TECHNICAL REVIEW

No. 3 — 1983

Contents

FOURIER ANALYSIS OF SURFACE ROUGHNESS

by

Michael Brock (M. Sc.)

ABSTRACT

Correct description and measurement of surface roughness play an overwhelmingly important role in the design and production of mechanical parts. To minimize production costs, the surface roughness of parts should be just within requirements; on the other hand, some surfaces need to be well defined relative to a specification for their proper functioning (e.g. bearings). The most commonly used surface roughness parameters are R_a and R_{max}, but surface profile, autocorrelation function, height distribution function and other techniques, are also found. In many applications, however, none of these methods give sufficient information about the surface structure.

In this article the application of Fourier analysis of surface roughness is discussed. It is shown that the spectrum obtained by Fourier transformation of the surface profile is ideal for revealing the characteristics of a surface, and furthermore covers a wider range of applications than any of the other commonly used methods. Combined with some of these methods of characterization, the spectrum gives a nearly complete description of a surface's structure. This will be illustrated by examples in this article, which also includes spectra of the most common surface types, instrumentation, and examples of applications.

SOMMAIRE

La mesure et la description correctes de la rugosité de surface jouent un rôle dominant dans la conception et la production des pièces mécaniques. Pour minimiser le coût de production il ne faut pas réduire la rugosité des surfaces des pièces plus que nécessaire, mais d'un autre côté certaines surfaces doivent, de par leur fonction même, être bien définies pour assurer un bon fonctionnement (p.ex. roulements). Les paramètres de rugosité les plus couramment utilisés sont R_a et R_{max}, mais on trouve aussi le profil de surface, la fonction d'autocorrélation, la fonction de distribution de hauteur et encore d'autres techniques. Dans de nombreuses applications, cependant, aucune de ces méthodes ne donne une information suffisante sur la structure de la surface.

Cet article traite de l'application de l'analyse de Fourier à la rugosité de surface. Il montre que le spectre obtenu par la transformation de Fourier est idéal pour révéler les caractéristiques de la surface et qu'en plus il couvre une gamme d'applications plus large que n'importe quelle autre méthode couramment utilisée. Combiné à quelques unes de ces méthodes de caractérisation, le spectre donne une description presque entière de la structure de la surface. Ceci est illustré par cet article qui comprend également des spectres des types de surfaces les plus courants, des montages de mesure et des exemples d'applications.

ZUSAMMENFASSUNG

Die korrekte Beschreibung und Messung der Oberflächenrauhigkeit spielt eine außerordentlich wichtige Rolle bei der Konstruktion und Herstellung mechanischer Teile. Um die Produktionskosten zu minimieren, sollte die Oberflächenrauhigkeit nicht geringer sein, als gerade notwendig; auf der anderen Seite müssen einige Oberflächen gut definiert sein, entsprechend gegebenen Spezifikationen (z.B. Lager), um ihre Funktion sicherzustellen. Die häufigsten Rauheitsparameter sind R_a und R_{max}, es kommen aber auch Oberflächenprofil, Autokorrelationsfunktion, Höhenverteilungsfunktion und andere Techniken vor. Für viele Anwendungen gibt jedoch keine dieser Methoden genügend Information über die Oberflächenstruktur.

In diesem Artikel wird die Anwendung der Fourieranalyse für die Oberflächenrauhigkeit diskutiert. Es wird gezeigt, daß sie ideal ist, um die Eigenschaften der Oberfläche zu beschreiben. Darüberhinaus schließt sie Anwendungsbereiche ein, die von keiner der anderen Methoden abgedeckt werden. Zusammen mit einigen dieser Methoden gibt das Spektrum eine nahezu vollständige Beschreibung der Oberflächenstruktur. Dieses wird anhand einiger Beispiele gezeigt. Der Artikel enthält außerdem Spektren der am häufigsten vorkommenden Oberflächen, Geräteaufbauten und Anwendungsbeispiele.

Introduction

Interest in measuring surface roughness has been on the increase during the last decades for several reasons. It is known that the surface structure plays a vital role in the lifetime and function of a mechanical surface since it influences lubrication performance, probability of crack formation and corrosion stability. Besides, the production cost of a mechanical part is closely related to the specified roughness, as the production time increases significantly when a low roughness level (R_a-value) is required. This is qualitatively illustrated in Fig.1, where the relative production time is given as a function of specified roughness level. [Ref. 1]. Enormous sums can thus be wasted if a material is manufactured to a better finish than necessary; on the other hand, a whole production series may have to be rejected, if it does not fulfil the roughness specifications. The surface roughness is therefore an extremely important parameter in design and production, which must consequently be measured in a relevant and correct manner. It is important here to emphasize that it is not sufficient to measure a roughness parameter precisely. If the parameter does not express exactly the characteristics of the surface that should be specified, the precise measurement will not be of much use.

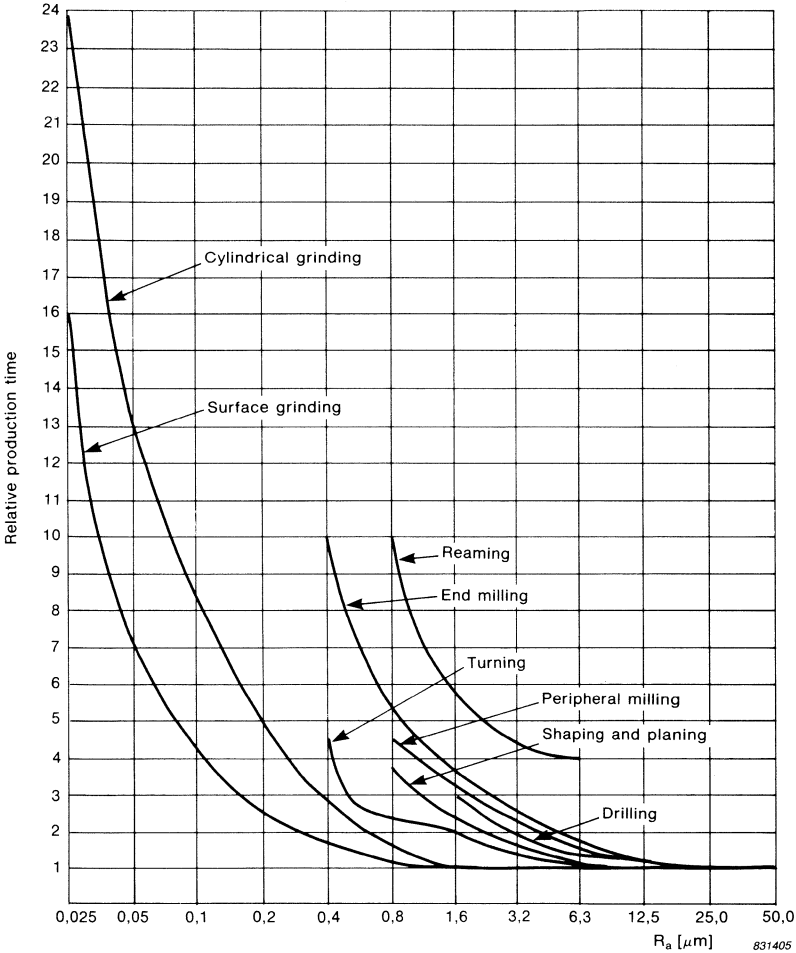


Fig. 1. Relative production time as a function of specified roughness level. (Different manufacturing processes cannot be compared) Ref.[1]

To date, most of the efforts in surface roughness research have been concentrated on work with single parameters describing different characteristics of a surface profile. R_a, R_{max} and R_q are some of the most commonly used. The surface profile, height distribution and autocorrelation function represent other methods of characterizing a surface structure. Approximately 20 different parameters are standardized worldwide by ISO. However, the definitions of most of the parameters differ slightly. Even small variations in the standards give totally different results from country to country; primarily because the use of the standardized filters inserted to cut off the undesired waviness in the surface are not uniform universally.

In some applications, neither the parameters nor the profile or height distribution — even if measured correctly — describe the surface unambiguously with respect to a certain specified characteristic. Examples can even be found where use of the conventional parameters give misleading results. From a signal analysis point of view this is not surprising; all relevant information in a signal unfortunately cannot be reduced to one single parameter. Although this is well recognized by most working with signal analysis in practice (e.g. in the field of sound and vibration), it is apparently not so in the field of surface roughness measurements. The main efforts are still concentrated on the parameters.

