Chapter 1

Surface Metrics

The metrology of specular surfaces demands a continuing dialogue between the dual processes of inspection and measurement.

1.1 Introduction

The above plea by the author is made to stress the essential difference between the two processes of inspection and measurement. The following definitions are taken from the *Chambers Dictionary*.

Specular: mirrorlike
Inspect: to look into
Measure: the ascertainment of extent by comparison with a standard

The need for a clear understanding of the meaning of terms, often loosely applied in an industrial situation, arises unavoidably when drafting standards. A measurement standard aims to improve communication between a supplier and a customer by codifying measurement parameters typifying current good practice. It follows that purely subjective assessments, although essential for inspection, should be supported ultimately by an objective measurement traceable to national standards. To help further in understanding the subject, a glossary defining a selection of important technical terms is provided.

It should be noted here that an international standard is only published after receiving substantial agreement by an international community of experts. All standards are subject to review after five years but can be revised at any time, should the need arise through the advance of technology or due to the discovery of errors.

Optical components, with which this book is mostly concerned, usually require a degree of surface quality unsurpassed by most manufactured products. A traditional precision mechanical engineering workshop presented with a design requiring a surface-shape accuracy of 10 nm and residual RMS roughness of 1 nm, even accepting the vagueness of this specification, would probably be less than keen to quote. Optical workshops, however, have a long tradition of working to this level of drawing tolerance. The precise control of the passage of light through an optical system requires the use of tolerances related to its wavelength. The tolerances on mechanical components, however, where fit, lubrication retention, and wear rates are of primary concern, may be one or two orders of magnitude less demanding. The materials used in the optical workshop, however, are usually brittle and so the design of surface-generating machinery has progressed over the years along different lines for the two disciplines.

Recent developments in photonics, however, are having the effect of bringing together these hitherto largely separate disciplines. Machine bearings with greater stiffness and operating precision, improved machine mounting, on-machine measurement, robotic control, and improved surface-generating systems are now giving rise to new machines embodying selected features from mechanical and optical workshop technologies. Innovative techniques[1,2] for the generation of precision optical surfaces are reviewed from time to time.

In spite of advances in technology, reaching the high degree of perfection required by optical surfaces is costly and demands detailed knowledge of a variety of processing technologies combined with considerable operator skill. Since the latest techniques of topographical analysis indicate that no practical surface can be perfect, residual errors must be quantifiable and toleranced in terms that can be related to quality.

Here we shall review and explain current thinking on the process of inspection of high-quality surfaces and on the measurement and standardization of total surface topography in terms of its constituent parameters. These metrics include surface form, surface finish, texture, and imperfections. Surface form describes the macroscopic or global shape of a surface. Surface finish includes the microscopic texture of the surface and localized imperfections. Texture embodies roughness and waviness. Imperfections include localized defects, such as digs and scratches.

These metrics are chosen for measurement because they can have influence on the functional and cosmetic quality of the component. The extent of this influence will depend on where the component is situated within a system and on the particular application. It is therefore important to have a clear understanding of the influence it will have on quality, as perceived by the customer, when specifying a metric tolerance, whether based on theory or practice. Moreover, these metrics should be measurable by objective means to a stated uncertainty and traceable to national standards. Purely subjective assessments of, for example, surface scratches have given rise in the past to misunderstandings and so should be avoided if possible. The results of an international survey of a selection of constructional parameter tolerances for a variety of different applications are presented in Chapter 7 just as a general guideline to current practice based largely on subjective assessments. To complete the picture, some consideration will be given to the influence of these metrics on quality and also to the measurement of surface contamination. The current status of automatic inspection technology over large areas of high-quality surfaces is also presented.

A number of international standards relating to this subject have been published recently or are in draft form. Their historical development, new features, and their methods of operation are critically reviewed because they can provide insight into the need for future developments.

Attempts to assess the quality of a specular surface have traditionally been carried out subjectively by looking first at the image of a distant object reflected in the surface and then at the surface itself. If the surface is flat, the image is undistorted, and if no surface damage can be seen, we may conclude that the surface is of high quality. This inspection process, as we shall see, can achieve a high level of sensitivity in some respects but lacks precision and accuracy. Such observations can, however, be a necessary and valuable precursor to carrying out the subsequent process of measurement involving comparison with standards.

