9.1 INTRODUCTION

In contrast to the concepts we have studied hitherto, surface metrology is basically concerned with deviations between points on the same surface. On the other hand, in all other topics, the fundamental concern has been the relationship between a feature of a part or assembly and some other feature. Even though surface texture is important in many fields of interest such as aesthetics and cosmetics, among others, the primary concern in this chapter pertains to manufactured items that are subject to stress, move in relation to one another, and have close fits joining them. Surface roughness (a term used in a general way here, since it has specific connotations that will be explained shortly) or surface texture depends, to a large extent, on the type of the manufacturing operation. If rough surface for a part is acceptable, one may choose a casting, forging, or rolling operation. In many cases, the surfaces that need to contact each other for some functional requirement have to be machined, possibly followed by a finishing operation like grinding.

The reasons for pursuing surface metrology as a specialized subject are manifold. We would like to make our products operate better, cost less, and look better. In order to achieve these objectives, we need to examine the surfaces of the parts or components more closely, at the microscopic level. It would be naive to assume that two apparently flat contacting surfaces are in perfect contact throughout the apparent area of contact. Most of the earlier laws of friction were based on this assumption (perhaps until 1950). In reality, surfaces have asperities, which
refer to the peaks and valleys of surface irregularities. Contact between the mating parts is believed to take place at the peaks. When the parts are forced against each other, they deform either elastically or plastically. In case of elastic behaviour, they return to the full height after deformation by the mating surface. If they behave plastically, some of the deformation is permanent. These aspects have a bearing on the friction characteristics of the parts in contact. As mechanical engineering is primarily concerned with machines and moving parts that are designed to precisely fit with each other, surface metrology has become an important topic in engineering metrology.

9.2 SURFACE METROLOGY CONCEPTS

If one takes a look at the topology of a surface, one can notice that surface irregularities are superimposed on a widely spaced component of surface texture called waviness. Surface irregularities generally have a pattern and are oriented in a particular direction depending on the factors that cause these irregularities in the first place. Figure 9.1 illustrates some of these features.

Surface irregularities primarily arise due to the following factors:
1. Feed marks of cutting tools
2. Chatter marks on the workpiece due to vibrations caused during the manufacturing operation
3. Irregularities on the surface due to rupture of workpiece material during the metal cutting operation
4. Surface variations caused by the deformation of workpiece under the action of cutting forces
5. Irregularities in the machine tool itself like lack of straightness of guideways

Thus, it is obvious that it is practically impossible to produce a component that is free from surface irregularities. Imperfections on a surface are in the form of succession of hills and valleys varying in both height and spacing. In order to distinguish one surface from another, we need to quantify surface roughness; for this purpose, parameters such as height and spacing of surface irregularities can be considered. In mechanical engineering applications, we are primarily concerned with the roughness of the surface influenced by a machining process. For example, a surface machined by a single-point cutting tool will have a roughness that is uniformly spaced and directional. In the case of a finish machining, the roughness is irregular and non-directional. In general, if the hills and valleys on a surface are closely packed, the wavelength of the waviness is small and the surface appears rough. On the other hand, if the hills and valleys are relatively far apart, waviness is the predominant parameter of interest and is most likely caused by imperfections in the machine tool. If the hills and valleys are closely packed, the surface is said to have a primary texture, whereas surfaces with pronounced waviness are said to have a secondary texture.

9.3 TERMINOLOGY

**Roughness** The American Society of Tool and Manufacturing Engineers (ASTME) defines roughness as the finer irregularities in the surface texture, including those irregularities that result from an inherent action of the production process. Roughness spacing is the distance between successive peaks or ridges that constitute the predominant pattern of roughness. Roughness height is the arithmetic average deviation expressed in micrometres and measured perpendicular to the centre line.

**Waviness** It is the more widely spaced component of surface texture. Roughness may be considered to be superimposed on a wavy surface. Waviness is an error in form due to incorrect geometry of the tool producing the surface. On the other hand, roughness may be caused by problems such as tool chatter or traverse feed marks in a supposedly geometrically perfect machine. The spacing of waviness is the width between successive wave peaks or valleys. Waviness height is the distance from a peak to a valley.

**Lay** It is the direction of the predominant surface pattern, ordinarily determined by the production process used for manufacturing the component. Symbols are used to represent lays of surface pattern, which will be discussed in Section 9.5.