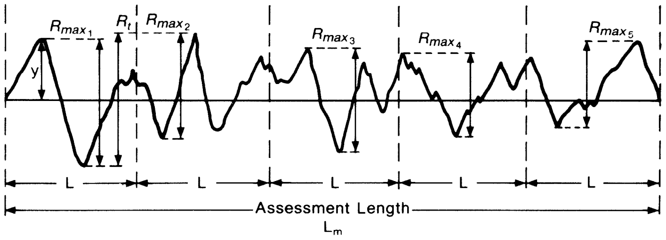
In signal analysis the transformation from the time domain into the frequency domain is widely used, because the information in a frequency spectrum is much easier to interpret and deal with than the corresponding information in the time signal. This is also valid for surface roughness analysis, which — of course — in a way is also signal analysis. The spectrum that is obtained by Fourier transformation of the surface profile contains most of the relevant information in the profile. Thus the spectrum is probably the best solution to the problem that has always existed in roughness analysis: finding an all purpose "parameter".

In the following, the use of Fourier analysis in surface investigation will be discussed, and the advantages and disadvantages will be stated. The wavelength spectrum will be compared and correlated to the conventional parameters, and it will be shown how the spectrum can be used to evaluate if a parameter measurement is sufficient in a given case and — if so — to choose an optimal parameter and filter. Spectra of typical surfaces will be shown and interpreted, and application examples will illustrate how the spectrum can be used to evaluate a lubricant, how it can be used in the calibration and testing procedure, and how it can be used in product testing. Another type of analysis will also be briefly mentioned: The Hilbert transformation by which it is possible to investigate a very large dynamic range in the surface profile. Finally, examples of different instruments will be given that make the Fourier and Hilbert transformation possible.

Roughness Parameters

As already mentioned, definitions of the roughness parameters differ slightly. To clarify the notation in this article, the definitions of the most commonly used parameters are given in the following.

R_a is the universally recognized parameter of roughness. It is the arithmetic mean of the profile departures, y, (see Fig.2) from the mean line. It is normally determined as the mean result of several (normally 5) consecutive sampling lengths, L.



$$R_a = \frac{1}{L}\int_0^L |\, y(x) \,|\, dx$$

$$R_t = \text{Maximum peak} - \text{minimum valley within } L_m$$

$$R_q = \sqrt{\frac{1}{L}\int_0^L y^2(x)\, dx}$$

$$R_{tm} = \left(R_{max_1} + R_{max_2} + R_{max_3} + R_{max_4} + R_{max_5} \right) / 5$$

$$R_{max} = max \,|\, R_{max,\, n} \,|$$

$$R_{pm} = \left(R_{p_1} + R_{p_2} + R_{p_3} + R_{p_4} + R_{p_5} \right) / 5$$

831509

Fig. 2. Definitions of commonly used parameters

For R_a as for most other parameters, the profile must be filtered with a well-defined cut-off filter, before the parameters are calculated. This is to avoid influence from low frequency / long wavelength components — normally mentioned as waviness rather than roughness — on the parameter calculation. As there is often considerable roughness in the surface profile around the cut-off wavelength, the filter selection is rather critical, and should therefore always be accurately specified. In practice, however, this is the exception rather than the rule, whereby a roughness measurement can give almost any desired result when the filter is undefined. Since the standardized cut-off wavelengths are 0,08, 0,25, 0,8, 2,5 and 8,0 mm, the profile signal amplitude will be reduced by 25% (–2,5 dB) by a second order RC-filter at these wavelengths. In recent years a phase linear filter has also been used to avoid unnecessary distortion of the original profile. The cut-off wavelengths and amplitude characteristics are the same for the new filter type.

When a profile is filtered, the meanline is also automatically fixed. Another method to fix the meanline is mathematical rather than electrical. In this case, the profile is divided into suitable sampling lengths within which straight lines are defined as meanlines. These straight lines are normally fixed by trend line analysis using linear regression, but other methods are also known. This last method is of course a product of the digitization of the roughness measuring equipment. However, it should be noted that digital filtering (similar to the electrical) can also be performed in a computer. The two methods of filtering give slightly different results (up to 15% for normal surfaces) when the parameters are calculated.

The above considerations are also valid for R_q, R_t, R_{max}, T_{tm}, R_p and R_{pm} — some of the other commonly used parameters. R_q is equivalent to R_a; it is only the RMS-value instead of the mean value. R_t is the maximum peak-to-valley height within the assessment length. $R_{max,n}$ is the maximum peak-to-valley height within sampling length No. n; R_{max} is the maximum $R_{max,n}$ within five consecutive sampling lengths, and R_{tm} is the mean value of five consecutive $R_{max,n}$-values (see Fig.2). Finally, R_p is the maximum profile height from the meanline within a sampling length, and R_{pm} is the mean value of R_p determined over five sampling lengths.

So far, only discrete parameters have been mentioned, but other surface descriptions are also used. The height distribution curve is one of them and is illustrated in Fig.3. By integrating the height distribution curve the bearing ratio curve is determined, (Fig.3), showing how the bearing ratio parameter t_p varies with selected level. These two characterizations are both very important and usable in practice. The autocorrelation function is also used, but as for all the more advanced "parameters" the calculations take time in normal computers, and the information is difficult to interpret, limiting their use in practice.

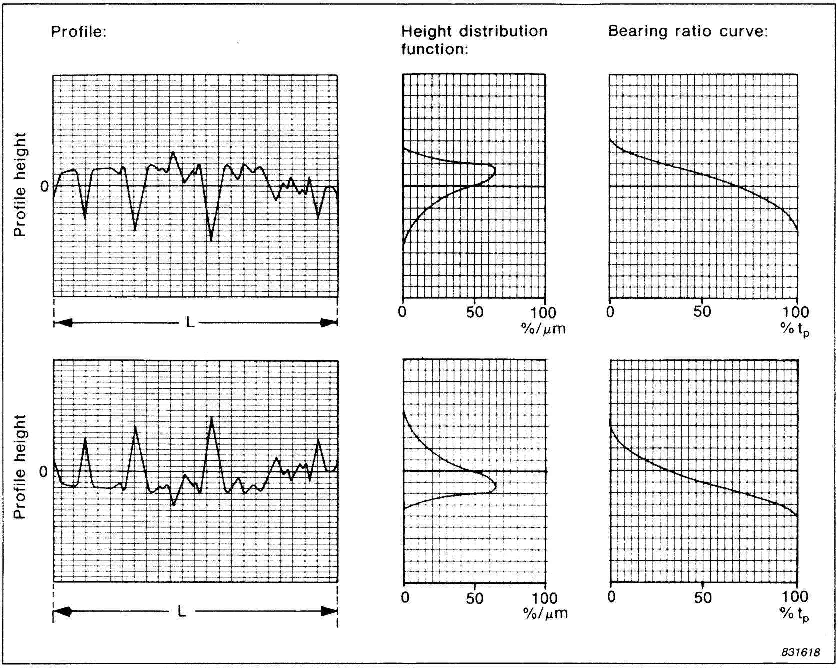


Fig. 3. Profile, height distribution and bearing ratio curve for a surface

Fourier Analysis of a Surface Profile

According to Fourier, it is possible to break down a signal into its components at various frequencies. The physical interpretation of each of these components could be the RMS-value measured on a signal filtered with a very narrow band filter. By using a large number of parallel narrow band filters, tuned to different frequencies, the RMS-value could be determined at all these frequencies. A graph showing the RMS-value in a signal as function of frequency is called an RMS-spectrum (see Fig.4). Instead of using parallel narrow band filters to obtain a frequency spectrum, the signal can be Fourier transformed. The Fourier transformation is a mathematical approach which — as the filters do — divides a signal into its frequency components. It is possible to transform all practical signals, and thus also any surface profile. In practice the Fourier transformation is carried out on very closely spaced samples of the signal that is going to be transformed. The Fourier analysis and its relation to parallel filter analysis are illustrated in Fig.4.

