (see Figure 1.3). Because the *material removal rate* may vary by many orders of magnitude, an optimized number of process steps with appropriate between-step specifications is needed to determine the most

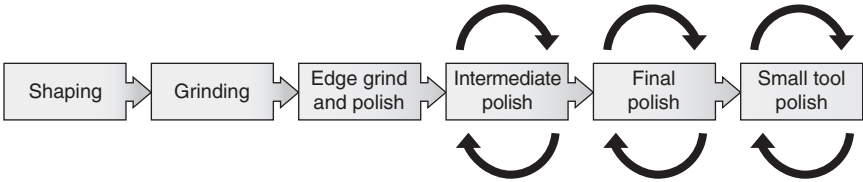


Figure 1.1 Typical steps in a conventional optical-fabrication process.

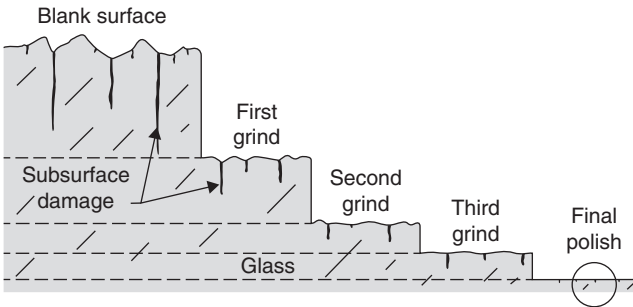


Figure 1.2 A schematic of material removal during various steps of the grinding/polishing process, illustrating surface-fracture removal.

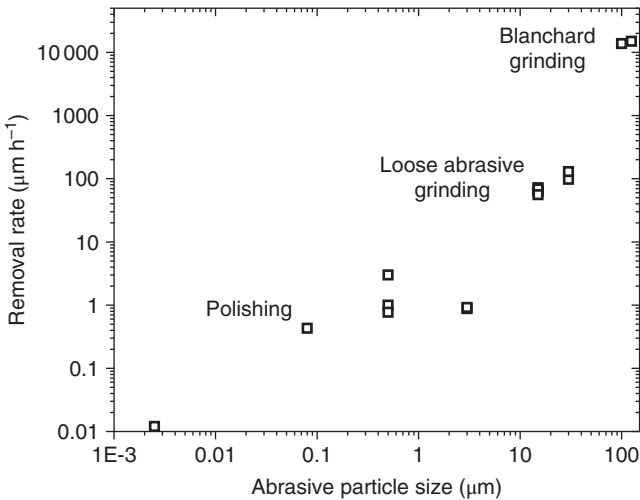


Figure 1.3 Log-log plot of material removal rate versus abrasive-particle size, determined for fused-silica glass.

economical fabrication process. Ultimately, the overall process time, and hence cost, of a given optical fabrication process is driven by a combination of

- the removal rates of the process steps (dominated by the latter, slower process steps)
- the number of process steps
- the number of iterations required in each step to yield an acceptable workpiece.

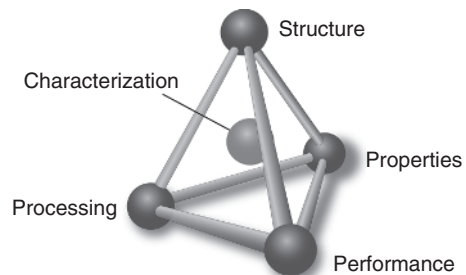
A common factor among the fabrication processes is the set of fundamental interactions at various spatial scale lengths between the

- workpiece, which will become the optic
- lap or tool, which leads to the time- and spatially dependent mechanical loading of the workpiece
- slurry or lubricant, which often contains particles to remove material from the workpiece.

The description and understanding of these phenomena and how processing affects workpiece structure, properties, and performance provide the materials-science basis of optical fabrication, as represented in Figure 1.4 https://en.wikipedia.org/wiki/Materials_science [11]. Defining these fundamental interactions or phenomena and the relationships among processing, structure, properties, and performance requires very controlled, systematic processing experiments and characterization of structures and properties, combined with quantitative modeling. Historically, this has been difficult to achieve, owing to a large number of simultaneous interactions and phenomena at various spatial scale lengths, as well as the large number of process variables.

