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Surface Texture Measurements of Gear Surfaces Using Stylus Instruments

INTERMEDIATE

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NPL Authors and Contributors

Wenjuan Sun
Andrew Lancaster
Claudiu Giusca*

*Former NPL employee, currently employed by Cranfield University

Newcastle University Authors and Contributors

Robert Frazer

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National Physical Laboratory
Hampton Road
Teddington
Middlesex
TW11 0LW
United Kingdom

Telephone: +44 (0)20 8977 3222
e-mail: training@npl.co.uk
www.npl.co.uk

Foreword

In this guide, the authors aim to provide simple guidance for readers seeking to understand gear surface texture measurements made using stylus instruments. Target readers include designers of gears who require knowledge of gear measurements, gear manufacturers who would like to control the quality of the gear surface manufactured and metrologists who would like to perform measurements of gears. The content is written at a technical level that requires prior knowledge of Measurement Good Practice Guide 37, 'The measurement of surface texture using stylus instruments' [1], and basic knowledge of uncertainty evaluation. This guide is focused on general measurement tasks, and it is not the authors' intention to cover all potential measurement tasks.

The first and second chapters provide background knowledge of gears and gear surface texture. The third, fourth and fifth chapters provide instruction on gear surface measurements, gear surface texture parameter calculations and uncertainty evaluation.

The focus of this guide is the measurements of spur and helical involute gears used in renewable energy drivetrains, although the guide is likely to be applicable to a wider range of gear geometries. Surface texture measurements of the active contacting face of the flanks and the non-contacting root fillets of the gear teeth are considered.

For complete guidance on using stylus instruments, calibration and uncertainty calculation, readers are encouraged to review Good Practice Guide 37, 'The Measurement of Surface Texture using Stylus Instruments' for more information.

This guide is not intended to be an authoritative guide to the surface texture and gear specification standards and the primary reference should always be the standards themselves.

Wenjuan Sun PhD, et al.

Acknowledgements

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Draft International Standards are subject to change. Reference should be made to the final published version of the standard where applicable.

Contents

Chapter 1

Introduction to gears

- Fundamentals of gears
- Gear manufacturing processes
- Surface texture and gear performance

Fundamentals of gears

Gears are key components of power transmission systems, with applications spanning the automotive, aerospace, medical and power generation sectors, to name a few. A gear works by engaging its peripheral teeth with those of another gear, allowing rotary power to be transferred from one gear to the other gear. A system of gears can be arranged to modify the speed and direction of a rotation or the amount of torque which is transmitted. In this section, the relevant gear geometry vocabulary will be introduced. This introduction is followed by an overview of effects of gear surface texture on efficiency and lifetime, and includes a discussion of common failure modes.

BS ISO 1122-1:1998 has standardised the vocabulary describing gear geometry [2]. Figure 1 summarises the geometrical terms of interest in this guide, and Table 1 lists the ISO definitions.

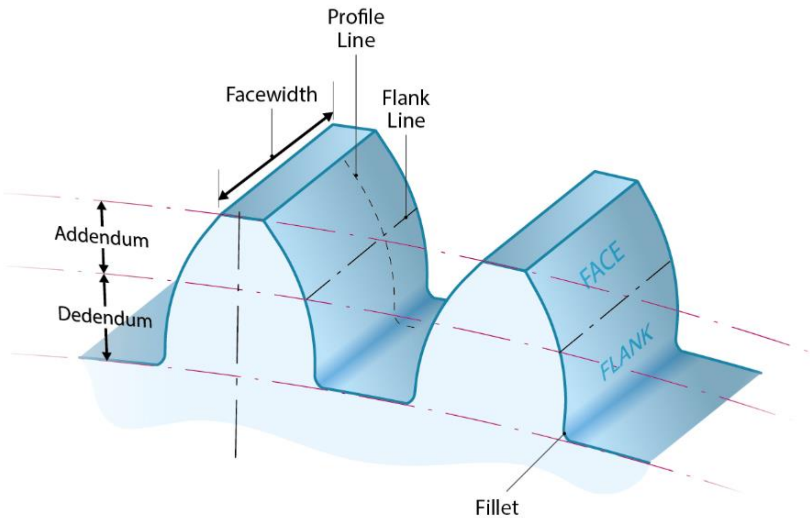

Figure 1. *Gear geometry vocabulary relevant to the measurements covered by this guide.*

Term	Definition
Tooth flank	The part of the surface which lies between the tip surface and the root surface
Facewidth	Length over the toothed part of the gear
Tooth profile	Line of intersection of a tooth flank with any defined surface which also cuts the reference plane
Flank Line	Line intersection of a tooth flank with a coaxial surface of revolution
Fillet	Curved surface between the usable flank and the root surface
Reference surface	Imaginary conventional surface relative to which the dimensions of the teeth of a gear are defined
Addendum	Part of a gear tooth between the reference surface and the tip surface
Dedendum	Part of a gear tooth between the reference surface and the root surface

Table 1. *Summary of relevant BS ISO 1122-1:1998 [2] gear geometry terms.*

The form of a gear tooth ensures that gears can run smoothly and provide uniform motion of the driven gear when the driven gear rotates at constant speed. Gears that fulfil this criterion are said to be conjugate. There are many different conjugate tooth forms but the involute curve (the arc drawn as a taut string is unwound from a circle) is the most common gear profile because it is easy to make, easy to measure and insensitive to centre distance tolerances.

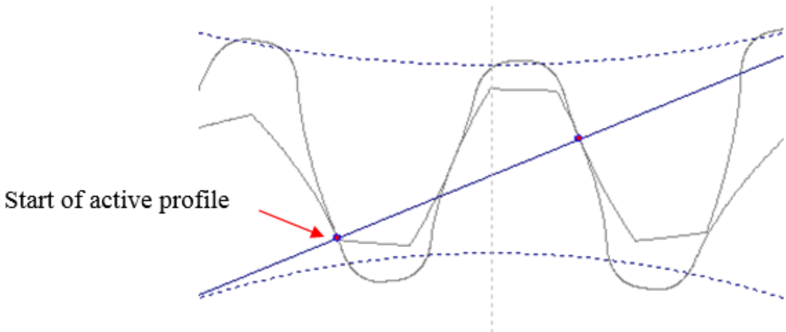

Figure 2. *Gear positions at the start of active profile (part of a tooth which contacts the tooth flanks of a mating gear along the line of action). The upper gear has a higher rolling velocity than the lower gear at the start of the active profile (SAP), leading to a large sliding action.*

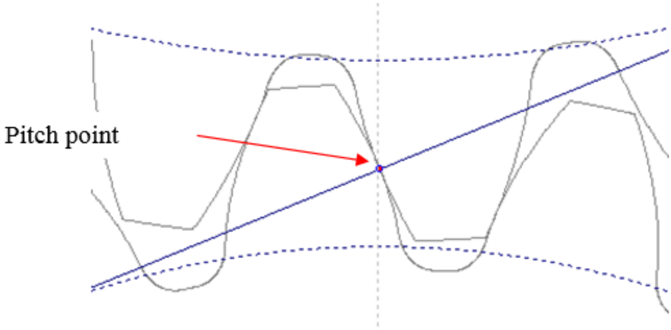

Figure 3. *Gear positions at the pitch point, which lies on the line between the two gears where sliding speed is zero. The action is purely rolling as they both have the same rolling velocity at this time.*

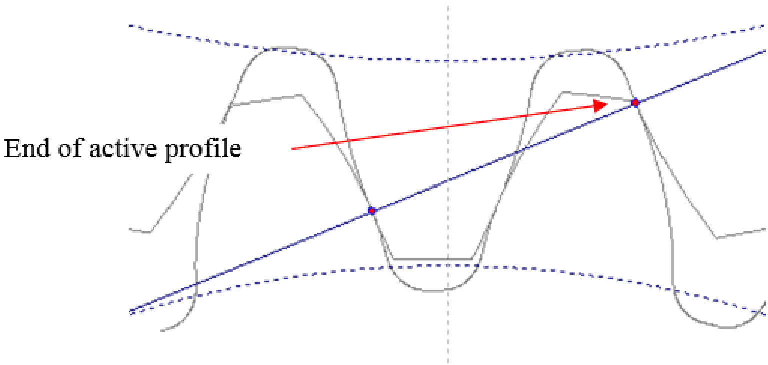

Figure 4. *Gear positions at the end of active profile. The upper gear has a lower rolling velocity than the lower gear at the end of the active profile (EAP), again leading to a sliding action.*

The interaction between two involute teeth varies along the tooth profile and is a combination of rolling and sliding. Figure 2, Figure 3 and Figure 4 show the motion of meshed gear teeth. The sliding action arises from the difference in rolling velocity between the two teeth at the mesh (contact) point, and is high when the teeth first mesh. The sliding speed then reduces until the pitch point, which lies on the line between the two gear centres, where the action is purely rolling. Once the mesh point passes the pitch point, the difference in rolling velocities increases and the sliding speed once again increases. The change in action means that different sections of the gear tooth experience different meshing conditions which modifies the failure modes. Knowledge of surface texture in different locations is required to fully understand their behaviour. The characterisation of the surface roughness in the sliding direction (root to tip for a driving gear or tip to root in a driven gear) is therefore of prime importance.