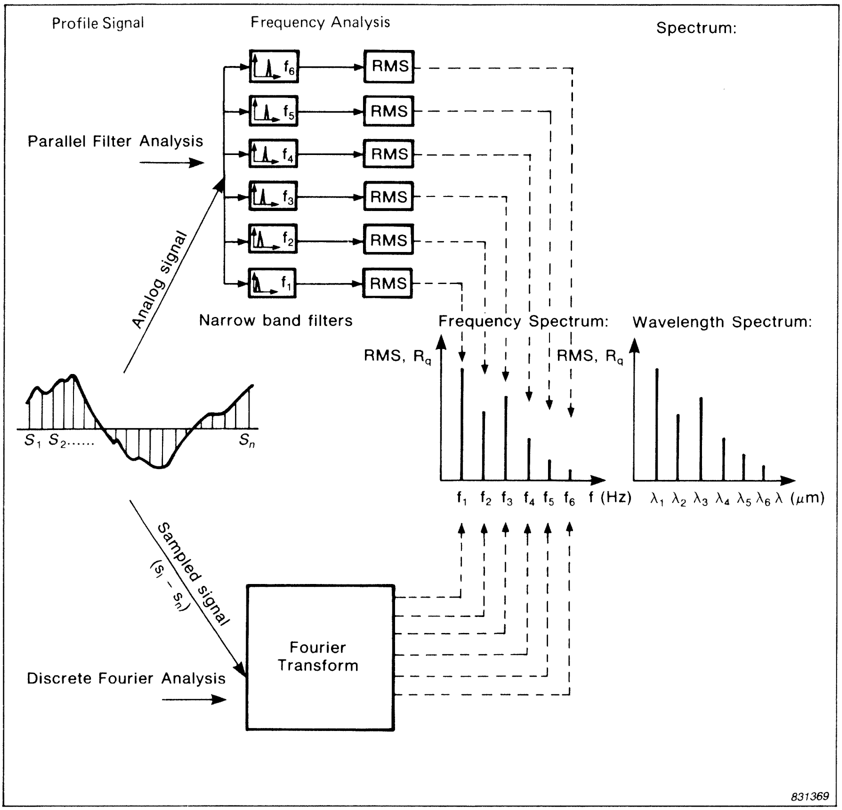


Fig. 4. Fourier analysis versus parallel filter analysis

When dealing with surface roughness spectra, it can be convenient to convert the frequency axis into a wavelength axis. This can easily be done, because the surface wavelength, λ, equals the traverse speed, v_{trav} divided by frequency, f. (λ(mm) = v_{trav}(mm/s) / $f(Hz)$). Also on the amplitude axis, different calibrations can be convenient. On this axis the RMS-value is displayed, and on spectra of surface profiles, the RMS-value can be interpreted as R_q-value. A linear axis is probably the most natural for roughness spectra. However, the main advantage of the logarithmic scale must not be overlooked — a much wider dynamic range can be displayed in the same spectrum. This is of great importance when a single profile is investigated, and furthermore the spectra of very different profiles can be compared without changing the range on the amplitude axis. When a logarithmic scale is used, a fixed reference must be chosen, and 0,001 micron seems to be convenient. A roughness dB scale can then be defined as $dB_r = 20 \log (R_q / 0{,}001)$. Thus 0 dB_r equals 0,001 micron, 20 dB_r equals 0,01 micron, 40 dB_r equals 0,1 micron etc.

A wavelength spectrum contains, simultaneously, both the amplitude and wavelength information as seen from the above. A typical amplitude parameter like R_q can be determined directly from the spectrum by summation of the squared R_q-values at the discrete frequencies

$$R_{q,\,total} = \sqrt{R_{qf_1}{}^2 + R_{qf_2}{}^2 + \dots R_{qf_n}{}^2}$$

Thus the spectrum can be directly correlated to at least one of the conventional parameters. The other discrete parameters cannot always be directly determined from the spectrum, but different approximations can sometimes be applied. This will be discussed later. The auto-correlation function can be directly determined from the Fourier spectrum through an inverse Fourier transformation. However, since the spectrum is in general a much better representation, this possibility is seldom used. The height distribution function and bearing curve can be directly correlated to the spectrum only for very simple non-realistic profiles. In fact it appears that these two functions form the optimal supplement to the spectrum, because they represent the amplitude distribution while the spectrum represents the wavelength distribution.

To clarify the interpretation of the spectrum, some simple examples of surface profiles and the corresponding wavelength spectra will be given in the following.

Fig.5 shows probably the simplest case of all. The surface profile is in this case theoretical and represents a pure sine. The profile contains only one wavelength and is therefore transformed to a spectrum with one single peak. When dealing with a pure sine signal, all other parameters and functions can easily be calculated. The R_q-value is equivalent to the height of the peak as R_q equals zero at all other wavelengths. The R_a-value can be calculated as $R_q \cdot 2\sqrt{2}/\pi$ and R_{max} as $R_q \cdot 2\sqrt{2}$. The auto-correlation function and height distribution function and bearing ratio curve are also easy to determine in this case. The two latter functions are shown on Fig.5.

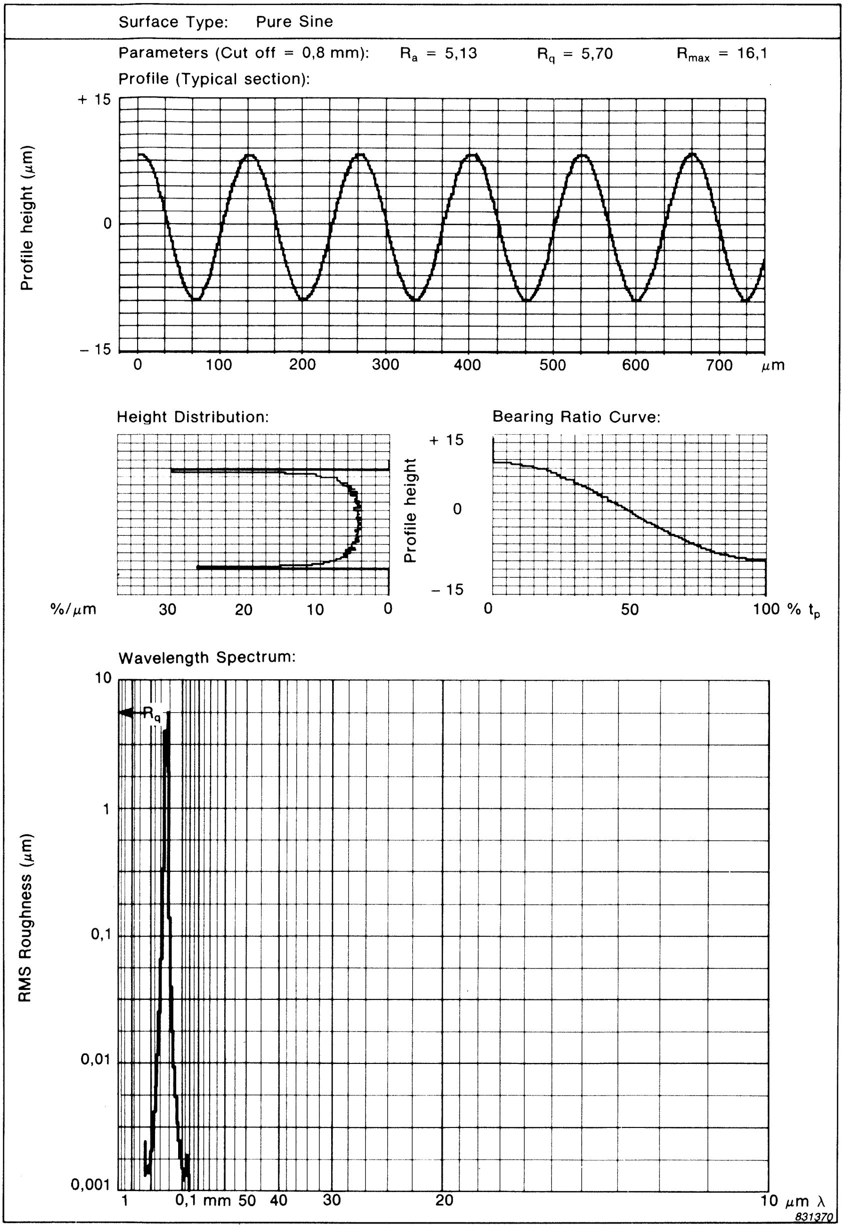


Fig. 5. Height distribution function, bearing ratio curve and spectrum of an ideal sine surface profile

In Fig.6 the ideal sine profile has been replaced by an ideal triangular profile with the same basic wavelength. The same characteristics as given for the sine surface in Fig.5 are also given in this figure. Again, the R_q-value can be calculated as the root of the sum of the squared RMS-values, but the other parameters generally cannot be calculated accurately from the spectrum, when it contains more than one peak. However, if the height of one of the lines in the spectrum is very much greater than all the other lines, its value alone can be used to calculate the parameters, R_q, as well as the others, with good approximation. In this case, where the basic wavelength component is 10 times higher than the second component, the basic component alone can therefore be used.