In some ways similar to optical fabrication, chemical–mechanical planarization (CMP) is a fabrication method used for integrated circuits. CMP processing has received much study, because of its importance in the integrated-circuit industry. The key objective of CMP is to planarize the various layers of multilayer structures of a variety of materials (aluminum, silicon, silicon dioxide, copper, and tungsten, to name a few) with little or no defectivity. Though CMP

Figure 1.4 A schematic of the important relationships in performing materials science. Source: From Callister and Rethwisch 2010 [11] and https://en.wikipedia.org/wiki/Materials_science.



is governed by mechanics, tribology, and chemistry similar to that of optical fabrication, the technologies have distinct differences.

In CMP, the focus is planarizing and simultaneously polishing multimaterials, as depicted in Figure 1.5 [18–20]. By contrast, optical fabrication is focused on the *surface figure* and polishing of a single material at a time. The object of planarization is to reduce the entire multimaterial layer to the same thickness, while the object of achieving an optimal *surface figure* is to get a desired shape, whether flat, spherical, aspherical, or other. Hence with optical fabrication, the kinematics, or the relative motions of the tool with respect to the workpiece, is often more involved, and the slurry chemistry is quite different, as only one material (vs many) is utilized. CMP processes tend to be conducted at very high pressures (30–40 kPa), high relative velocities, and short polishing times – often minutes for final polishing and tens of minutes for stock removal. Optical fabrication generally uses lower pressures (0.7–7 kPa), lower velocities, and much longer polishing times (1 to >100 h). Even in making a flat optic, the *surface figure* differs from planarization. This is because an optical flat is specified based on optical path differences in reflection or transmission, while CMP planarization is specified on the thickness uniformity of the surface layer; this subtle, but important, difference implies that planarization allows for workpiece bending, which is generally undesirable in controlling *surface figure*. Finally, optical fabrication often requires slurry recirculation systems, owing to long polishing times, whereas CMP processes may make single-pass use of the polishing slurry.

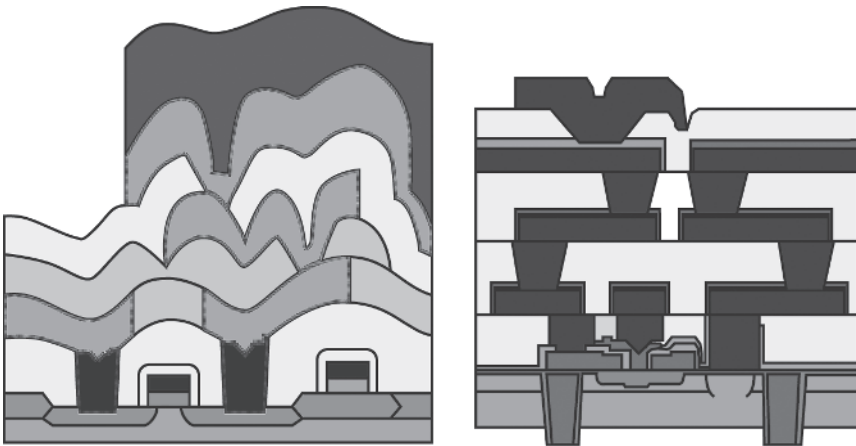


Figure 1.5 Comparisons of integrated circuits fabricated with and without CMP. Source: From Li 2007 [18].

1.2 Major Characteristics of the Optical-Fabrication Process

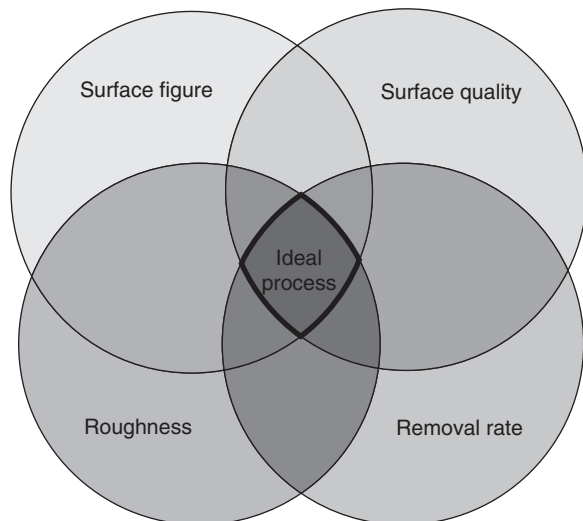
The major characteristics of the optical-fabrication process and resulting optic are defined as follows:

- (1) *Surface figure*. The long-range surface shape of the workpiece
- (2) *Surface quality*. The characteristics of the surface, including subsurface mechanical damage (scratches and digs), clarity, particle cleanliness and impurities, and structural modification to the workpiece surface
- (3) *Surface roughness*. The short-range surface topography of the workpiece
- (4) *Material removal rate*. The rate at which material is removed from a workpiece surface at a given process step.

Figure 1.6 illustrates how these characteristics overlap. Each plays an important role in the performance and cost of the optic.

- *Surface figure* influences overall light-wavefront modification desired for that optic
- *Surface quality* affects the degree of scatter and use survivability (e.g. vulnerability to laser damage or operating strength)
- *Surface roughness* affects surface scatter and, for high-power laser applications, laser-beam contrast
- *Material removal rate* affects the processing time and cost of the optic

Figure 1.6 Venn diagram illustrating the four major characteristics of optical fabrication. Ideally, an optimal process is developed that meets all specifications simultaneously.



An ideal optical-fabrication process is one optimized for all four of these major characteristics. Yet a common challenge in making process changes is that improvements to one characteristic may occur at the expense of another. For example, achieving very low roughness usually involves processing conditions that yield low *material removal rates* and thus a costlier optic.

Surface figure is typically measured by interferometric techniques (e.g. Refs [21, 22]) that describe the long-scale shape of the final workpiece. *Surface figure* is often described by Zernike polynomials (such as power, astigmatism, coma, or irregularity, as indicated in Figure 1.7) and a power-spectral-density plot (as in Figure 1.8). Zernike polynomials are a convenient way of describing the final surface of a round optic as a series of components of various aspects of the surface in the form [23], as follows:

$$z_p = a_n^m(R_n^m \cos m\varphi) + a_n^{-m}(R_n^{-m} \sin m\varphi) + a_n^0(R_n^0), \quad (1.1)$$

where a_n^m is the coefficient associated with a particular term, R_n^m are the radial polynomials, n is the radial order, m is the azimuthal frequency, and φ is the azimuthal angle. Note m and n are nonnegative integers with $n \geq m$. The sine–cosine terms in Equation (1.1) represent nonrotationally symmetric surfaces, and the last term represents rotationally symmetric surfaces. These polynomials have many useful characteristics, not least that they can be related directly to the classical aberrations and defined for circular, annular, and elliptical apertures. The *surface figure* specifications may involve transmitted or reflected wavefront, or both. In the case of transmitted wavefront, the homogeneity of the bulk material is important for many specifications [16, 24, 25].

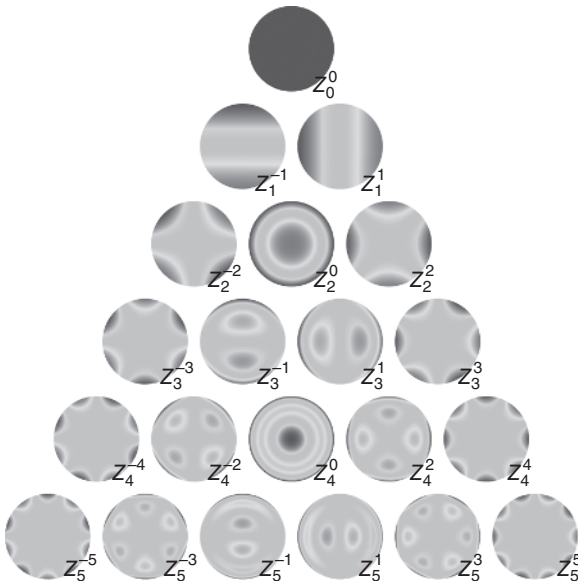


Figure 1.7 The first 21 Zernike polynomials describing the workpiece's surface figure, ordered vertically by radial degree and horizontally by azimuthal degree. Source: https://en.wikipedia.org/wiki/Zernike_polynomials.