A plane light wave reflected from a nominally flat clean surface will carry an impression of residual height variations across the surface. We can expect that the spread of light obtained when the reflected beam is brought into focus, called the point spread function (PSF), will bear intensity information related quantitatively to the shape of the surface. Due to the mechanism of propagation, the light intensity variations arising from slowly varying form errors (low spatial frequencies) will be found near the center of the PSF and more rapidly varying surface errors (high spatial frequencies), due to poor finish, will be away from the center. If a scratch that contains a wide range of spatial frequencies is present, there will be a spread of light right across the PSF in the form of a line at right angles to the direction of the scratch.

Although this simple optical technique of examining the PSF can reveal surface errors of nanometer dimensions and is useful as a rapid tool for surface inspection, it has not been widely adopted for measurement. The lack of phase information, which tells us about the direction of travel of parts of the beam in the PSF, means that, without some prior information[3] about the character of the defect, we cannot calculate the shape of the wavefront and hence deduce surface shape errors. Fortunately, developments in optical technology have given rise to the computer-aided interferometer[4–6] that is capable, in principle, of measuring the shape of optical wavefronts to very high accuracy. Recent developments in image position sensing that enable the direction of travel of rays of light to be determined with great precision are creating renewed interest in electronic means for measuring[7–9] wavefront shapes first reported in 1965.

These optical techniques that combine the processes of inspection and measurement have been supported by the development of surface profilers from the fields of precision engineering and materials science. Sharp probes can now be scanned, in a production environment, over a surface to reveal surface height variations of atomic dimensions.[10] The employment of widely differing disciplines from the separate fields of optics and mechanics to measure the same surface provides valuable information regarding the strengths and weaknesses of both. We can, in this way, obtain a higher level of confidence regarding our uncertainty of measurement.

A wide variety of optical technologies for engineering metrology have been developed in recent years including, for example, photogrammetry, holographic interferometry, fringe projection, moiré interferometry, and speckle methods. These methods appear not, so far, to have found significant application in the high-precision optical field.

The material presented here is based on research conducted over the last 30 years at a number of organizations around the world. Work continues in an attempt to ensure that any standards proposed are supported by the best available technology and accepted by both the manufacturers and users of optical-quality surfaces.

1.2 Why Measure Surfaces?

Good reasons are required for measuring surfaces. The process is costly. We need to select, buy, calibrate, and maintain instruments. They must be installed in clean measurement areas. Operating staff need to be trained and given the opportunity to keep abreast of new developments. Laboratory accreditation may be needed to comply with quality assurance requirements. Then we have to consider the cost of labor and materials in undertaking and reporting measurements, and in dealing with the inevitable feedback from customers. Negotiation with design authorities may be needed to modify constructional tolerances to achieve acceptable production yields. All these costs influence profitability in a competitive manufacturing environment, so we need to be aware of the benefits to be derived from measurement to ensure that we do enjoy them.

1.2.1 System function

The quality of an image produced by an optical system is determined by the optical design chosen, the quality of the optical materials, and the manufacturing processes. We shall not be considering here the influence of the optical materials, the coatings of optical surfaces, the cementing process, or the errors associated with centering, edging, and mounting on the final image quality. Although these topics may occasionally be touched on, our main concern here is the specification and measurement of the optical surfaces to be generated.

Errors in the shape or form of a surface have a direct effect on the shape of a wavefront passing through an optical system. As little as a quarter of a wavelength of light deformation of a wavefront shape can transfer approximately 20% of power out from the center of the PSF to its edges. This broadens the PSF and gives rise to a reduction in the capability of the system to resolve extended images. If a diffraction-limited image quality is required over an extended image plane using ultraviolet radiation, the nature of the design process requires the use of a large number of surfaces, some of which will need to be made to tolerances perhaps two orders of magnitude better than this figure.

A reduction in the limit of resolution of an image is accompanied by a loss in contrast of structures that can still be resolved, although significant amounts of wavefront deformation can be tolerated before the level of veiling glare extending over the whole image plane can be detected. A much greater contribution to veiling glare[11] arises from poor-quality optical coatings and from the surface finish and the coatings of the mechanical parts of the system.

Optical systems designed for metrology, such as aerial survey cameras, require accurate geometrical correspondence between the object and image, as well as high-quality images. Low image distortion requires small tolerances on surface form as well as very accurate lens centration.