Regarding the spectrum of the pure triangular profile, it is obvious that some discrete lines have been added compared to the spectrum of the ideal sine profile. This means that the triangular profile does not contain only one basic wavelength component; a number of components are needed to form the profile.

Generally it can be stated, that any periodic surface consists of a given number of discrete wavelength components with certain amplitudes. Thus a periodic surface can be identified from a spectrum with a certain pattern of discrete wavelength components.

On a real surface profile, the periodic shape is never ideal as in Figs.5 and 6. It is therefore normally interesting to determine the roughness overlapping the ideal profile. For the sine profile in Fig.5 this overlapping roughness can be interpreted as roughness on the ideal profile shape, and for the triangular profile in Fig.6 simply as roughness on the straight lines of the ideal profile. To determine this roughness by a parameter measurement, it would be normal practice (and also according to some standards) to insert a cutoff filter to attenuate the basic wavelength (in this case a 0,08 mm filter would probably be selected) and then measure the parameters on the filtered profile. However, this method will normally lead to totally meaningless results. Fig.6 shows that it is not sufficient to cut away the basic wavelength, because the ideal profile also contributes other wavelength components. Thus the result of the above measurement has normally no correlation at all to the overlapping roughness. Consequently, it is not possible to cut away a normal periodic waveform with a standardized long wavelength cutoff filter, because the periodic waveform has components at several wavelengths. Only if the overlapping roughness is higher than the contributed components in the spectrum, is the measurement relevant.

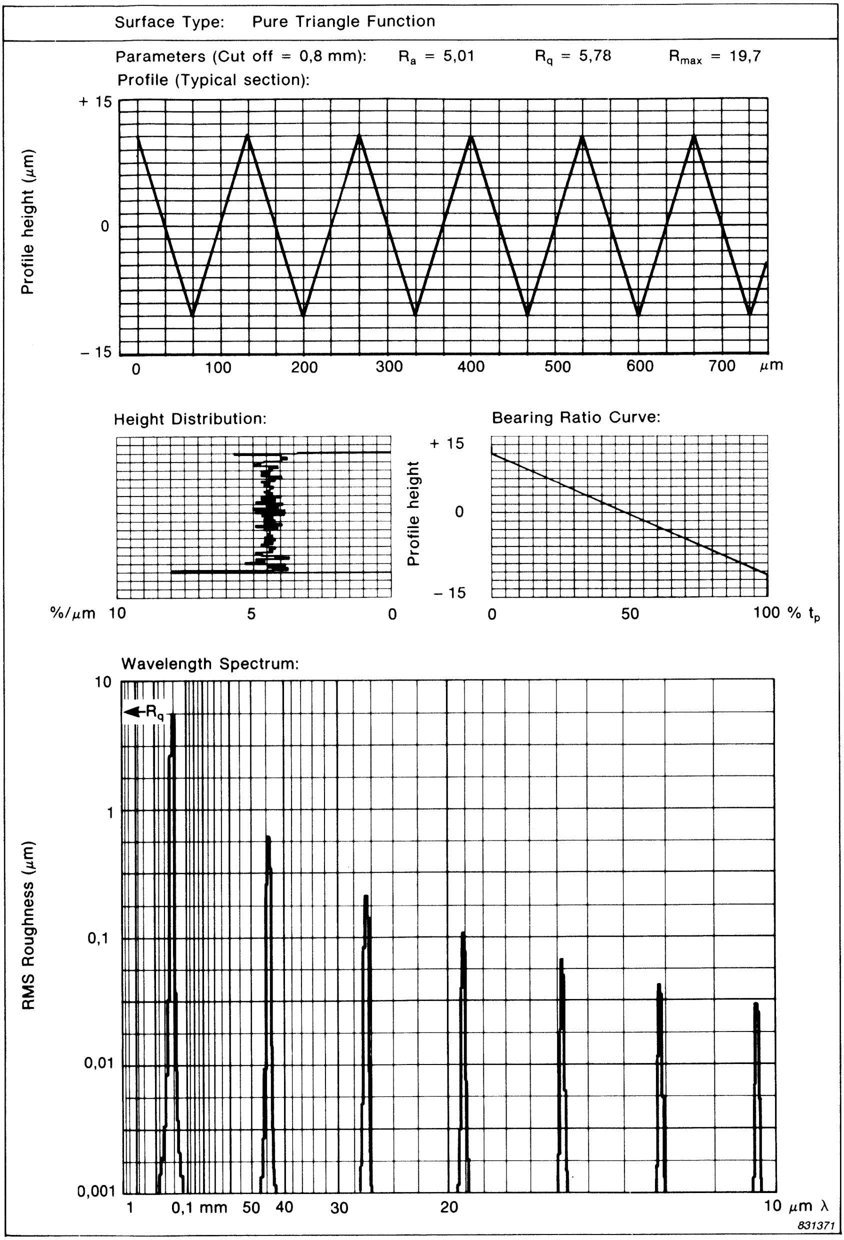


Fig. 6. Height distribution function, bearing ratio curve and spectrum of an ideal triangular surface

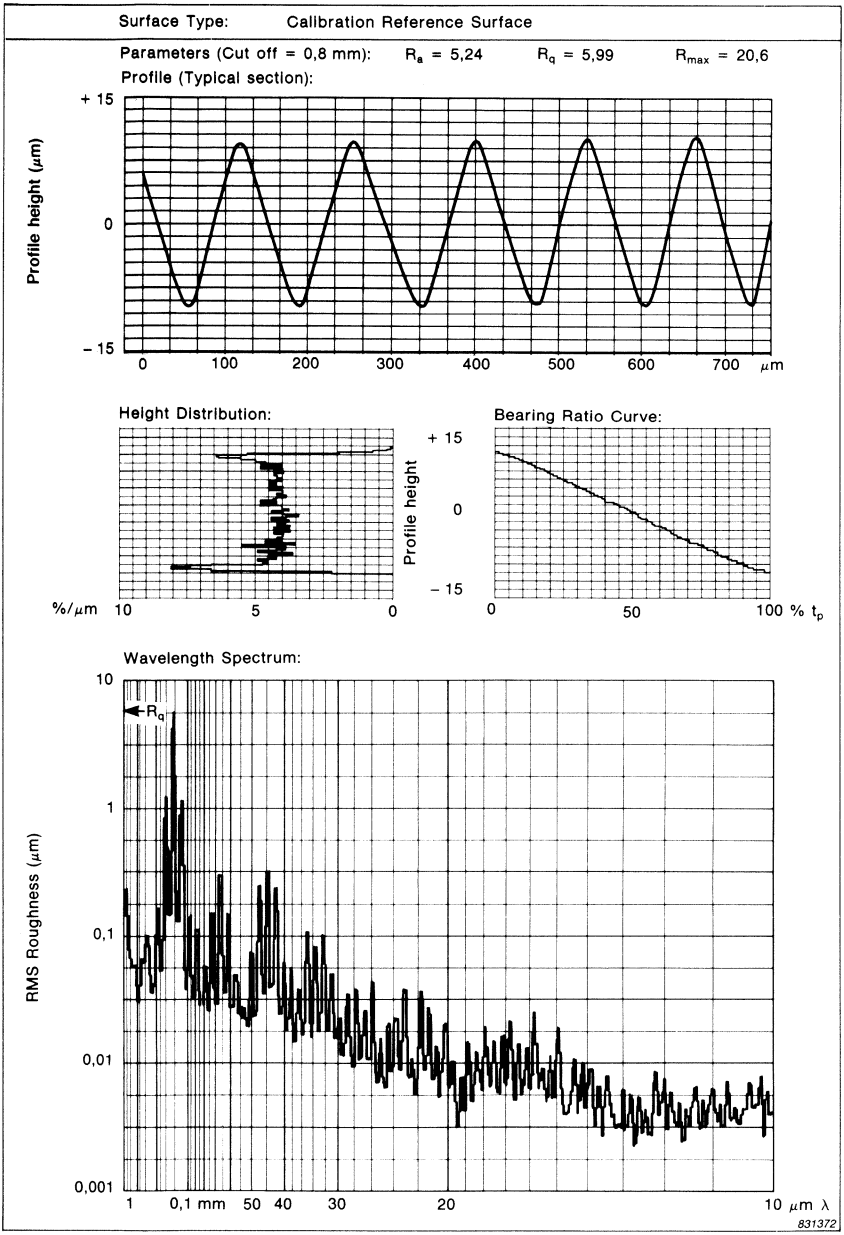
In general, a correct measurement of the roughness overlapping an ideal surface profile can only be performed using spectral analysis. In the spectrum, the discrete lines of the ideal profile shape can easily be identified, and the roughness level between these lines can be measured.