**Flaws** These are the irregularities that occur in isolation or infrequently because of specific causes such as scratches, cracks, and blemishes.

**Surface texture** It is generally understood as the repetitive or random deviations from the nominal surface that form the pattern of the surface. Surface texture encompasses roughness, waviness, lay, and flaws.

**Errors of form** These are the widely spaced repetitive irregularities occurring over the full length of the work surface. Common types of errors of form include bow, snaking, and lobbing.
9.4 ANALYSIS OF SURFACE TRACES

It is required to assign a numerical value to surface roughness in order to measure its degree. This will enable the analyst to assess whether the surface quality meets the functional requirements of a component. Various methodologies are employed to arrive at a representative parameter of surface roughness. Some of these are 10-point height average (Rz), root mean square (RMS) value, and the centre line average height (Ra), which are explained in the following paragraphs.

9.4.1 Ten-point Height Average Value

It is also referred to as the peak-to-valley height. In this case, we basically consider the average height encompassing a number of successive peaks and valleys of the asperities. As can be seen in Fig. 9.2, a line AA parallel to the general lay of the trace is drawn. The heights of five consecutive peaks and valleys from the line AA are noted down.

The average peak-to-valley height Rz is given by the following expression:

\[ R_z = \frac{(h_1 + h_3 + h_5 + h_7 + h_9) - (h_2 + h_4 + h_6 + h_8 + h_{10})}{5} \times \frac{1000}{\text{Vertical magnification}} \mu m \]

9.4.2 Root Mean Square Value

Until recently, RMS value was a popular choice for quantifying surface roughness; however, this has been superseded by the centre line average value. The RMS value is defined as the square root of the mean of squares of the ordinates of the surface measured from a mean line. Figure 9.3 illustrates the graphical procedure for arriving at an RMS value.

With reference to this figure, if \( h_1, h_2, \ldots, h_n \) are equally spaced ordinates at points 1, 2, \ldots, \( n \), then

\[ h_{RMS} = \sqrt{\frac{h_1^2 + h_2^2 + \ldots + h_n^2}{n}} \]

9.4.3 Centre Line Average Value

The Ra value is the prevalent standard for measuring surface roughness. It is defined as the average height from a mean line of all ordinates of the surface, regardless of sign. With reference to Fig. 9.4, it can be shown that

\[ R_a = \frac{A_1 + A_2 + \ldots + A_N}{L} = \frac{\sum A}{L} \]

Interestingly, four countries (USA, Canada, Switzerland, and Netherlands) have exclusively adopted Ra value as the standard for measuring surface roughness. All other countries have included other assessment methods in addition to the Ra method. For
instance, France has seven additional standards.

It should be mentioned here that the Ra value is an index for surface texture comparison and not a dimension. This value is always much less than the peak-to-valley height. It is generally a popular choice as it is easily understood and applied for the purpose of measurement. The bar chart shown in Fig. 9.5 illustrates the typical Ra values obtained in basic manufacturing operations.

<table>
<thead>
<tr>
<th>Process</th>
<th>Ra value in micrometres</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50–25</td>
</tr>
<tr>
<td>Flame cutting</td>
<td></td>
</tr>
<tr>
<td>Sawing</td>
<td></td>
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<td>Drilling</td>
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<td>Milling</td>
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<td>Reaming</td>
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<td>Laser machining</td>
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<td>Grinding</td>
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<td>Lapping</td>
<td></td>
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<tr>
<td>Sand casting</td>
<td></td>
</tr>
<tr>
<td>Forging</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 9.5** Bar chart indicating the range of Ra values for various manufacturing operations

*Note:* The bars indicate the entire range. In most cases, the Ra value is restricted to the mid 50% portion of the bars.

### 9.5 SPECIFICATION OF SURFACE TEXTURE CHARACTERISTICS

Design and production engineers should be familiar with the standards adopted for specification of the characteristics of surface texture. Symbols are used to designate surface irregularities such as the lay of surface pattern and the roughness value. Figure 9.6 illustrates the symbolic
There are basically two approaches for measuring surface finish: comparison and direct measurement. The former is the simpler of the two but is more subjective in nature. The comparative method advocates assessment of surface texture by observation or feel of the surface. Microscopic examination is an obvious improvisation of this method. However, it still
has two major drawbacks. First, the view of a surface may be deceptive; two surfaces that appear identical may be quite different. Second, the height of the asperities cannot be readily determined. Touch is perhaps a better method than visual observation. However, this method is also subjective in nature and depends, to a large extent, on the judgement of a person, and therefore not reliable.