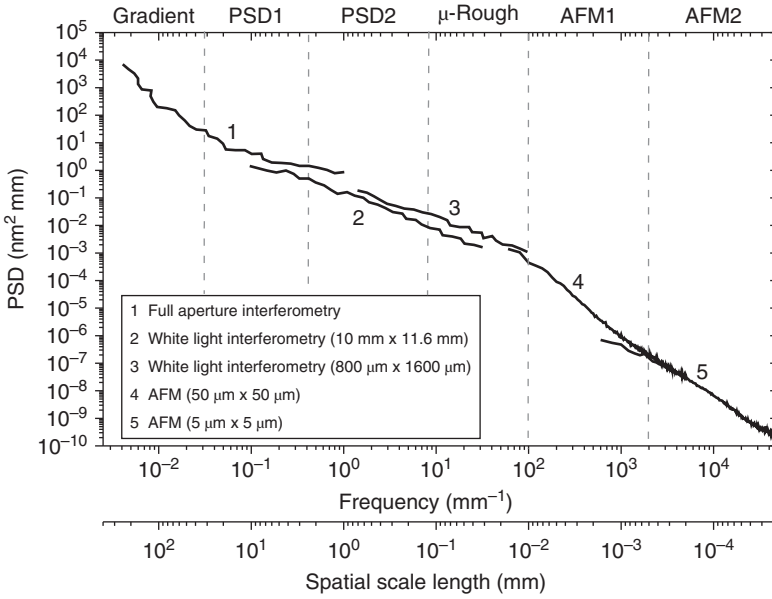


Figure 1.8 Example of a composite power spectral density of an optical surface over many spatial scale lengths, using different measurement techniques at different scale lengths. Typical techniques to measure spatial scale lengths are labeled. The left side of the plot represents long-range spatial scale lengths (referred to as surface figure). The right represents short-range spatial scale lengths (referred to as surface roughness).

Surface quality is a measure of the surface perfection achieved on a work-piece after finishing and cleaning. Examples of *surface quality* metrics include mechanical interactions such as surface microfractures or subsurface damage (SSD), plastic deformation, and densification; foreign particles or residue; and chemical interactions, such as surface molecular moieties and molecular impurities in the near-surface layer. SSD-type *surface quality*, commonly referred to scratch/dig, is usually specified using various standards [26–28]. For laser optics, an added requirement is to specify scratch/dig after a short chemical-etching process to reveal all such defects.

Surface roughness is a measure of the topographical relief of a surface. It is often used not only to describe ground surfaces (at μm -scale length) but also for optically smooth surfaces (at Angstrom- to nanometer-scale length). Roughness, δ , is typically described by the root mean square (RMS) of the surface topography:

$$\delta = \sqrt{\frac{1}{N} \sum_{i=1}^N z_{oi}^2} \quad (1.2)$$

where N is the number of discrete, equally spaced measured points along a surface, and z_o is the local surface height above or below the mean height of the surface. Note that the computed RMS roughness will depend on the total length of the surface profile (the maximum spatial length), the surface area being averaged over (i.e. lateral resolution), and the distance between data points (the minimum spatial-scale length) [29, 30]. Hence, RMS is not a unique value and depends strongly on measurement technique.

Another important description of *surface roughness* is the power spectral-density function (also called power spectra), which is the spatial frequency spectrum of *surface roughness*, measured in inverse length units, calculated from the Fourier transform of the surface height data (z_o). The power spectra over the smaller spatial scale lengths in Figure 1.8 describe roughness [29]. From long- to short spatial-scale lengths, the various spatial bands are referred to as the RMS gradient, PSD-1, PSD-2, μ -roughness, and atomic force microscopy (AFM) roughness. Power spectra are a convenient way in which to describe optical surfaces, since they can be related to the scattering per unit solid angle from a surface. They are also powerful in identifying periodic structures on a surface, as manifested by a spike in the power spectrum. An example set of specifications, including roughness, for a high-power laser optic is shown in Table 1.1.