Gear manufacturing processes

Gears for renewable energy drivetrains are manufactured from case-hardened steel and are commonly produced by soft cutting followed by heat treatment and a hard-finishing process such as form grinding, honing or other processes to finish the gear meshing surfaces. The root fillet regions also undergo grinding in some instances. The grinding process results in a grinding lay, illustrated in Figure 5, which is aligned approximately perpendicularly to the gear sliding direction. The lay is the direction of the predominant surface pattern. Lay usually derives from the actual production process used to manufacture the surface and results in directional striations across the surface.

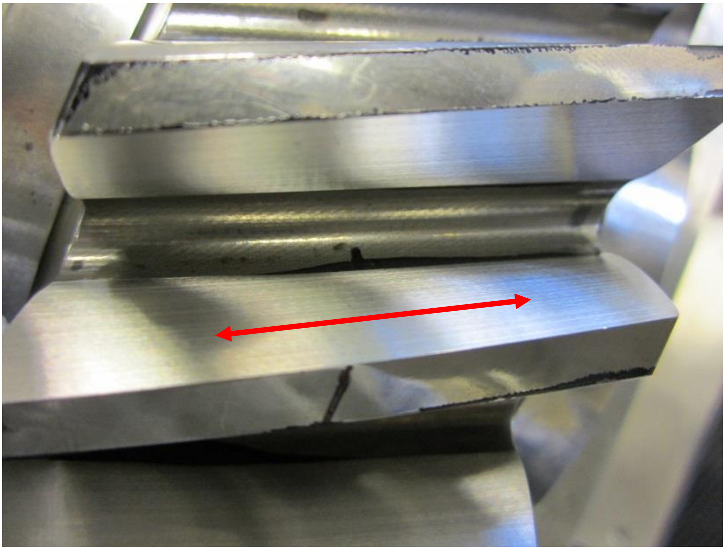

Figure 5. *Grinding lay from a gear form grinding machine.*

Other common lay directions left by gear manufacturing processes are detailed in BS ISO TR 10064-4 [3] and illustrated in Figure 6.

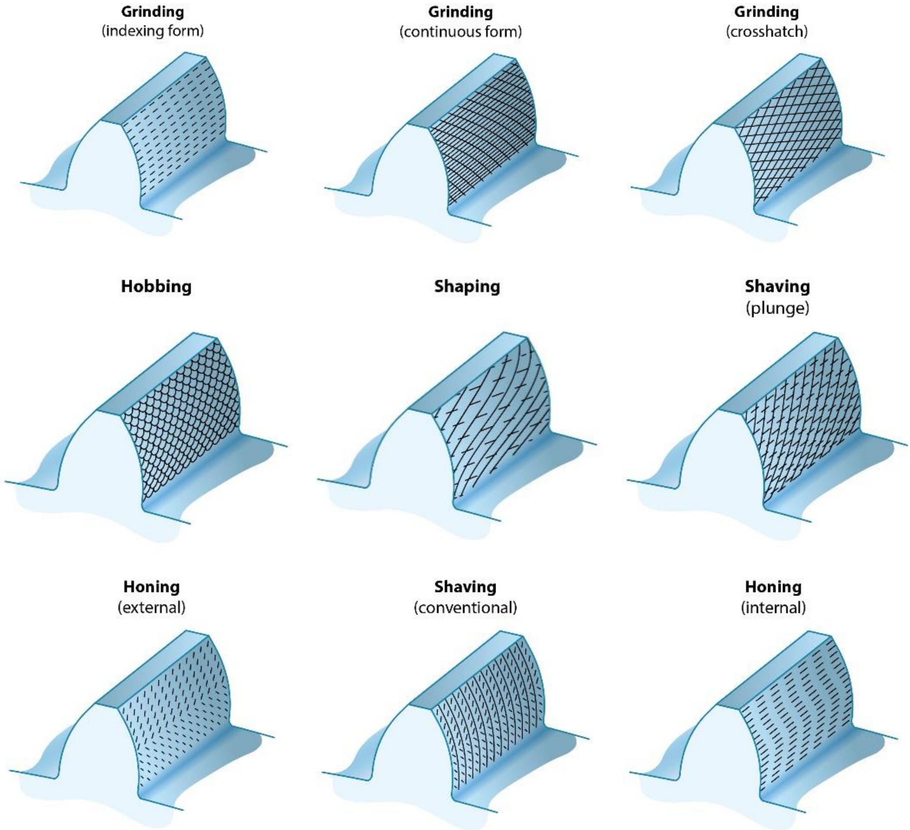

Figure 6. *Common gear manufacturing processes and lay directions. Reproduced from BS ISO TR 10064-4 [3].*

Grinding processes tend to produce repeatable form deviations on each gear tooth, but the grinding wheel can become blunt and its surface contaminated over time. A blunt or contaminated wheel may produce a different surface texture. It is common to redress or re-cut the form of the grinding wheel after the grinding wheel has cut a specified number of teeth. Gear teeth ground after the grinding wheel has been redressed will likely have different surface deviations and cutting characteristics from those ground before it. Additional surface texture measurements are necessary to fully quantify the parameters of the gear if the grinding wheel has been redressed. Knowledge of the redressing process, and when it was performed during gear grinding, is required to develop an efficient and effective measurement strategy.

Superfinishing is another manufacturing process commonly used for renewable energy drivetrains and uses small polishing stones which are suspended in a medium and vibrated in a bath along with the gears to remove the grinding marks. Superfinishing is usually accelerated through the use of chemicals and must be tailored to each application to optimise the time taken and the volume of the media. The shape of the involute means that the effect of the superfinishing process varies over both the profile and facewidth of each tooth, and may not be consistent between teeth.

Surface texture and gear performance

The surface texture of a gear plays an important role in many aspects of gear behaviour. Investigations into the effect of surface texture on gear performance have been of interest for many years. It has been observed that gear lifetime increases when gears are superfinished to improve their surface texture [4]. The frictional torque exerted on a gear can drop significantly as the surface texture improves [5], which is accompanied by a drop in the bulk temperature of the gear tooth and a small increase in efficiency. Increased efficiency after polishing is widely reported [6, 7].

The noise generated by the gears is linked to the surface waviness [8].

The surface roughness can be the most significant factor influencing the lubrication of gears [9] (note that the work referenced uses the pre-1997 parameter definitions, see NPL Good Practice Guide 37 for details). In the contacting regions of the tooth flank, poor surface roughness affects friction and can cause contact fatigue such as micro- and macro-pitting, as discussed below. Poor surface roughness can also cause lubrication breakdown and the resulting welding and separation of teeth can cause scuffing failure. Reducing the surface roughness will reduce the amount of damage [10] as fewer asperities break through the lubricant film. In the noncontact root region, surface roughness contributes to the risk of cracks initiating a bending fatigue type of failure (see section 'Tooth breakage due to bending fatigue').

Some effects of surface texture are quantified in ISO standards, which are detailed in the following sections of this chapter. The terminology used is defined in ISO 10825:1995 [11]. Note that surface texture is only one of several factors which determine gear performance and must be viewed as part of the larger set of gear properties. The importance of considering all the properties of the gear is illustrated in relevant literature [12], where improving the surface texture actually caused an acceleration of the gear failure because it inhibited the development of micro-pitting. The design of the gear meant that the micro-pitting was actually slowing a more aggressive macro-pitting mechanism. However, this type of effect is rare.

The surface texture of gears changes during operation because of asperity contact and wear. Changes in the measured values of the roughness parameters can be used to monitor the current state of the gears.

Micro-pitting

Micro-pitting is caused by asperities on the surface of the two gears extending beyond the depth of the lubricating film. It appears as an area of 10 µm-20 µm deep pits on the surface of the gear tooth, as shown in Figure 7, and can develop into a more serious form of damage, such as the macro-pitting illustrated in Figure 8. PD ISO/TR 15144-1 [13] covers the calculation of the local lubricant thickness. As the surface roughness (characterised by *Ra*) falls, the number of asperities which extend beyond the lubricant film also decreases which reduces the risk of micro-pitting occurring on the gear tooth.