Fig.7 shows an example of a real triangular profile with its typical characteristics, which is used as R_a calibration reference for the portable Surtronic 3 roughness meter. No significant difference between the real surface in Fig.7 and the corresponding ideal surface in Fig.6 can be observed on the height distribution and the bearing ratio curve. On the profile, a slight difference can be seen, but it cannot be quantified. On the spectrum, however, significant changes can be observed. The spectrum still consists mainly of discrete lines. However, there are many more, and the roughness level between the lines is not zero, as it was for the ideal surface.

As mentioned earlier, a spectrum consisting of discrete lines should be interpreted as a surface profile with a certain periodic waveform. Thus the profile in Fig.7 is certainly periodic, but its waveform is different from the ideal. This is evident from the spectrum which is dominated by discrete lines. However, the pattern of these lines is different from the ideal pattern in Fig.6, indicating that the real profile is distorted compared to the ideal. By comparing the discrete line pattern of the two surfaces, a direct measure for the distortion in the real profile can be obtained.

The distortion in the real profile can be interpreted as periodic roughness overlapping the straight lines in the ideal profile in Fig.6. Another type of overlapping roughness is non-periodic, and can be determined by investigating the roughness level between the discrete lines in the spectrum. The physical explanation of this type of roughness is random irregularities in the manufacturing process, while the explanation of the overlapping periodic roughness is geometrical defects in the production tools.

Finally in this paragraph, the interpretation of the wavelength spectrum will be summarized. The spectrum of a periodic surface contains a typical pattern of discrete lines while the spectrum of a random surface contains no discrete lines. In practice, no periodic surfaces are ideal, so any real periodic surface profile will contain some roughness overlapping the ideal profile shape. This roughness can be divided into periodic distortion roughness and random roughness, and both types



Surface Type: Calibration Reference Surface

Parameters (Cut off = 0,8 mm): $R_a = 5{,}24$ $R_q = 5{,}99$ $R_{max} = 20{,}6$

Profile (Typical section):

Height Distribution:

Bearing Ratio Curve:

Wavelength Spectrum:

Fig. 7. Calibration reference surface for Surtronic 3

can be determined by investigating the spectrum: All discrete lines in the spectrum of the real surface that are not identical to the discrete lines in the spectrum of the ideal surface, are due to periodic distortion of the ideal profile shape. The level between the discrete lines in the spectrum of the real surface is a measure of random roughness.

Spectra of Typical Surfaces

In this section, the spectra of the most typical types of machined surfaces will be shown and interpreted.

Turned surfaces

In Figs.8, 9 and 10 three different types of a turned surface are analysed with respect to surface profile, parameters (R_a, R_q and R_{max}), height distribution function, bearing ratio curve and wavelength spectrum.

The surface in Fig.8 seems rather "clean" when the profile is investigated. This is confirmed by the wavelength spectrum where the random roughness level is approximately 30 times lower than the highest discrete peak. The feed mark distance can be seen on the profile, but is more easily determined from the spectrum by looking at the wavelength of the lowest discrete peak (0,3 mm). How close the profile shape is to the ideal expected shape cannot be determined when the spectrum of the ideal profile is not given. However, the pattern of discrete peaks in the spectrum is an unambiguous description of this profile shape, and can be used if the profile is to be compared with others. However, the orientation of the surface (e.g. if the surface is upside down) cannot be seen from the spectrum. In the case of a turned surface, it is difficult to imagine how a surface with a correct spectrum within certain specifications could be manufactured to be inverted. However, in cases where this is possible, the height distribution function or bearing ratio curve are excellent supplements to the spectrum, otherwise the profile must be examined directly. In Fig.8 the height distribution function and bearing ratio curve clearly indicate the orientation of the surface.

The R_q-value of the surface in Fig.8 is a little higher than the highest peak. This is because the second highest peak is only about 1/3 of the highest peak. Thus an integration of the highest peaks must be performed to determine the exact R_q-value.