Table 1.1 An example set of high-level specifications on a typical laser optic, defined in terms of surface figure (here, specifically transmitted wavefront through Zernike terms), roughness bands (fine-scale power spectra), surface quality (subsurface damage or scratch/dig), and bulk properties.

Type	Property	Value
Surface	Peak-to-valley	211 nm ($\lambda/3$)
	Gradient	<7 nm cm ⁻¹ ($\lambda/90$ /cm)
	PSD-1	1.8 nm rms
	PSD-2	1.1 nm rms
	Roughness	0.4 nm rms
	Scratch/Dig ^{a)}	20/10
Bulk	Index homogeneity	<5 ppm
	Absorbing inclusions (>5 μ m)	0
	Transparent inclusions lenslets	0

Values typical for 3 ω National Ignition Facility optics (40 cm aperture).

a) Post etch with number of scratches (width > 8 μ m) <12.

1.3 Material Removal Mechanisms

At the macroscopic level, the *material removal rate* for a given process step is conventionally described by the Preston equation: [31]

$$\frac{dh}{dt} = k_p \sigma_o V_r, \quad (1.3)$$

where dh/dt is the average thickness *removal rate*, k_p is the Preston coefficient, σ_o is applied pressure, and V_r is the average relative velocity of the polishing particle, relative to the substrate. Simply stated the rate of removal increases linearly with pressure and velocity. It is clear, however, that despite its tremendous practical utility, the equation is unsatisfying from a materials-science perspective because it does not specifically identify the many microscopic and molecular phenomena that occur during processing.

Before dissecting the Preston equation in Chapter 2, it is important to describe the basic microscopic and molecular mechanisms by which a material can be removed from the surface of a workpiece. There is a robust literature on the various proposed removal mechanisms (e.g. Refs [9, 10, 32, 33]). A unifying consideration for most of these removal mechanisms is the load per particle or load per asperity. The four basic mechanisms for removing material from a surface are brittle removal, chemical/physical dissolution, plastic deformation, and chemical reaction, as follows:

- In *brittle removal* (i.e. fracturing), the load per particle is sufficiently large that fractures of various types are induced on the surface, leading to fractured-particle removal. The grinding processes used for glass and ceramics are governed by brittle removal.
- *Chemical or physical dissolution* is the process by which material is removed by etching, via an acid or a base, or by gas-phase ion bombardment, either by reacting or physically removing atoms from the surface. The *material removal rate* is determined by chemical reaction rate, largely independent of load. Etching behavior (isotropic vs anisotropic, congruent, or incongruent, reaction rate vs mass transport limited) has large implications in the evolution of the surface.
- In *plastic deformation*, the load per particle is in a regime where it is lower than the fracture limit, resulting in a plastic flow of material and removal from the surface. Clearly, metals and soft materials may demonstrate such behavior, but glasses and other brittle materials have also been shown to exhibit such removal, with plasticity at the nm level.
- In particle *chemical reaction*, the load per particle is low – below the plastic-deformation limit. The particle's chemical characteristics allow a

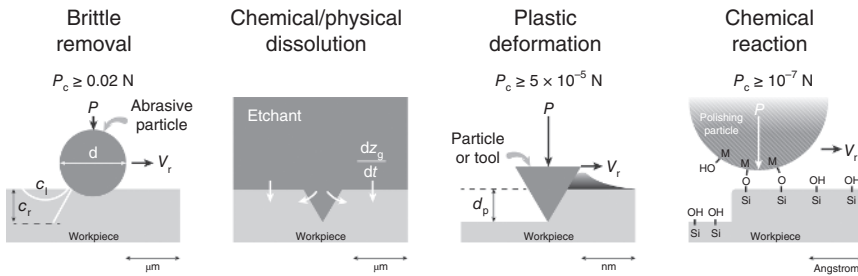


Figure 1.9 A schematic describing the various types of material removal mechanisms.

molecular-level reaction with the workpiece surface that causes material removal. The most common example in glass polishing is using cerium-oxide particles, where removal occurs via condensation and hydrolysis reactions. This phenomenon is known as the chemical tooth effect [10]. Figure 1.9 illustrates the material removal mechanisms given; further details are provided in subsequent chapters.

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