Figure 7. *Gear micro-pitting (grey staining) contact fatigue damage.*

Pitting due to contact stress

Pitting (or macro-pitting) occurs when the contact stress on the gear surface becomes too large. BS ISO 6336-2:2006 specifies calculations to predict macro pitting risk and uses the maximum roughness height *Rz* as an influence factor to calculate the permissible contact stress for the gear [14]. As the *Rz* value for the surface is reduced, the permissible contact stress increases, reducing the likelihood of pitting on the gear. An example of macro-pitting is shown in Figure 8.

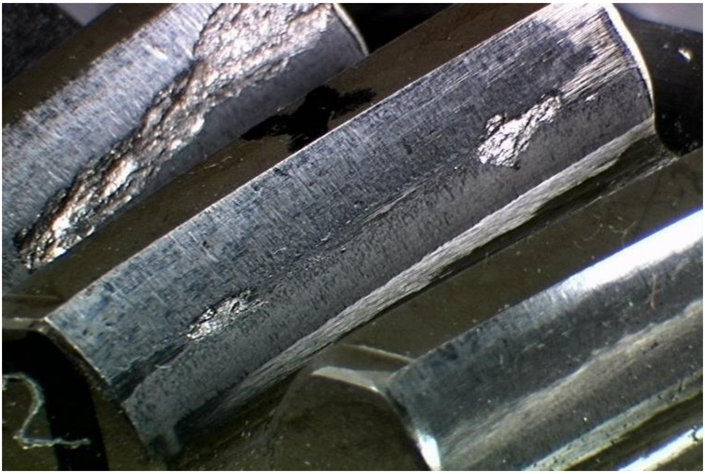

Figure 8. *Macro-pitting fatigue damage on gear teeth.*

Tooth breakage due to bending fatigue

The surface roughness in the root fillet, along with its overall geometry, contribute to the risk of tooth failure due to bending fatigue. This failure mode is illustrated in Figure 9, and the region of maximum bending stress is shown in Figure 10. The surface roughness effect is quantified in BS ISO 6336-3:2006 [15], which uses *Rz* in its calculation of tooth bending strength. The safety factor against tooth bending increases as the surface roughness is reduced.

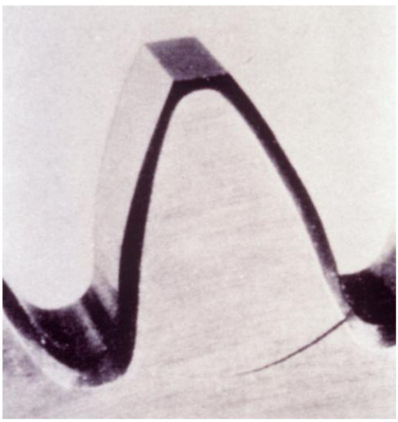

Figure 9. *Gear bending fatigue failure initiated in the root fillet radius.*

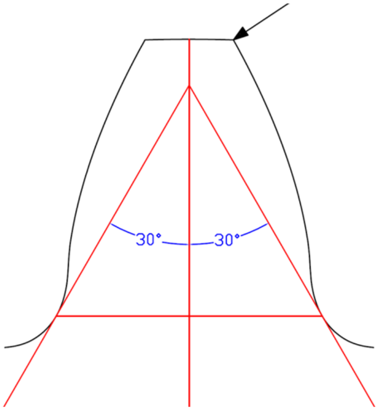

Figure 10. *30^o tangent position for root fillet roughness measurement at the predicted region of maximum bending stress in BS ISO 6336-3 [16]. The arrow is the applied load.*

Scuffing

Scuffing failure is caused by lubrication breakdown leading to welding and then separation of the gear teeth. The arithmetical mean deviation of the roughness profile , *Ra*, is used in BS ISO/TR 13989-1 [17] and BS ISO/TR 13989-2 [18] to link the surface texture to scuffing damage. An increase in the surface roughness leads to a higher coefficient of friction which in turn leads to increased scuffing damage to the gears. An example of scuffing damage is shown in Figure 11.

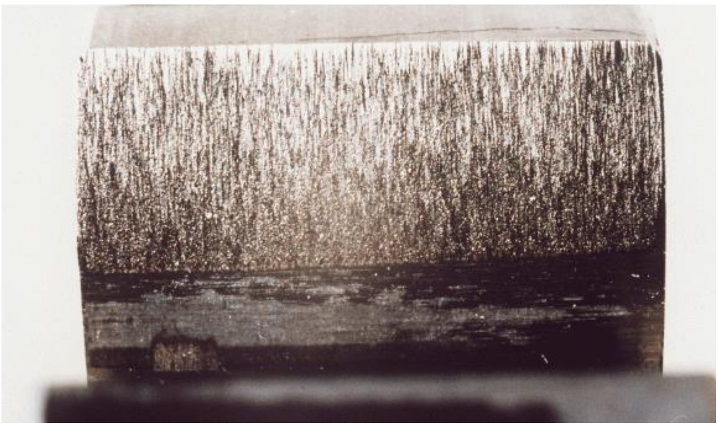

Figure 11. *Scuffing (scoring) caused by lubricant failure leading to welding and sliding of the mating gear tooth flanks.*

Chapter 2

Introduction to surface texture

- Surface texture terms and definitions
- Contact stylus instruments and measurements

Surface texture terms and definitions

In this section, general terms related to surface texture will be introduced. For more information, readers are encouraged to consult NPL Good Practice Guide 37 [1] and BS 1134-2 [19].

BS ISO 4287 is the International Standard that relates to the terms, definitions and surface profile texture parameters in current use [20]. Surface texture is the deviation of the real surface of an object from its ideal form. It is typically measured perpendicularly to the lay and described as three components – the primary, waviness and roughness profiles. The three profiles are defined by the periodicities of the deviations that they contain. The terms and definitions used are included in Table 2 and more information can be found in BS ISO 4287 [20]. The primary profile contains deviations above a wavelength λs, which is used to define a short-wavelength (low-pass) filter. The roughness is defined by a band-pass filter which runs from λs to a longer wavelength λc, and the waviness by a filter which runs from λc to a higher wavelength λf. An example of the three filters is given in Figure 12. Filters and the suitable choices for the cut-off values can be found in NPL Good Practice Guide 37. This guide will focus primarily on the roughness profiles. It should be noted that the notations of these parameters may change in future versions of the standards.

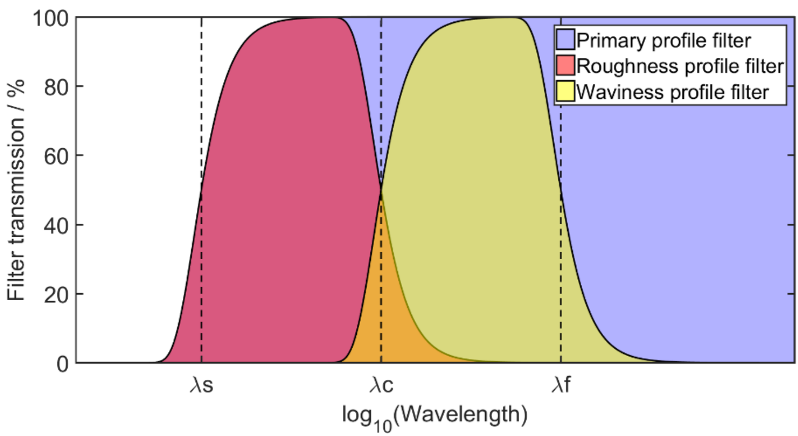

Figure 12. *Example Gaussian filters for the primary, roughness and waviness profiles. The filters are based on BS ISO 4287:1997 [20] and BS EN ISO 11562:1997 [21].*

The appearance of the profile being assessed is affected by the direction of the view relative to the direction of the lay. Determinations of surface texture are made at 90˚ to the lay. Where the direction of the lay is functionally significant, it is important to specify this on an engineering drawing detailing the type of lay and the direction (see BS EN ISO 1302 [22]). BS

EN ISO 13565-1 indicates that the traversing direction for assessment purposes shall be perpendicular to the direction of the lay unless otherwise indicated [23].