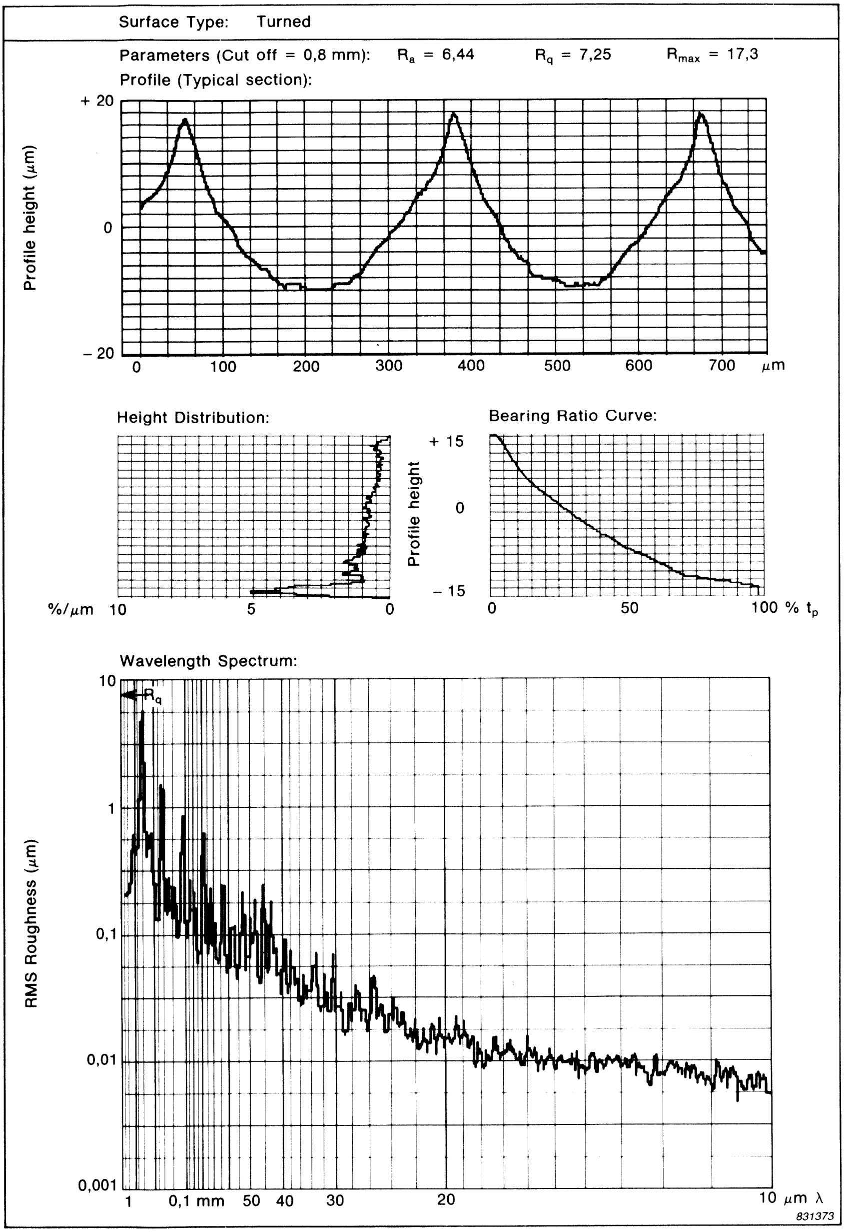


Fig. 8. Characteristics of a turned surface

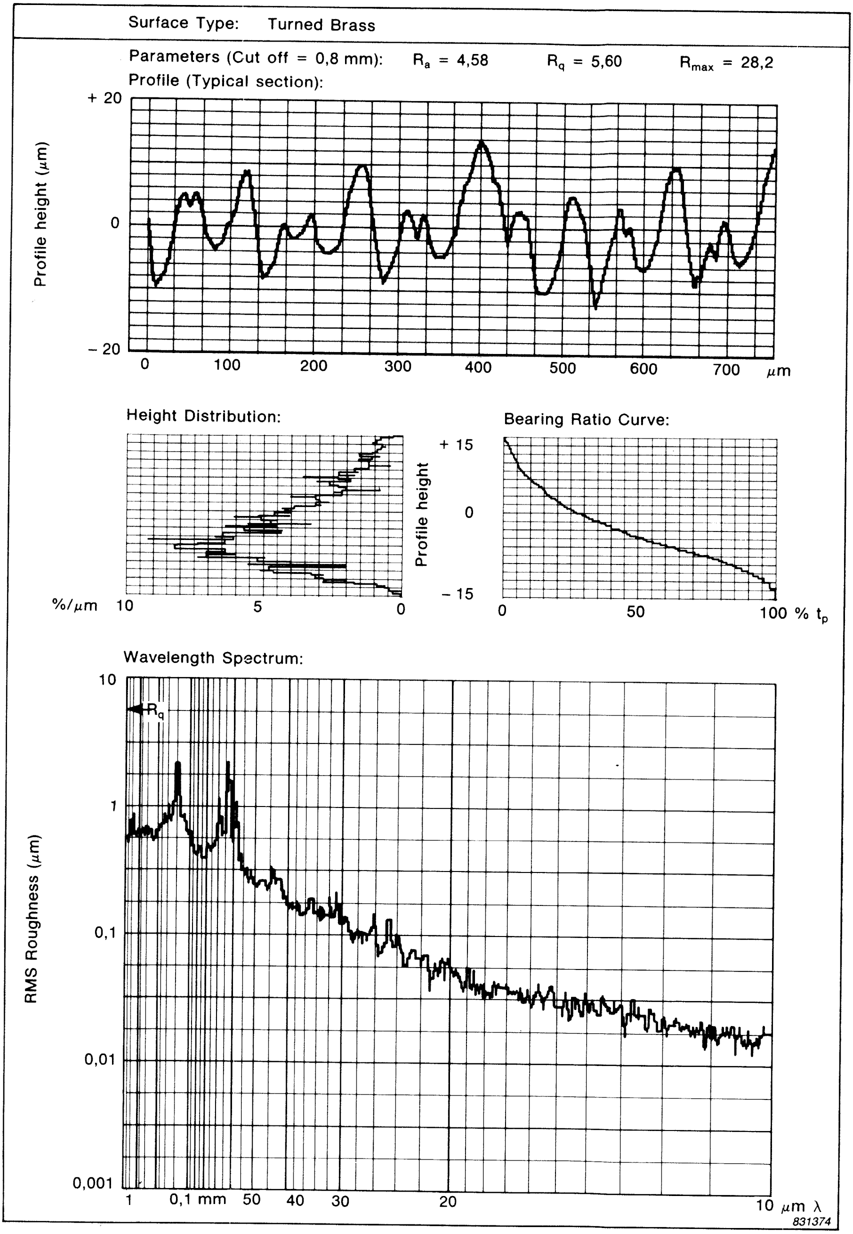
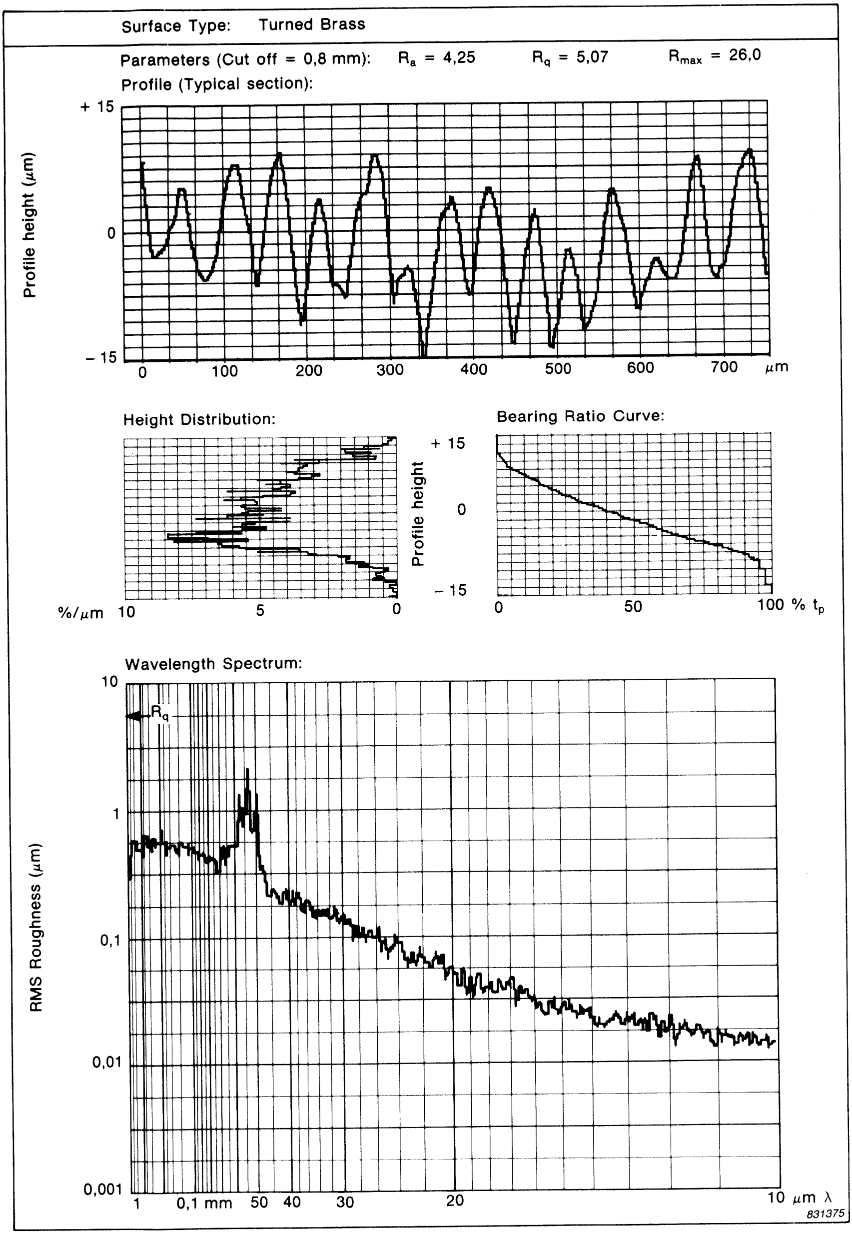


Fig. 9. Characteristics of a turned surface



Surface Type: Turned Brass

Parameters (Cut off = 0,8 mm): $R_a = 4{,}25$ $R_q = 5{,}07$ $R_{max} = 26{,}0$

Profile (Typical section):

Height Distribution:

Bearing Ratio Curve:

Wavelength Spectrum:

Fig. 10. Characteristics of a turned surface

The turned surfaces displayed in Figs.9 and 10 are different from the first. The profiles of these surfaces are more irregular, and the feed marks are difficult to recognize. The differences are, however, revealed in the spectra. Here the feed marks are clearly visible as discrete peaks in the spectrum. For the surface in Fig.9, the adjustment of the feed mechanism can be seen to be 125 microns, while for the surface in Fig.10 it is 55 microns. The irregularity of the surface profile is due to random overlapping roughness, which can be seen from the spectra to be $^1/_5$ to $^1/_8$ of the feed mark peaks. The surface profile in Fig.8 looks more regular, which is also confirmed from the spectrum where the level is $^1/_{30}$ of the feed mark peak. It has been explained earlier that the overlapping random roughness is due to machining irregularities. This is confirmed from the two spectra in Figs.9 and 10, since the random roughness is identical, for the same tool and machine being used to produce both surfaces. For the surface in Fig.8 another production machine was used, which gives a different random roughness spectrum.

The exact R_q-values for the surfaces in Fig.9 and 10 have to be found by integration of the spectrum, as they are not dominated by discrete peaks.