System function can also be degraded by the quality of the component surface texture. Residual light scatter from imperfectly polished surfaces, although having little effect on the PSF or the optical transfer function (OTF) of a system, could impair low-contrast image detection. The surface texture of mirrors used in a laser gyroscope is required to be of the highest standard because light scatter has a direct influence on drift rate.

The remaining metric related to finish is surface imperfections. These can occur as digs and scratches. If they appear on a graticule placed in an image plane, their effect may be described as functional since they would add to the pattern present, whereas if they exist elsewhere their effect may be considered as cosmetic. The exception to this arises in the case of optical components used in a laser system. Imperfections, even of nanometer dimensions, can, when exposed to high laser power or energy pulses, trigger weaknesses in the material structure, causing surface damage or even complete shattering of the component. Surface imperfections on a component used with laser radiation can therefore result in a reduction in its life, and so may be regarded as functional.

At the time of writing, material imperfections in the inner layer of toughened glass panels used in cars, windows, walls, and roofs are causing considerable concern.[12] Unstable impurities in the form of nickel sulphide crystals can cause shattering of panels without any warning. Means are required for detection, measurement, and classification since bubbles of the same size, always present, cause no problem.

1.2.2 Appearance

The appearance of optical components has improved over the years. Before the clarity of optical materials had reached its present high standard,[13] small surface imperfections and polish defects on a telescope lens would have been disguised by particle suspensions and some striae. As these usually had relatively little influence on the image seen, the manufacturers were ready to advise customers that lenses were designed for looking through and not at.

It is perhaps unfortunate that the appearance of an optical component usually bears no obvious relation to its performance. We cannot see the small deformations of a surface that could ruin an image or judge the little influence that an easily seen scratch will usually have on system use. The customer may, as a consequence, be likely to regard a system having a visible scratch as lacking in quality. If the manufacturer will pass a component with a scratch that can be seen, how will he have judged the significance of other errors not visible to the eye?

Surface defects, such as residual roughness and imperfections, will always be present to some degree and will be seen as an indication of component appearance quality, even though functional quality may be unimpaired. Some objective means for measurement and agreed acceptance tolerances are therefore necessary.

1.2.3 Manufacturing efficiency

Manufacturing efficiency can always be improved, providing present performance is known. In order to be aware of performance, we need to have knowledge of the shape and dimensions of products produced so that they can be compared with those appearing on specifications. If tolerances are exceeded, then product yields will be reduced. In order to improve manufacturing efficiency we need to know why this has happened. It is important, therefore, that the measurement process provides some diagnostic information that can be acted upon to rectify any drop in yield. Measurement is, therefore, essential for quality control, fault diagnoses, and process optimization.

1.2.4 Benefits

We have seen that the information provided by measurement is necessary for efficient manufacture but, if wisely interpreted, might also lead to benefits resulting from increased yields, cost reductions, and product improvements.

Still further benefits have been found to arise when a particular measurement has been made on a number of different products by different organizations, and the results are compared in a round-robin interlaboratory comparison. Several such exercises have been carried out over the last 50 years involving optical measurements, such as OTF, surface form errors, and laser beam profiles. The resulting spread of results, usually much greater than expected, when analyzed have provided much valuable information on instrument design problems, measurement procedures, and the need for calibrated reference components. This knowledge can then be embodied in new measurement standards of benefit to all manufacturers and users of optical systems.

1.3 Definition of Surface Metrics

Modern techniques for surface examination, such as the scanning electron microscope (SEM) and the scanning probe microscope (SPM), are capable of revealing structures of atomic dimensions. A lateral resolution of 1 nm and vertical resolution of 0.05 nm may be achieved with the SPM. It is to be expected, therefore, that any surface tested with sufficient care will be found to be less than perfect. But fortunately perfection is not required in real applications.

The whole amount of topographical information that could be recorded from measurements on an optical surface of, say, 50 mm diameter is so great as to be of little practical value without some form of data reduction. Figure 1.1 is an SEM image of real scratches on a glass substrate. The great amount of topographical information seen in the scratches and in the substrate extending even over such small areas illustrates this point.