Terms	Definition
λs	Filter which defines the intersection between the roughness and the even shorter wave components present in a surface
λc	Filter which defines the intersection between the roughness and waviness components
λf	Filter which defines the intersection between the waviness and the even longer wave components present in a surface
Surface profile	Profile that results from the intersection of the real surface by a specified plane
Roughness profile	Profile derived from the primary profile by suppressing the longwave component using the profile filter λc
Waviness profile	Profile derived by suppressing the longwave component using the profile filter λf, and suppressing the shortwave component using the profile filter λc
Sampling length, lp, lr, lw	Length in the direction of the *x*-axis used for identifying the irregularities characterizing the profile under evaluation
Evaluation length, ln	Length in the direction of the *x*-axis used for assessing the profile under evaluation

Table 2. *Terms and definitions established in BS ISO 4287 [20]. Refer to Figure 12 and Figure 13 for illustration.*

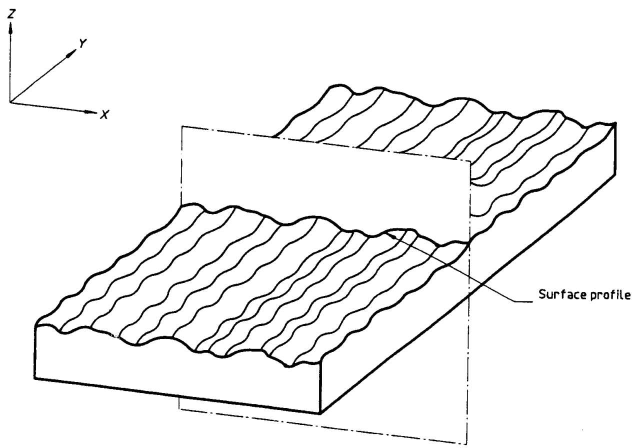

Figure 13. *Surface profile and co-ordinate system defined by BS ISO 4287 [20].*

Figure 14 shows how the effect of the lay on the measured surface texture depends on the direction in which the measurement is taken.

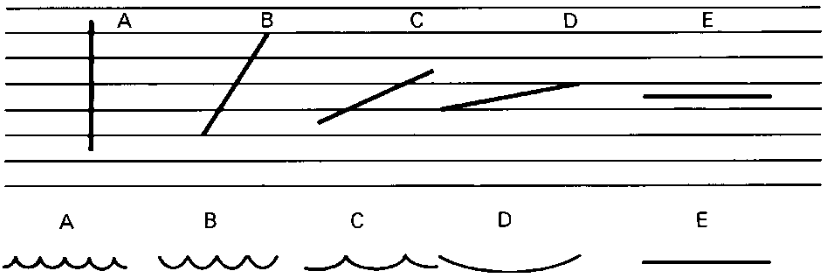

Figure 14. *The effect of measuring in different directions to the surface lay, courtesy of Taylor Hobson Ltd. Note that the direction of lay runs across the page.*

The cut-off wavelength is the means by which the resulting profile waveform is made to simulate the effect of restricting the assessment to the sampling length. When the sampling length is indicated on the drawing or documentation then the cut-off wavelength, λc, should be chosen to be equal to this sampling length. Table 3 shows the relationship between cut-off wavelength, tip radius and maximum sampling spacing.

λc /mm	λs /µm	Roughness cut-off wavelength ratio $\lambda c/\lambda s$	r_{tip} max /µm	Maximum sampling spacing /µm
0.08	2.5	30	2	0.5
0.25	2.5	100	2	0.5
0.8	2.5	300	2	0.5
2.5	8	300	5	1.5
8	25	300	10	5

Table 3. *Relationship between the roughness cut-off wavelength λc, tip radius and maximum sampling spacing, from BS EN ISO 3274 [24].*

When a component is manufactured from a drawing, the surface texture specification will normally include the sampling length for measuring the surface profile. The most commonly used sampling length is 0.8 mm. However, when no indication is given on the drawing, the user will require a means of selecting the most appropriate value for their particular application. The sampling length should only be selected after considering the nature of the surface texture and which characteristics are required for the measurement. In Table 4, it can be seen that a value of 0.8 mm could be used for nearly all of the machined surfaces. More information will be given in section titled 'Interpreting the results.'

Process	Cut-off wavelength/mm 0.25	0.8	2.5	8.0	25.0
Milling		✓	✓	✓	
Turning		✓	✓		
Grinding	✓	✓	✓		
Honing	✓	✓			
Lapping	✓	✓			
Super finishing	✓	✓			
Polishing	✓	✓			

Table 4. *Choice of cut-off wavelength for a number of common machining operations for gears.*

Contact stylus instruments and measurements

Stylus instruments are by far the most common instruments for measuring surface texture today. BS EN ISO 3274 defines the various elements of a typical stylus instrument [24] and Figure 15 shows the interrelationship between the elements. A typical stylus instrument consists of a stylus that physically contacts the surface being measured and a transducer to convert its vertical movement into an electrical signal. Other components include:

- A pick-up that draws the stylus over the surface at a constant speed
- An electronic amplifier to boost the signal from the stylus transducer to a useful level
- A device, also driven at a constant speed, for recording the amplified signal or a computer that automates the data collection

The part of the stylus in contact with the surface is usually a diamond tip with a carefully manufactured profile. Owing to their finite shape, some styli on some surfaces will not penetrate into valleys and will give a distorted or filtered measure of the surface texture. Certain parameters will be more affected by the stylus shape than others. The effect of the stylus forces can have a significant influence on the measurement results and if the force is too high, damage may occur to the surface being measured. If the force is too low, the stylus will not stay reliably in contact with the surface.

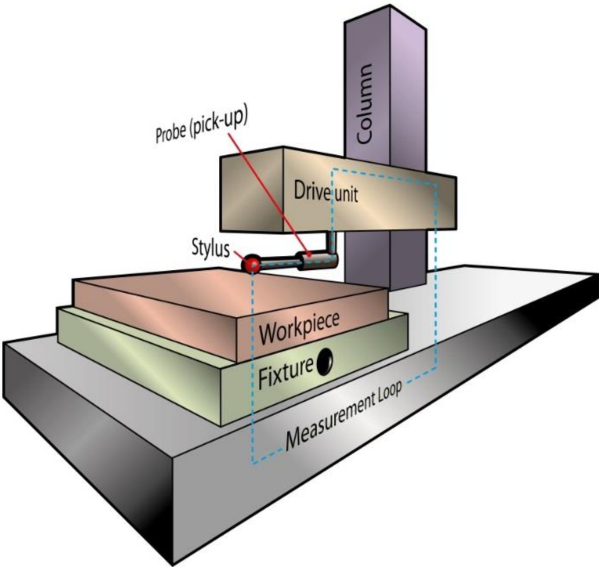

Figure 15. *Elements of the typical stylus instrument, from BS EN ISO 3274 [24].*

The following chapters describe how to prepare instruments and samples for measurements, how to perform scans, how to process the data and finally how to evaluate surface texture parameters for gears.

Chapter 3

Surface texture measurements

- Environmental conditions
- Preparation of measurement instruments
- Workpiece preparation
- Gear tooth replicas
- Choice of sampling length, evaluation length and total traverse length
- Measurements of gear surface texture

In this guide, only stylus instruments are considered for gear surface texture measurements. It is good practice to make sure the measurement instruments and gear samples are setup properly prior to making measurements.

Environmental conditions

To obtain the best possible performance from a surface texture measuring instrument, the measurements should be conducted in a safe and stable environment:

- The measurement instrument should be used in an environment that is as free as possible from dust, vibration and direct sunlight.
- The ambient temperature is maintained in the range 20 ˚C ± 10 ˚C (with a condensation-free humidity of less than 85 % relative humidity)

Preparation of measurement instruments

It is good practice to switch on the electrical unit of the measurement instrument at least one hour before any measurements take place – this will allow time for the instrument to stabilise (the manufacturer's instructions will normally specify a minimum stabilisation time for a given instrument). Calibration of the instrument is essential prior to measurement (see NPL Good Practice Guide 37). Before calibration, the stylus should be visually checked for signs of wear or damage and the user should ensure that the workpiece is free of dust or dirt by using an appropriate cleaning method (which are described in the next section). Visual examination of a 2 µm tip stylus may not be possible without the aid of specialised instrumentation such as a scanning electron microscope (see more information in NPL Good Practice Guide 37).