Milled surfaces

Fig.11 shows the characteristics of a typical milled surface, for which the basic wavelength is approximately 1 mm as shown by the spectrum. As the random roughness level is more than a factor of 10 lower than the feed mark peak, the R_q-value is close to the height of this peak.

It will be shown later that conventional parameter measurement would not be suitable for this type of surface, as the dominating wavelength is very close to the most commonly used cutoff wavelength.

The random roughness spectrum for this type of surface is very similar, though not identical, to the random roughness spectra for the turned surfaces.

Ground/polished surfaces

For the ground and polished surfaces in Figs.12 and 13 no significant differences can be seen on either the parameters, the profiles, the height distribution functions, or the bearing ratio curves. However, the surfaces look totally different when seen by the naked eye. The difference lies in the manufacturing process and is also clearly visible in the surface wavelength spectrum. The surface in Fig.12 is ground and

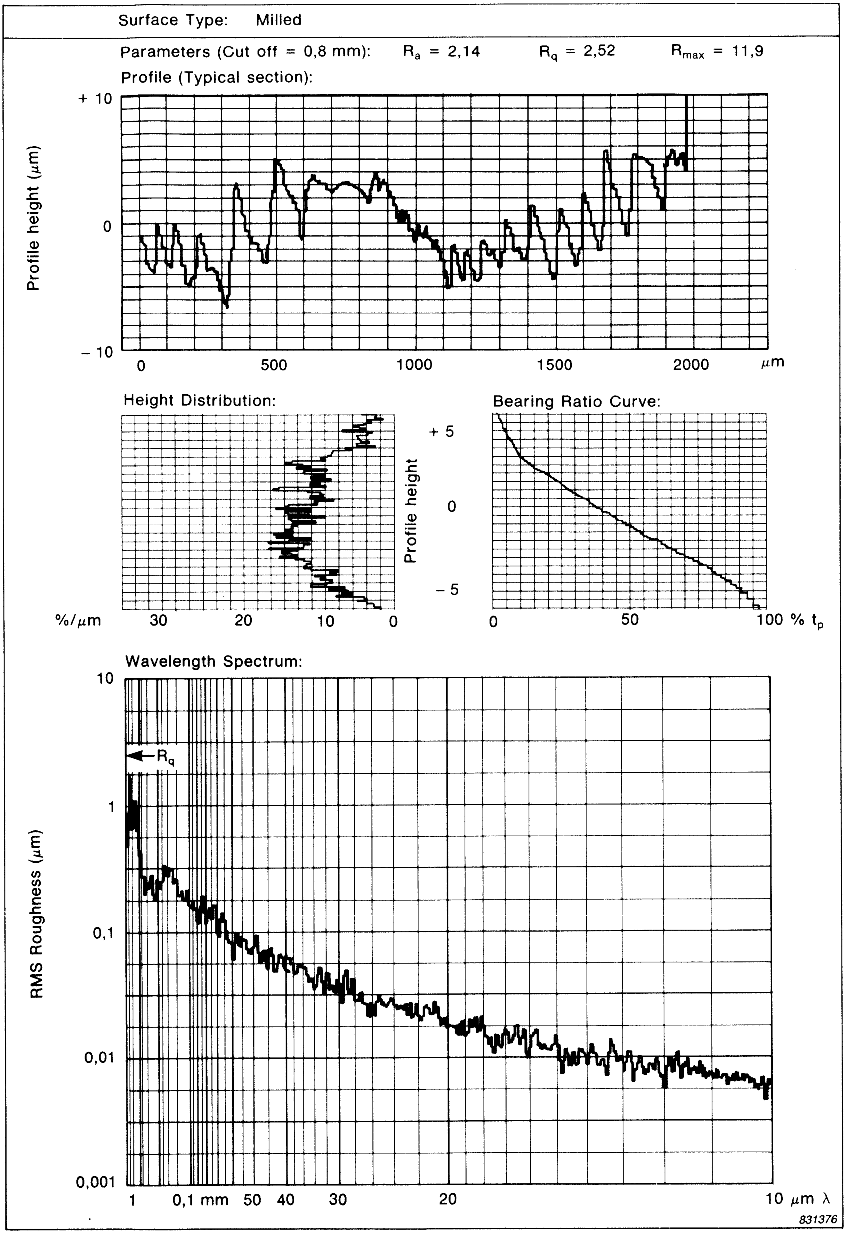


Fig. 11. Characteristics of a milled surface

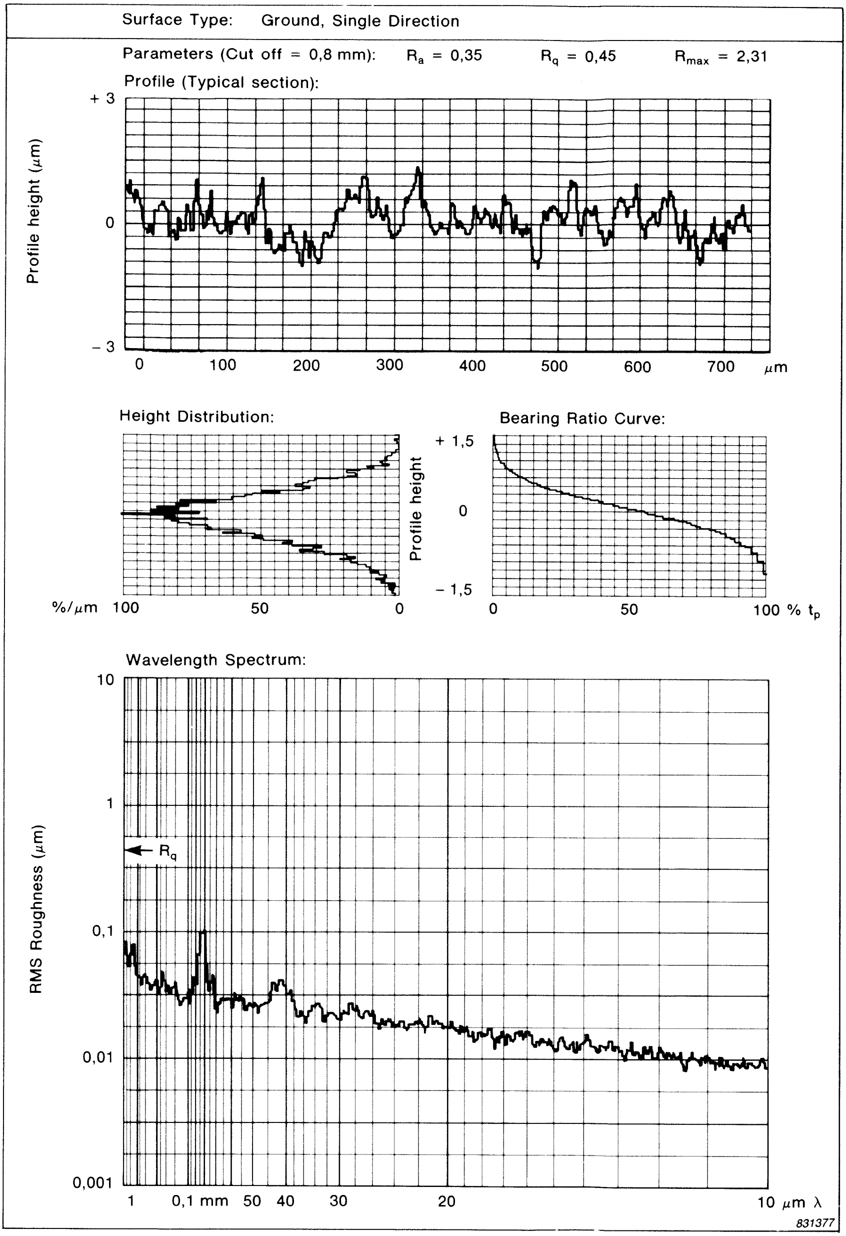


Fig. 12. Characteristics of a surface ground/polished in one single direction

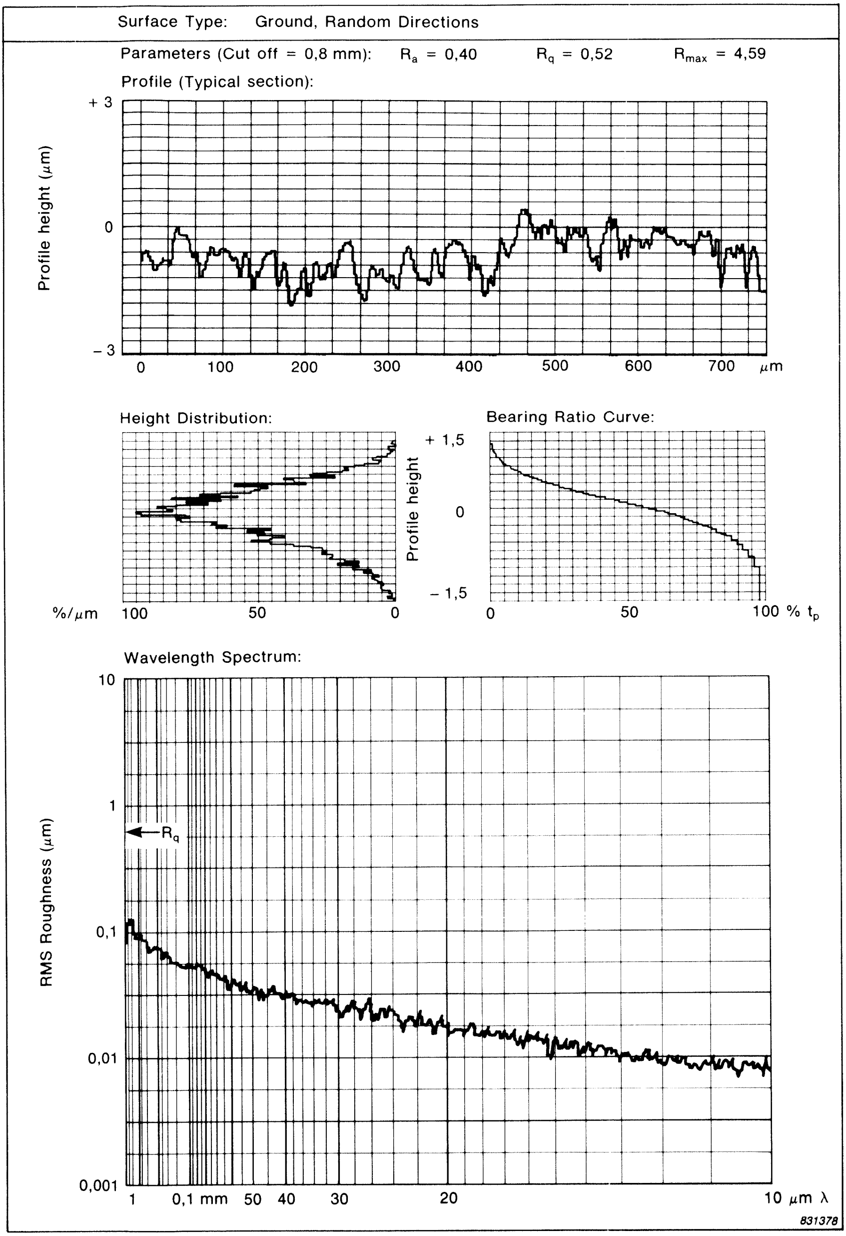


Fig. 13. Characteristics of a surface ground/polished in random directions

polished in one direction only, and therefore a weak dominating wavelength in the surface perpendicular to the grinding direction can be seen. The surface in Fig.13 is ground and polished with the same machine, but in random directions, and the surface is therefore totally non-periodic as indicated by the spectrum. This example illustrates that only spectral analysis can distinguish between two very similar surfaces.

Glassblasted surfaces