These limitations have driven metrology experts to devise ways and means of directly measuring surface texture by employing direct methods. Direct measurement enables a numerical value to be assigned to the surface finish. The following sections explain the popular methods for the determination of surface texture.

9.7 STYLUS SYSTEM OF MEASUREMENT

The stylus system of measurement is the most popular method to measure surface finish. The operation of stylus instruments is quite similar to a phonograph pickup. A stylus drawn across the surface of the workpiece generates electrical signals that are proportional to the dimensions of the asperities. The output can be generated on a hard copy unit or stored on some magnetizable media. This enables extraction of measurable parameters from the data, which can quantify the degree of surface roughness. The following are the features of a stylus system:

1. A skid or shoe drawn over the workpiece surface such that it follows the general contours of the surface as accurately as possible (the skid also provides the datum for the stylus)
2. A stylus that moves over the surface along with the skid such that its motion is vertical relative to the skid, a property that enables the stylus to capture the contours of surface roughness independent of surface waviness
3. An amplifying device for magnifying the stylus movements
4. A recording device to produce a trace or record of the surface profile
5. A means for analysing the profile thus obtained

9.7.1 Stylus and Datum

There are two types of stylus instruments: true datum and surface datum, which are also known as skidless and skid type, respectively. In the skidless instrument, the stylus is drawn across the surface by a mechanical movement that results in a precise path. The path is the datum from which the assessment is made. In the skid-type instrument, the stylus pickup unit is supported by a member that rests on the surface and slides along with it. This additional member is the skid or the shoe. Figure 9.8 illustrates the relationship between the stylus and the skid.

Skids are rounded at the bottom and fixed to the pickup unit. They may be located in front of or behind the stylus. Some instruments use a shoe as a supporting slide instead of a skid. Shoes are flat pads with swivel mountings in the head. The datum created by a skid or a shoe is the locus of its centre of curvature as it slides along the surface.

The stylus is typically a diamond having a
cone angle of 90° and a spherical tip radius of 1–5 µm or even less. The stylus tip radius should be small enough to follow the details of the surface irregularities, but should also have the strength to resist wear and shocks. Stylus load should also be controlled so that it does not leave additional scratch marks on the component being inspected.

In order to capture the complete picture of surface irregularities, it is necessary to investigate waviness (secondary texture) in addition to roughness (primary texture). Waviness may occur with the same lay as the primary texture. While a pointed stylus is used to measure roughness, a blunt stylus is required to plot the waviness.

9.8 STYLUS PROBE INSTRUMENTS

In most stylus-based instruments, a stylus drawn across the surface of a component being inspected generates electrical signals that are proportional to the changes in the surface asperities. An electrical means of amplifying signals, rather than a purely mechanical one, minimizes the pressure of the stylus on the component. Changes in the height of asperities may be directly read by a meter or a chart. Most instruments provide a graph of the stylus path along the surface. The following paragraphs explain some of the popular stylus probe instruments used for measuring surface roughness.

9.8.1 Tomlinson Surface Meter

This is a mechanical–optical instrument designed by Dr Tomlinson of the National Physical laboratory of the UK. Figure 9.9 illustrates the construction details of the Tomlinson surface meter. The sensing element is the stylus, which moves up and down depending on the irregularities of the workpiece surface. The stylus is constrained to move only in the vertical direction because of a leaf spring and a coil spring. The tension in the coil spring P causes a similar tension in the leaf spring. These two combined forces hold a cross-roller in position between the stylus and a pair of parallel fixed rollers. A shoe is attached to the body of the instrument to provide the required datum for the measurement of surface roughness.

A light spring steel arm is attached to the cross-roller and carries a diamond tip. The translatory motion of the stylus causes rotation of the cross-roller about the point A, which in turn is converted to a magnified motion of the diamond point. The diamond tip traces the profile of the workpiece on a smoked glass sheet. The glass sheet is transferred to an optical projector and magnified further. Typically, a magnification of the order of 50–100 is easily achieved in this instrument.

![Tomlinson surface meter](image-url)
In order to get a trace of the surface irregularities, a relative motion needs to be generated between the stylus and the workpiece surface. Usually, this requirement is met by moving the body of the instrument slowly with a screw driven by an electric motor at a very slow speed. Anti-friction guide-ways are used to provide friction-free movement in a straight path.