Workpiece preparation

Cleanliness is important for the accurate measurement of gears and preparation of workpieces is critical to surface texture measurements. Workpiece surfaces should be cleaned and properly mounted before the measurements are obtained. It is good practice to use the most appropriate approach from the following list to clean the workpiece:

- Wipe any dust from the workpiece surface prior to measurement using a lint free cloth
- Remove any gross contamination, preferably by blowing the surface with filtered air
- Remove any oil or grease from the surface using a suitable solvent
- In some cases chemical cleaning is preferable to the use of lint free cloth; if the surface texture is coarse then the cloth may deposit fabric on the surface which will affect the measurement

The following considerations should be taken with regards to mounting the workpiece:

- The workpiece should be located on the instrument base when using tabletop machines or on an appropriate surface if using a portable instrument. This step may require clamping mechanisms on the workpiece. In general, for heavy objects no clamping is required, but when the workpiece is small, light and likely to move when measured, the use of clamps is recommended. Care should be taken to ensure that the clamping forces do not distort the workpiece. In some cases, the use of waxes, soft modelling clay or double-sided sticky tape are alternatives to clamping. The use of restraining materials that are elastic by nature should be avoided due to the possibility of movement while measurements take place.
- The workpiece should be aligned to the traverse direction of the measuring stylus within the working range of the instrument. A fixture such as one illustrated in Figure 16 will assist with the aligning the gear on a general surface texture measuring instrument. Figure 17 shows the fixture used on a general surface measuring instrument for alignment purposes. For larger gears this is impracticable and it is thus necessary to align the instrument with respect to the gear.

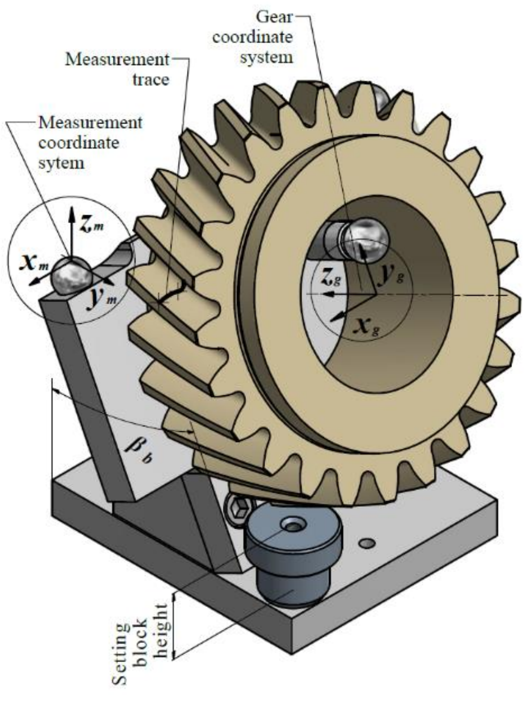

Figure 16. *Example fixture to approximately align the gear surface with the measuring instrument co-ordinate system.*

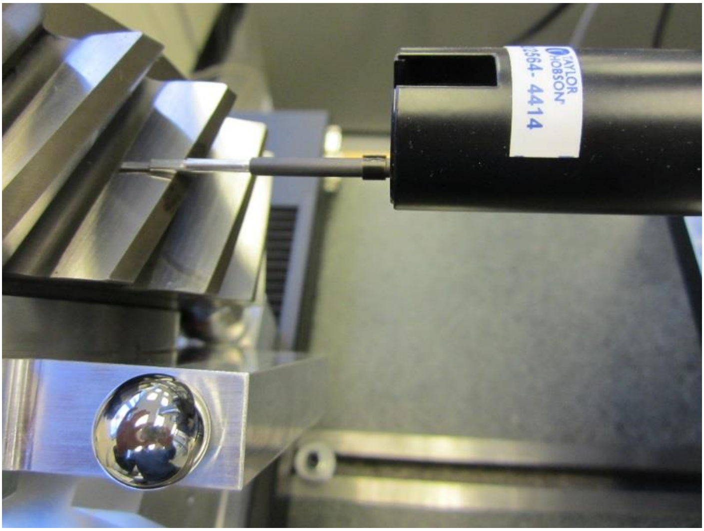

Figure 17. *An alignment fixture used to locate a small test gear and ensure the contact stylus is approximately normal to the gear surface.*

Gear tooth replicas

It is not always possible to directly measure gear surfaces. When it is impossible to access surface directly, surface replication can be considered to reproduce surface texture and allow surface information to be extracted by measurement instruments.

There are many replication materials available. For stylus measurements, the replica material should:

- Be rigid so that it can be measured by contact measurement instruments
- Be able to replicate the features of interest – this is important if the focus is on surface roughness evaluation

When replicas are used, it is good practice to test the characteristics of the replica before using it. This can be done by comparing measurements of the replica with measurements of the surfaces being replicated. It should also be noted that the texture of replica is the inverse of the actual surface and need to be converted before analyses.

Choice of sampling length, evaluation length and total traverse length

Before the measurements take place, it is necessary to select the sampling length, evaluation length and total traverse length. The selection of the values of these lengths will depend on the type and manufacture of the instrument and the surface texture on the workpiece under investigation.

Sampling length *lp*, *lr*, *lw*

Sampling length is defined as the length in the direction of the *x*-axis (refer to Figure 13) used for identifying the irregularities that characterise the profile under evaluation. Specifying a sampling length implies that structure in a profile that occurs over greater lengths is not relevant to the particular evaluation. The sampling length for the primary profile *lp* is equal to the evaluation length *ln* (see section 'Evaluation length *ln*'). The sampling length for *lr* (roughness) is numerically equal to the wavelength of the profile filter λc, the sampling length for *lw* (waviness) is numerically equal to the wavelength of the profile filter λf. Parameters should be evaluated over the sampling length, but an average of parameters from several sampling lengths (see evaluation length) improves the reliability of the evaluation.

Evaluation length *ln*

Evaluation length is the total length in the *x*-axis used for the assessment of the profile under evaluation. It is normal practice to evaluate roughness and waviness profiles over several successive sampling lengths, the sum of which gives the evaluation length. For the primary profile, the evaluation length is equal to the sampling length. BS ISO 4287 advocates the use of five sampling lengths as the default for roughness evaluation [20]. In practice, an evaluation length of six sampling lengths is recommended as the filtering process for surface roughness evaluation will have effects on the end of the data that need to be considered. No default is specified for waviness. With a few exceptions, it is good practice that parameters should be evaluated in each successive sampling length and the resulting values averaged over all the sampling lengths in the evaluation length. Some parameters are assessed over the entire evaluation length. To allow for the effects of acceleration at the start of a measurement and deceleration at the end of a measurement, the instrument traverse length is normally rather longer than the evaluation length.

Total traverse length

Total traverse length is the total length of surface traversed in making a measurement. It is usually greater than the evaluation length due to the need to allow a short over-travel at the start and end of the measurement to allow mechanical and electrical transients to be excluded from the measurement and to allow for the filtering of edge effects.

Measurements of gear surface texture

It is good practice that measurement areas should be visually checked prior to measurements. Visual examination of the workpiece will show whether the surface texture is markedly different over various areas or homogeneous over the whole surface.

Surface texture parameters are not useful for the description of surface defects such as scratches and pores. Defects should not be considered during surface texture inspection. Areas where there are obvious holes, scratches or other machining damage should be avoided.

Procedure for measuring gear flank and root roughness

1. Measure the profile of the contacting flank region. The total traverse length should be at least six times of the roughness sampling length (i.e. $> 6 \times \lambda c$).
2. Measure the profile of the gear root fillet. Often the total traverse length may not be long enough to include six roughness evaluation lengths due to the limited length of root fillet region. In this case, and when practicable, several measurements can be made in the same region and the results can be evaluated using the guidance provided in ISO BS 4288 page 3 and section 6.2 [25].
3. Calculate surface texture parameters across the gear surface. It is recommended to measure in a minimum of six regions over the facewidth on the gear's contacting flank (including both addendum and dedendum) at three axial positions and another three regions in the root near the position of maximum bending stress to evaluate the surface texture across the workpiece surface. The measurement positions of gear flank are specified in Figure 18 (red dots) and the measurement positions of the root fillet are illustrated in Figure 18 (yellow dots). The root region at the 30^{o} tangent point is illustrated in Figure 10.

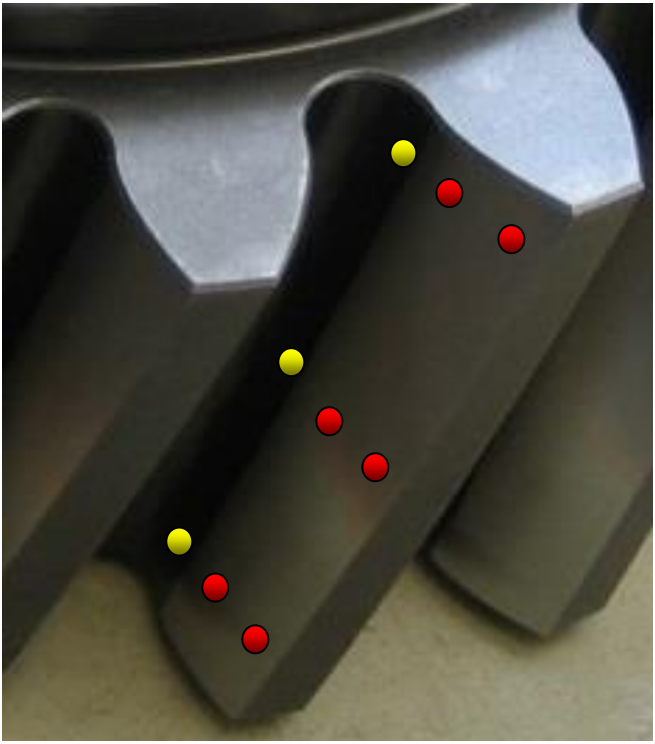

Figure 18. *Measurement positions: six (red) in the active flank region and three (yellow) in root region.*

With an appropriate contact stylus it may be possible to make a single continuous scan from the root fillet region to the tip of the gear. An example of such a scan is shown in Figure 19. Surface parameters can be evaluated for both root and flank using the long measurement.