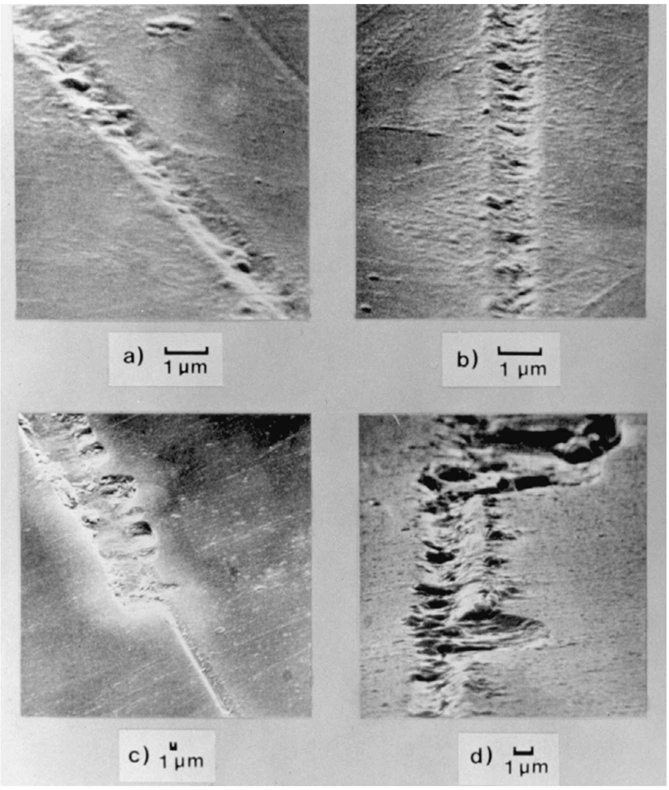

Figure 1.1 Magnified SEM images of real scratches on a glass substrate.

The simple geometrical laws of light propagation involving refraction and reflection form the basis of optical system design. In order to ensure that a given ray from a point in an object arrives at the desired image point, all optical surfaces encountered on the way must have a slope determined by the designer. The variation in value of this slope across the surface, when integrated, constitutes the form or shape of the surface. Most optical surfaces are spherical and of known radius that can vary from 1 mm to infinity, although increasingly surfaces of precisely known nonspherical form are being produced. The usual method of surface generation based on grinding and lapping ensures that errors in form are macroscopic laterally (greater than 1 mm extent) and microscopic vertically (less than 500 nm). Errors in surface form can usually be attributed to the generating machine. Since they can seriously degrade the performance of the optical component, for example, in terms of limiting resolution, it is essential that their magnitude be kept within limits defined on the optical drawing.

The final stage of surface generation usually involves polishing away the remains of surface irregularities left by lapping. These may occur as random or periodic height variations called, respectively, roughness and waviness, extending over the whole surface where they are collectively termed the surface texture or as localized imperfections usually consisting of digs and scratches. These remaining microscopic defects of texture and imperfections are referred to as the finish of the surface. The lateral spread of individual finish defects is usually less than 0.01 mm and their depth is usually less than 100 nm.

Diffraction and light scatter govern the significance of finish. Although optical system resolution may not be much affected by residual surface finish, an image could suffer reduced contrast and the presence of imperfections will degrade the cosmetic quality and therefore the value of the component. Imperfections cause additional problems with laser optics and low-light-level imaging systems, where a scratch can produce a disturbing line of light across an image plane. Imperfections can also give rise to radiation absorption and high field concentrations that may trigger surface damage in the presence of high-power/energy laser beams.

Unwanted light scatter can also arise from the imperfect deposition of thin film coatings and from surface contamination occurring before, during, or after system assembly. Unfortunately, most surface treatments after surface generation serve to degrade the quality of the surface to some extent.

Since all of the parameters defined above influence in some way the quality of the component, they should all be toleranced by the designer.

1.3.1 Surface metrics influencing quality

Figure 1.2 provides an exaggerated pictorial and underneath a schematic summary of the parameters or metrics that together define total surface topography. These metrics are chosen because of their relevance to the processes of design, surface generation and measurement, or to the appearance of a component. They are defined in the glossary.

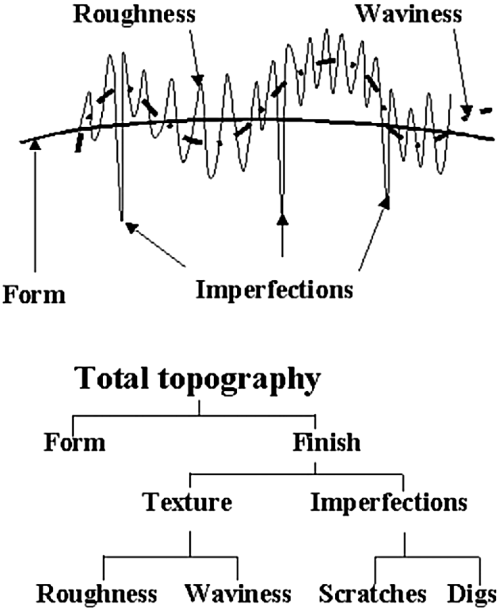

Figure 1.2 Surface metrics influencing quality.