### 9.8.2 Taylor–Hobson Talysurf

The Taylor–Hobson talysurf works on the same principle as that of the Tomlinson surface meter. However, unlike the surface meter, which is purely a mechanical instrument, the talysurf is an electronic instrument. This factor makes the talysurf a more versatile instrument and can be used in any condition, be it a metrology laboratory or the factory shop floor.

Figure 9.10 illustrates the cross section of the measuring head. The stylus is attached to an armature, which pivots about the centre of piece of an E-shaped stamping. The outer legs of the E-shaped stamping are wound with electrical coils. A predetermined value of alternating current (excitation current) is supplied to the coils. The coils form part of a bridge circuit. A skid or shoe provides the datum to plot surface roughness. The measuring head can be traversed in a linear path by an electric motor. The motor, which may be of a variable speed type or provided with a gear box, provides the required speed for the movement of the measuring head.

As the stylus moves up and down due to surface irregularities, the armature is also displaced. This causes variation in the air gap, leading to an imbalance in the bridge circuit. The resulting bridge circuit output consists of only modulation. This is fed to an amplifier and a pen recorder is used to make a permanent record (Fig. 9.11). The instrument has the capability to calculate and display the roughness value according to a standard formula.

### 9.8.3 Profilometer

A profilometer is a compact device that can be used for the direct measurement of surface texture. A finely pointed stylus will be in contact with the workpiece surface. An electrical pickup attached to the stylus amplifies the signal and feeds it to either an indicating unit or a recording unit. The stylus may be moved either by hand or by a motorized mechanism.

The profilometer is capable of measuring roughness together with waviness and any other surface flaws. It provides a quick-fix means of conducting an initial investigation before attempting a major investigation of surface quality.
9.9 WAVELENGTH, FREQUENCY, AND CUT-OFF

The complete traverse length of the stylus instrument is called the measuring traverse length. It is divided into several sampling lengths. The sampling length is chosen based on the surface under test. Generally, results of all the samples in the measuring traverse length are averaged out by the instrument to give the final result.

Skids simplify surface assessment while using stylus instruments. However, there is a distortion because of phase relationship between the stylus and the skid. This aspect is illustrated in Fig. 9.12. In case A, the stylus and the skid are in phase. Therefore, roughness (the primary texture) will be relatively undistorted. In case B, the two are out of phase. In this situation, waviness superimposes on the roughness reading and is misleading. In case C also, the stylus and skid are out of phase, resulting in an unrealistic interpretation of roughness value.

Thus, since the skid, like the stylus, is also rising and falling according to the surface asperities, stylus height measurement may be distorted. Therefore, care must be exercised for the selection of sampling length.

9.9.1 Cut-off Wavelength

The frequency of the stylus movement as it rises up and down the workpiece surface is determined by the traversing speed. Assuming that \( f \) is the frequency of the stylus movement, \( \lambda \) is the surface wavelength, and \( v \) is the traverse speed, one gets the following equation:

\[
f = \frac{v}{\lambda}
\]

Therefore, \( f \propto \frac{1}{\lambda} \), if \( v \) remains constant.

For surfaces produced by single-point cutting tools, a simple guideline for selecting cut-off wavelength is that it should not exceed one feed spacing. However, for many fine irregular surfaces, a cut-off length of 0.8 mm is recommended. Table 9.1 illustrates the recommended cut-off wavelengths for machining processes.

<table>
<thead>
<tr>
<th>Finishing processes</th>
<th>Cut-off length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superfinishing, lapping, honing, diamond boring, polishing, and buffing</td>
<td>0.25–0.8</td>
</tr>
<tr>
<td>Grinding</td>
<td>0.25–0.8</td>
</tr>
<tr>
<td>Turning, reaming, and broaching</td>
<td>0.8–2.5</td>
</tr>
<tr>
<td>Boring, milling, and shaping</td>
<td>0.8–8.0</td>
</tr>
<tr>
<td>Planning</td>
<td>2.5–25</td>
</tr>
</tbody>
</table>
9.10 OTHER METHODS FOR MEASURING SURFACE ROUGHNESS

In addition to the stylus-based methods of surface roughness measurement explained in Section 9.8, this section presents in brief some of the alternative methods used in the industry.