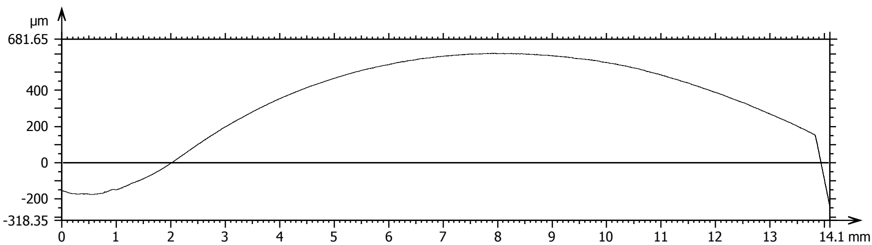

Figure 19. *Illustration of one continuous profile measured with a general surface texture instrument from tooth root to tip.*

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Chapter 4

Interpreting the results

- Procedure of data analysis
- The 16 % rule and its application
- When to use the max-rule

After the measurements have been performed, the measurement data needs to be processed. The following section provides the procedure for data analysis.

Procedure of data analysis

After measurements have been completed on gear flanks or root fillet, the data has to be processed prior to surface roughness parameter evaluation. The process includes removing the form, waviness and noise prior to roughness evaluation. The background information can be found in the section 'Introduction to surface texture.'

The procedure of surface roughness assessment using stylus instruments is given in BS ISO 4287 [20]. The steps include:

- Remove high frequency components. Appling a low pass filter λs to remove noise and other high frequency components from the remaining data
- Remove form. For a surface with known surface profile, the user can remove the ideal surface profile. For surfaces with unknown surface type, a high order polynomial fit can be used to remove the primary profile. This will be further discussed in the section 'Form removal'
- Remove surface waviness components for roughness evaluation. Applying a high pass filter λc to remove waviness components for evaluation

The recommended filter parameters are given in the Table 3. The following good practice is made to standardise this process for gear surfaces.

Form removal

Form removal of root fillet region

Most gear root fillets are of trochoidal form [26] (the shape is produced in gear manufacturing processes that use a cutter with a radius tip) with some processes manufacturing a full radius . The trochoid form can be significantly different to a circle with a radius of similar size by 0.2 mm. Using an unconstrained least squares circle-fit algorithm may result in excessive residual form deviations which will influence roughness parameter evaluation. It is good practice that root fillet radius form can be removed with a fifth order polynomial prior to roughness filtering.

Form removal of contacting flank region

The transverse profile of a gear is an involute form and the nominally normal profile. It is recommended that a fifth order polynomial is used to model the gear flank form.

Gears with no micro-geometry corrections (tip relief and crowning) will usually have little form features remaining. Some gears with linear tip relief will show some residual form deviation as illustrated in Figure 20, where the start of linear tip relief is at the 8 mm position on the profile trace.

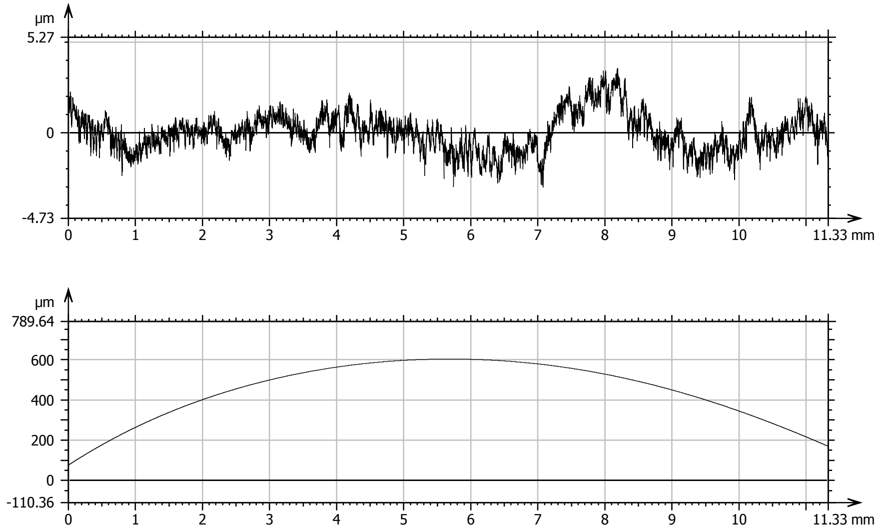

Figure 20. *The residual deviations of a ground gear flank containing linear tip relief after form removal with a fifth order polynomial. Top, residual with form removed. Bottom, form has been removed.*

Choose measurement data

After form removal, the user should select the range of measurement data for further analysis. It is important to follow the good practice in section 'Evaluation length *ln*'. For a measurement with a long scan range across the whole gear surface as introduced in section 'Measurements of gear surface texture', the user should be able to choose multiple regions of data for evaluation. An example is given in Figure 21.

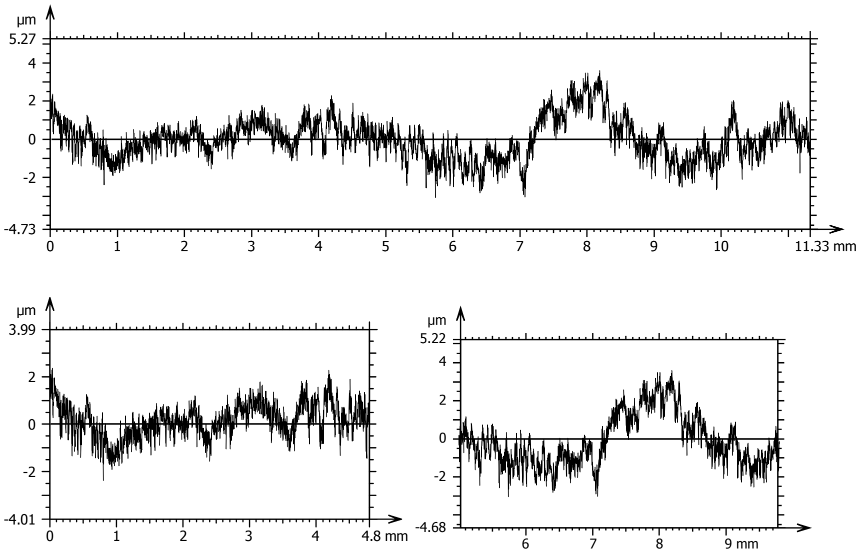

Figure 21. *Multiple sections can be extracted from a single primary profile to see how roughness parameters vary along the profile. Top, residual profile with form removed. Bottom left, first section of data chosen for evaluation. Bottom right, second section of data chosen for evaluation.*

Surface parameter evaluation

Having completed the preparation for the evaluation, the user should select appropriate measurement parameters for analysing the workpiece being investigated. When surface roughness tolerances are known, such as when indicated on a supplied technical drawing, it is conventional to select suitable measurement parameters according to the technical drawing. When the surface roughness is not known, sufficient preliminary measurements should be performed until there is a degree of confidence in the nominal surface roughness of the workpiece from which suitable measurement parameters can be determined.

For a full list of cut-off wavelengths, users should refer to Good Practice Guide 37 and Table 3 [1].However, if the measurement is to verify the functional performance of the contact surface of a gear, surface deviations of the wavelength similar to the Hertzian contact stress (stress between mating parts) region are recommended. As the Hertzian contact stress region is typically around 0.4 mm to 1.0 mm, it is good practice that a λc of 0.8 mm is used, even when evaluating superfinished or polished surface, as shown in Table 5. It is noted that filtering processes often fail to preserve long wavelength features and thus measuring and evaluating surface texture with a longer cut-off would be recommended when possible.