1.3.2 Causes of defects in surface topography

The design and use of instrumentation for measuring these important parameters will be described, including reference to relevant ISO standards recently published or still in draft form. But first we need to review the likely causes of defects, in case they can be reduced or even eliminated.

Significant form errors are most likely to be due to problems with the surface-form generator. They require immediate correction. Surface deformations of 100 nm or less may be due to the processing technology involving perhaps temperature control and/or mounting/cementing stresses.

Surface roughness, often evident as microdefects distributed over a lapped surface and seen with a magnifier, should be removed by further polishing. If, however, the surface has been generated by single-point diamond turning, the roughness may be due to tool wear[14,15] and the waviness due to tool vibration.

Surface imperfections in the form of digs and scratches can be due to a dry polisher or to component handling and/or cleaning. Surface degradation can also arise from a corrosive environment or, in the case of high energy/power systems, to laser damage. Other defects, such as stain, bubbles, striae, and surface crazing, are due to materials or coating problems.

It will be seen from the above that the study of our subject, which may be described as the morphology of optical surfaces, requires consideration of many other interrelated fields and disciplines. These include instrumentation, technology, manufacturing processes, testing, specifications, training, and standards. Figure 1.3

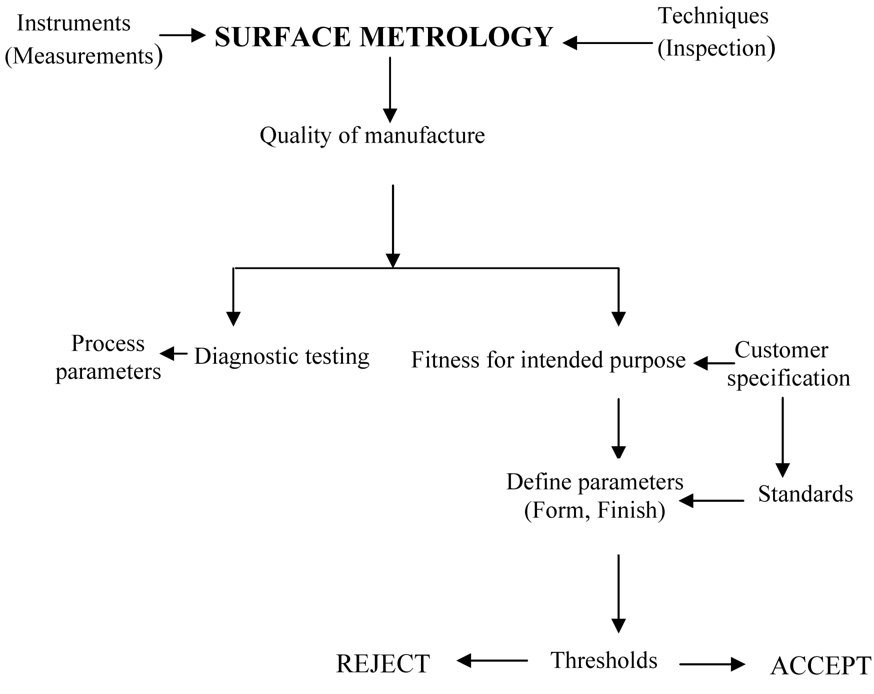

Figure 1.3 Optical surface morphology.

presents these relationships in an interactive pictorial form and illustrates the stages involved before reaching the final point of acceptance or rejection of a component.

1.4 Chapter Conclusions

We can summarize the measurement problems to be discussed as follows.

Modern surface analysis instruments, e.g., SEM and SPM, provide more deterministic data than can be used conveniently and indicate that no surface is likely to be perfect.

Metrics based on macroscopic (low spatial frequency, found by applying a low-pass filter) and microscopic (high spatial frequency, found by applying a high-pass filter) spreads in the lateral direction across a surface provide useful information on manufacturing processes and on component performance. A midrange spatial frequency or band-pass filter enables waviness to be measured.

The four metrics, comprising total topography, that need to be measured and standardized include: form, roughness, waviness, and imperfections.

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