9.10.1 Pneumatic Method

The *air leakage method* is often used for assessing surface texture. A pneumatic comparator is used for conducting mass inspection of parts. Compressed air is discharged from a self-aligning nozzle held close to the surface being inspected. Depending on height variations in the surface irregularities, the gap between the nozzle tip and the workpiece surface varies. This results in the variation of flow rate of air, which in turn varies the rotation speed of a rotameter. Rotation of the rotameter is an indication of surface irregularities. Alternatively, a float can also be used to measure surface deviations. The comparator is initially set using reference gauges.

9.10.2 Light Interference Microscopes

The light interference technique offers a non-contact method of assessing surface texture. Advantages of this method are that it allows an area of the workpiece surface to be examined, a wide range of magnifications to be used, and the opportunity for making a permanent record of the fringe pattern using a camera. Good magnification capability allows good resolution up to a scratch spacing of 0.5 µm.

A monochromatic light passing through an optical flat and falling on the workpiece surface generates the fringe pattern. The technique of measurement using interference fringes has already been explained in Chapter 7. However, assessment of surface irregularities cannot be directly related to the Ra value. Master specimens are used to generate a reference fringe pattern, which is compared with the fringe pattern of the workpiece in order to arrive at a conclusion regarding surface quality. This method provides a viable alternative for inspecting soft or thin surfaces, which normally cannot be examined using stylus instruments.

9.10.3 Mecrin Instrument

The Mecrin instrument assesses surface irregularities through frictional properties and the average slope of the irregularities. This gauge is suited for surfaces manufactured by processes such as grinding, honing, and lapping, which have low Ra values in the range 3–5 µm. Figure 9.13 illustrates the working principle of this instrument.

A thin metallic blade is pushed against the workpiece surface at a certain angle. The blade may slide or buckle, depending on the surface roughness and the angle of attack. At lower angles of attack, the blade tip will slide over the surface of the workpiece. As the angle of attack is increased, a critical

![Fig. 9.13 Principle of the Mecrin instrument](image-url)
value is reached at which the blade starts to buckle. This critical angle is a measure of the degree of roughness of the surface. The instrument is provided with additional features for easier handling. A graduated dial will directly give the reading of roughness value.

A QUICK OVERVIEW

- Workpiece surfaces have *asperities*, which are the peaks and valleys of surface irregularities. Contact between mating parts is believed to take place at the peaks. When the parts are forced against each other, they deform either elastically or plastically. In case of elastic behaviour, they return to the full height after deformation by the mating surface. If they behave plastically, some of the deformation is permanent. As these aspects have a bearing on the friction characteristics of the parts in contact, the study of surface texture has become an important part of metrology.
- To measure the degree of surface roughness, it is required to assign a numerical value to it. This will enable the analyst to assess whether the surface quality meets the functional requirements of a component. Various methodologies are employed to arrive at a representative parameter of surface roughness. Some of these are 10-point height average, RMS value, and the centre line average height.
- There are two approaches for measuring surface finish: comparison and direct measurement. The former is the simpler of the two, but is more subjective in nature. The comparative method advocates assessment of surface texture by observation or feel of the surface. On the other hand, direct measurement is more reliable since it enables a numerical value to be assigned to the surface finish.
- The stylus system of measurement is the most popular method to measure surface finish. Operation of stylus instruments is quite similar to a phonograph pickup. A stylus drawn across the surface of the workpiece generates electrical signals that are proportional to the dimensions of the asperities. The output can be generated on a hard copy unit or stored on some magnetizable media. This enables extraction of measurable parameters from the data, which can quantify the degree of surface roughness.
- Among the stylus-based measurement systems, the Tomlinson surface meter and Taylor–Hobson talsurf are popular.
- The complete traverse length of the stylus instrument is called the measuring traverse length. It is divided into several sampling lengths. The sampling length is chosen based on the surface under test. Generally, the results of all the samples in the measuring traverse length are averaged out by the instrument to give the final result.
- The frequency of the stylus movement as it rises up and down the workpiece surface is determined by the traversing speed. If $f$ is the frequency of the stylus movement, $\lambda$ is the surface wavelength, and $v$ is the traverse speed, then $f = v/\lambda$.

MULTIPLE-CHOICE QUESTIONS

1. Surface texture depends to a large extent on
   (a) material composition
   (b) type of manufacturing operation
   (c) skill of the operator
   (d) accuracy of measurement

2. Peaks and valleys of surface irregularities are called
   (a) waves
   (b) manifolds
   (c) asperities
   (d) perspectives

3. While roughness is referred to as a primary