Ra /µm	Sampling length *lr* /mm	Evaluation length *ln* /mm	High pass filter cut-off *λc* /mm	Low pass filter *λs* /µm	Cut-off wavelength ratio *λc*/*λs*	Max. stylus tip radius r_{tip} max /µm	Max sampling spacing /µm
0.1 < *Ra* ≤ 2	0.8	4	0.8	2.5	300	2	0.5

Table 5. *Recommended measurement parameters for gear surface roughness using stylus based instruments. Relationship between the roughness cut-off wavelengths λc and λs, tip radius and maximum sampling spacing from BS EN ISO 3274 [24]. Estimates for choosing roughness sampling lengths for the measurement of non-periodic profiles, BS ISO 4288 [25].*

An example filtered profile with an *Ra* value of 0.41 µm is shown in Figure 22. After applying a *λs* filter of 2.5 µm and removing the form, the waviness can then be removed by using a *λc* filter of 0.8 mm.

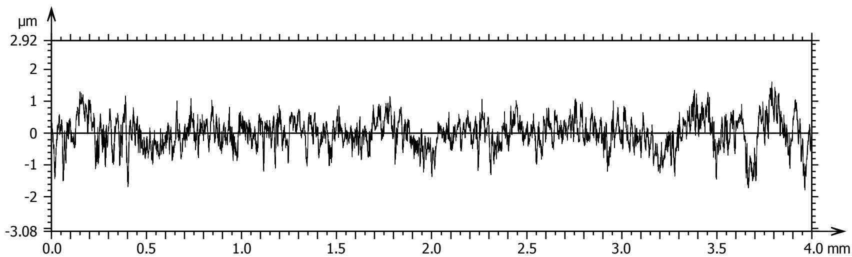

Figure 22. *The roughness profile of a section of a gear flank, with an Ra of 0.41 µm.*

After processing the data, users can then calculate the surface texture parameter required. *Ra* is still the most popular parameter used in gear surface evaluation. Information regarding a wide range of surface texture parameters can be found in Good Practice Guide 37.

An example of surface roughness parameter evaluation and uncertainty calculation is given in the section 'Summary of surface texture parameter evaluation on a gear flank'. There are studies about other surface texture parameters and their effectiveness in evaluating gear surfaces that are ongoing.

If the surface is homogeneous, then parameter values taken from anywhere on the surface can be used for comparison with requirements specified on drawings or specification documents. If the surface texture is markedly different over the whole surface, then parameter values determined over each area must be used separately for comparison to ensure the specification is satisfied.

The 16 % rule and its application

Where the requirements specify an upper limit of a parameter, the surface is considered acceptable if not more than 16 % of all the measured values, based on the evaluation length, exceed the value specified on the drawing [25]. This rule should only be applied when the measurements are distributed over a representative area of the surface.

Conversely, for requirements specifying a lower limit of the parameter, the surface is considered acceptable if not more than 16 % of all measured values, based on the evaluation length, are less than the value specified on the drawing.

When to use the max-rule

Where the requirements specify a maximum value of the parameter, none of the measured values of the parameter over the entire surface can exceed the value specified. To designate the maximum permissible value of the parameter, the ‘max’ index has to be added to the parameter symbol (for example, *Rzmax*) [25].

Chapter 5

Uncertainty evaluation using comparison specimens

- Comparison specimens
- Example of instrument calibration using a calibrated comparison specimen
- Summary of surface texture parameter evaluation on a gear flank

Comparison specimens

Guidelines for contact stylus instrument calibration are given in NPL Good Practice Guide 37. A simpler and more direct way of calibrating the contact stylus for surface texture measurements of gears using calibrated comparison specimens is given in this chapter.

A standard set of comparison specimens consists of a range of surface textures produced by grinding. The specimens allow the users to compare their machined component against a calibrated specimen with a similar level of surface texture parameter, usually *R*a. Figure 23 is a photograph of a set of commercially available comparison specimens. Readers can purchase a calibrated comparison specimen set with a certificate from many UKAS accredited laboratories.

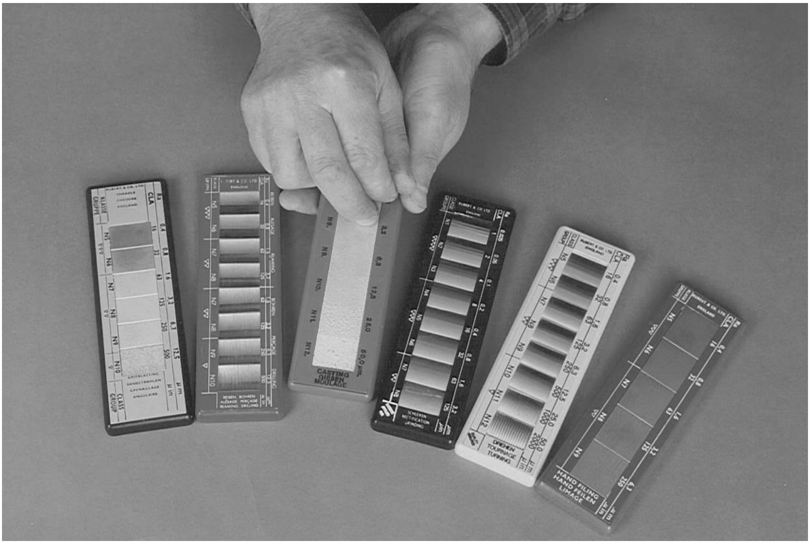

Figure 23. *A standard set of comparison specimens, courtesy of Rubert & Co Ltd.*

Example of instrument calibration using a calibrated comparison specimen

This section describes a calibration method that will enable traceable surface texture measurements of ground gear teeth that relies on a ground or similarly calibrated comparison specimen. In the example presented below, a face ground comparison specimen, model 315 manufactured by Rubert & Co Ltd, was used to calibrate a contact stylus instrument. The comparison specimen includes eight roughness ground patches of different *Ra* values ranging from 0.025 µm to 3.2 µm.

The patch of *Ra* 0.4 µm on the calibration specimen has been calibrated using a conisphere stylus with a nominal radius of 2 µm. The measurement conditions, which are stated on the calibration certificate were:

- Twelve measurements at different positions across the surface
- The sampling distance was 0.25 µm
- The evaluation length of each roughness profile was 4 mm
- Roughness parameters for each trace was calculated from five sampling lengths of 0.8 mm
- A nominal roughness cut-off wavelength ratio ($\lambda c/ \lambda s$) of 320 was used in the calculations
- The mean roughness parameter value of the twelve traces was calculated

The calibration result are listed in Table 6.

Parameter	Mean /nm	Expanded Uncertainty (*k*=2) /nm
Ra	442	17
Rp	1 561	180
Rq	562	20

Table 6. *Calibration results of the comparison specimen.*

Measurement instrument calibration procedure

1. Mount the calibrated artefact on the instrument table at an angle corresponding to the maximum curvature of the gear tooth.

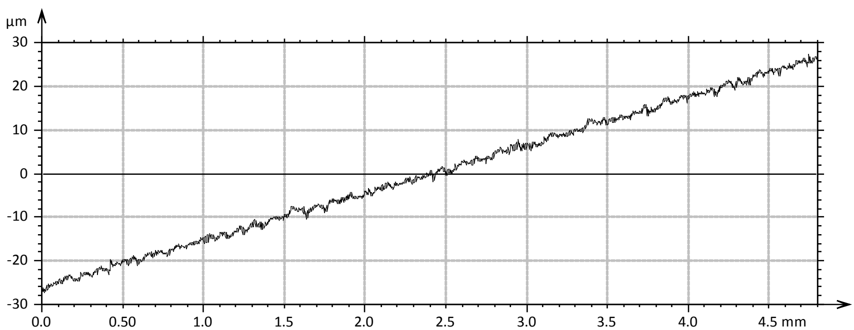

Figure 24. *Example of measured profile at an angle of 12 degrees which corresponds to the maximum tilt angle incurred during the gear face/flank measurement.*

2. Measure twelve profiles at least 4.8 mm long at different positions across the surface in the same measurement conditions to the ones listed in the calibration certificate of the comparison specimen. An example of results is shown in Figure 24.

3. Apply a low pass filter λs of 2.5 µm and level the sample in software, as shown in Figure 25. Note that a λs of 2.5 µm might not be appropriate if a nonstandard stylus radius or sampling distance is used (see Good Practice Guide 37).

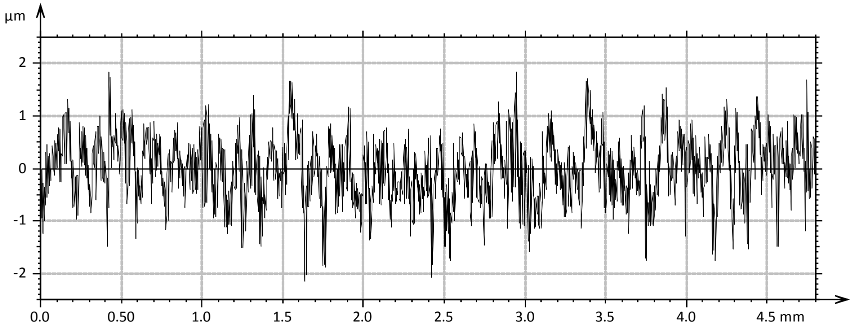

Figure 25. *Example of levelled primary profile.*

4. Calculate the profile surface texture parameters (*Ra*, *Rp* and *Rq*) for each trace from five sampling lengths of 0.8 mm using a nominal roughness cut-off wavelength ratio ($\lambda c/\lambda s$) of 320.

5. Calculate the mean value of the parameters and the standard deviation of the mean (σ), where σ is the standard deviation divided by the square root of the number of observations (n). Type A standard uncertainty (u_A) is equal to standard deviation of the mean.

6. Calculate the measurement error (δ) by subtracting the certified value from the measured average value.

7. Calculate the type B (u_B) standard uncertainty as a combination of traceability contribution, which is calculated using the data provided in the calibration certificate, and the measurement error using the following equation. The traceability contribution is equal to the expanded uncertainty (U_{cert}) reported on the certificate divided by the coverage factor (k_{cert}).

$$u_B^2 = \frac{U_{cert}^2}{k_{cert}^2} + \frac{\delta^2}{3}$$

8. Calculate combined standard uncertainty as a combination of Type A standard uncertainty, which is given the standard deviation of the mean, and Type B standard uncertainty using the following equation:

$$u^2 = u_A^2 + u_B^2 = \sigma^2 + \frac{U_{cert}^2}{k_{cert}^2} + \frac{\delta^2}{3}$$

9. Calculate the effective degrees of freedom using the following equation:

$$\nu = (n-1) \times \frac{u^4}{u_A^4}$$

10. Given the value of effective degrees of freedom, select the coverage factor *k* for a coverage probability of 95.45 % from Table G.2 given in GUM JCM100 [27].

11. Calculate the expanded uncertainty using the equation below:

$$U_{cal} = k_{cal} \times u$$

An example of instrument calibration and the results are summarised below in Table 7.

Identification	*Ra* /nm	*Rp* /nm	*Rq* /nm
Measurement 1	451	1530	568
Measurement 2	440	1492	555
Measurement 3	456	1558	575
Measurement 4	436	1641	558
Measurement 5	439	1701	561
Measurement 6	435	1508	549
Measurement 7	453	1408	563
Measurement 8	464	1803	590
Measurement 9	417	1402	530
Measurement 10	431	1496	545
Measurement 11	435	1480	555
Measurement 12	424	1433	543
Mean value	440.1	1537.7	557.7
Standard deviation	13.7	121.5	15.7
Standard deviation of the mean (σ)	3.9	35.1	4.5
Error (δ)	-1.9	-23.3	-4.3
U_{cert}/k_{cert}	8.5	90.0	10.0
u_A	*3.9*	35.1	4.5
u_B	*8.6*	91.0	10.3
u	9.4	97.5	11.3
Degrees of freedom (ν)	∞	∞	∞
k_{cal}	*2*	2	2
U_{cal}	**19**	**195**	**23**

Table 7. *Example of uncertainty evaluation of the Ra parameter of a gear surface.*

The Type B standard uncertainty associated with the *Ra* measurement performed on the gears will be equal to *u* calculated in the above procedure.

Summary of surface texture parameter evaluation on a gear flank

Following the instruction in section 'Procedure of data analysis', users should be able to measure and evaluate surface texture parameters of gear surfaces following the steps 3-5 and 7-11 in previous section. An example of results of a gear flank surface manufactured by grinding process has been given in the Table 8.

Identification	***Ra* /nm**	***Rp* /nm**	***Rq* /nm**
Measurement 1	428	1368	530
Measurement 2	423	1420	524
Measurement 3	422	1409	523
Mean value	424	1399	526
Standard deviation	3.2	27.4	3.8
Standard deviation of the mean (σ)	1.9	15.8	2.2
U_{cal}/k_{ccal}	9.4	97.5	11.3
u_A	1.9	15.8	2.2
u_B	9.4	97.5	11.3
u	9.6	98.8	11.5
Degrees of freedom (ν)	∞	∞	∞
k	2	2	2
U	**19**	**198**	**23**

Table 8. *An example of surface roughness parameter evaluation.*

Chapter 6

Supplementary information

- Health and safety
- References
- Links to other useful sources of information

Health and safety

Surface texture measuring instrument and artefacts themselves are intrinsically safe. Hazards are, therefore, likely to arise mainly from their misuse. Some specific things to look for when carrying out a risk assessment are listed below.

Chemical hazards

Chemicals may need to be used for cleaning workpieces or making replicas. Make sure the manufacturer's safety guidance is followed and the relevant personal protective equipment is worn. Substances may be covered by the COSHH regulations. Take care when using cleaning solvents and oils and always wear the appropriate protective equipment.

Handling heavy components

Lifting, transporting and setting of heavy components should be arranged according to health and safety regulations. Professional training is recommended before handling heavy components to avoid injury. Readers are recommended to find more information regarding different types of lifting aids in 'Making the best use of lifting and handling aids' [28] and more general guidance in 'Safe use of lifting equipment - Lifting operations and lifting equipment regulations 1998 - Approved code of practice and guidance' [29].

References

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[28] 2013 *Making the best use of lifting and handling aids* Health and Safety Executive INDG398(rev1)
[29] 2014 *Safe use of lifting equipment - Lifting operations and lifting equipment regulations 1998 - Approved code of practice and guidance* Health and Safety Executive L113

Links to other useful sources of information

Further reading

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Giusca, C L, Leach R K 2013 Calibration of the metrological characteristics of stylus instruments Good Practice Guide 129

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Standards – surface texture metrology

ISO 10825 (1995) Gears – Wear and damage to gear teeth – Terminology

BS EN ISO 5436 part 1 (2001) Geometrical product specifications (GPS) – Surface texture: Profile method – Measurement standards – Part 1 Material measures

BS EN ISO 5436 part 2 (2012) Geometrical product specifications (GPS) – Surface texture: Profile method – Measurement standards – Part 2 Software measurement standards

BS EN ISO 13565 part 2 (1998) Geometrical product specifications (GPS) – Surface texture: Profile method; Surface having stratified functional properties – Part 2: Height characterization using the linear material ratio curve

BS EN ISO 13565 part 3 (2000) Geometrical product specifications (GPS) – Surface texture: Profile method; surfaces having stratified functional properties – Part 3: Height characterization using the material probability curve

BS EN ISO 12085 (1998) Geometrical product specifications (GPS) – Surface texture: Profile method – Motif parameters

BS EN ISO 12179 (2000) Geometrical Product Specifications (GPS) -- Surface texture: Profile method -- Calibration of contact (stylus) instruments

BS EN ISO 16610 part 21 (2012) Geometrical product specifications (GPS) - Filtration - Part 21: Linear profile filters: Gaussian filters

Standards – general metrology

JCGM 200 (2008) International vocabulary of metrology. Basic and general concepts and associated terms (VIM)

ISO/IEC GUIDE 98-3(2008) Ed 1 Uncertainty of measurement. Guide to the expression of uncertainty in measurement

PD 6461-4 (2004) General metrology. Practical guide to measurement uncertainty

Other useful links

National Physical Laboratory, Dimensional Metrology
Hampton Road, Teddington, Middlesex TW11 0LW
+44 (0)20 8977 3222
www.npl.co.uk
dimensional_enquiries@npl.co.uk

British Standards Institute (BSI)
www.bsigroup.com

International Standards Organisation (ISO)
www.iso.ch

United Kingdom Accreditation Service
21 - 47 High Street, Feltham, Middlesex TW13 4UN, UK
+44 (0)20 8917 8556
www.ukas.com

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Surface Texture Measurements of Gear Surfaces Using Stylus Instruments

Good Practice Guide No. 147

Gears are a key component of power transmission systems, with applications spanning the automotive, aerospace, medical and power generation sectors, among many others. Written for designers of gears who have no knowledge of gear measurements, gear manufacturers who would like to control the quality of their product and metrologists who would like to carry out measurements of gears, this guide provides readers with basic understanding and instruction on measuring the surface texture of gears using a stylus instrument. Readers will learn basic knowledge of gears and gear surface textures, as well as learn about gear surface measurements and uncertainty evaluation. The guide also covers good practice regarding the gear surface texture parameter calculations and uncertainty evaluation.

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