The glassblasted surface is another type of surface that is totally non-periodic. The characteristics of a glassblasted aluminium surface are shown in Fig.14. The spectrum does not contain any discrete peaks, and the roughness is therefore totally random. The difference between this spectrum, and the random spectra for the ground and polished surfaces, illustrates again the use of spectral analysis for distinguishing different non-periodic surfaces, where other types of measurements fail.

The spectrum in Fig.14 is rather flat down to 0,1 mm wavelength. Between 0,1 mm and 10 microns wavelength, the roughness level decreases. The 0,1 mm wavelength is closely related to the grain size used in the glassblasting process. In general, the flat region extends to shorter wavelengths when smaller grains are used.

Turned and polished surfaces

Finally, an example will be given of a surface manufactured by a combination of two different processes. The surface displayed in Fig.15 is manufactured by turning, followed by polishing. To give the surface the correct finish, the feed marks from the turning process need to be totally removed by the polishing process. As in the previous examples, it is also difficult in this case to determine with conventional methods, if there is any periodicity in the surface. From the spectrum in Fig.15, however, it is easy to recognize the discrete peaks from the turning process, in spite of the random roughness level being only slightly lower than these peaks. Using the spectrum for checking the surface, it is possible to set very accurate and relevant criteria for the surface roughness. This will be discussed later.

In all the previous examples, the same axis has been used on the spectra of totally different surfaces, fine as well as rough, indicating the advantage of the wide dynamic range of the logarithmic y-axis.

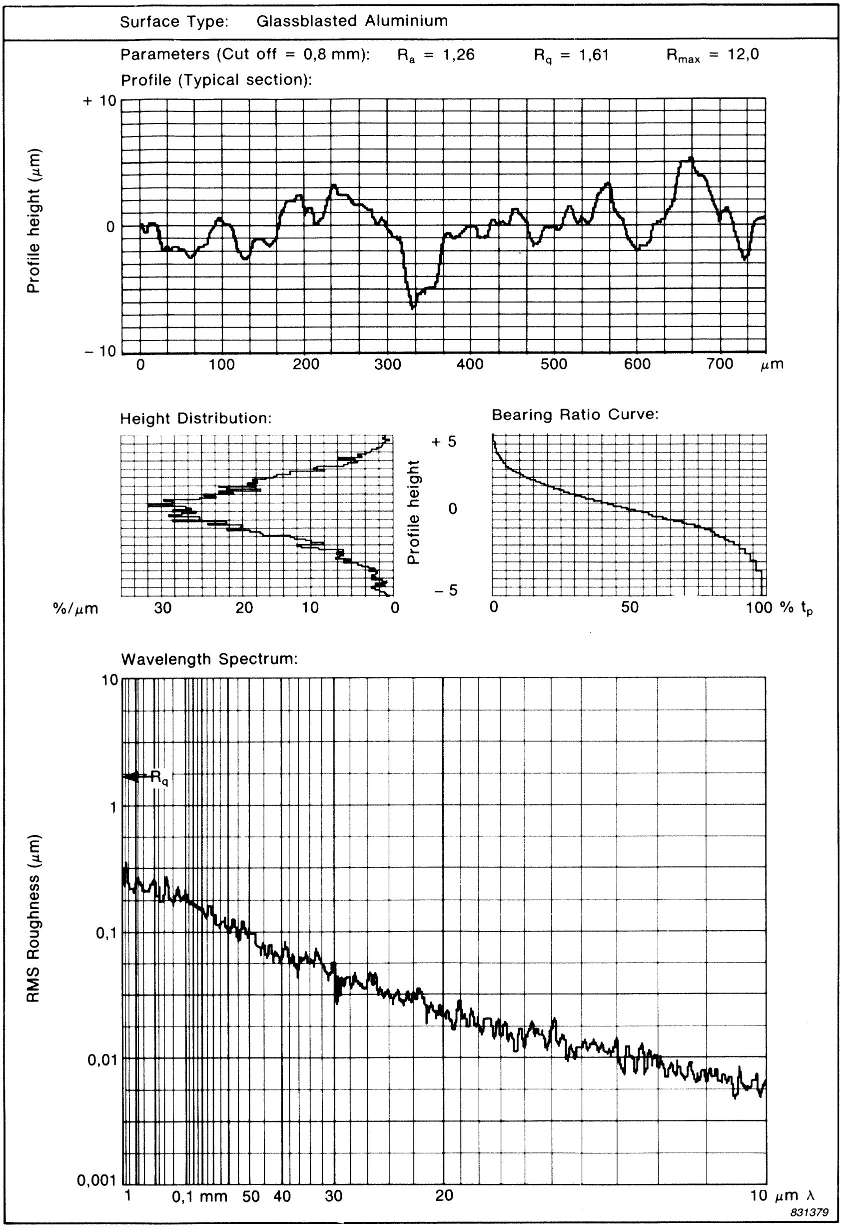


Fig. 14. Characteristics of a glassblasted surface

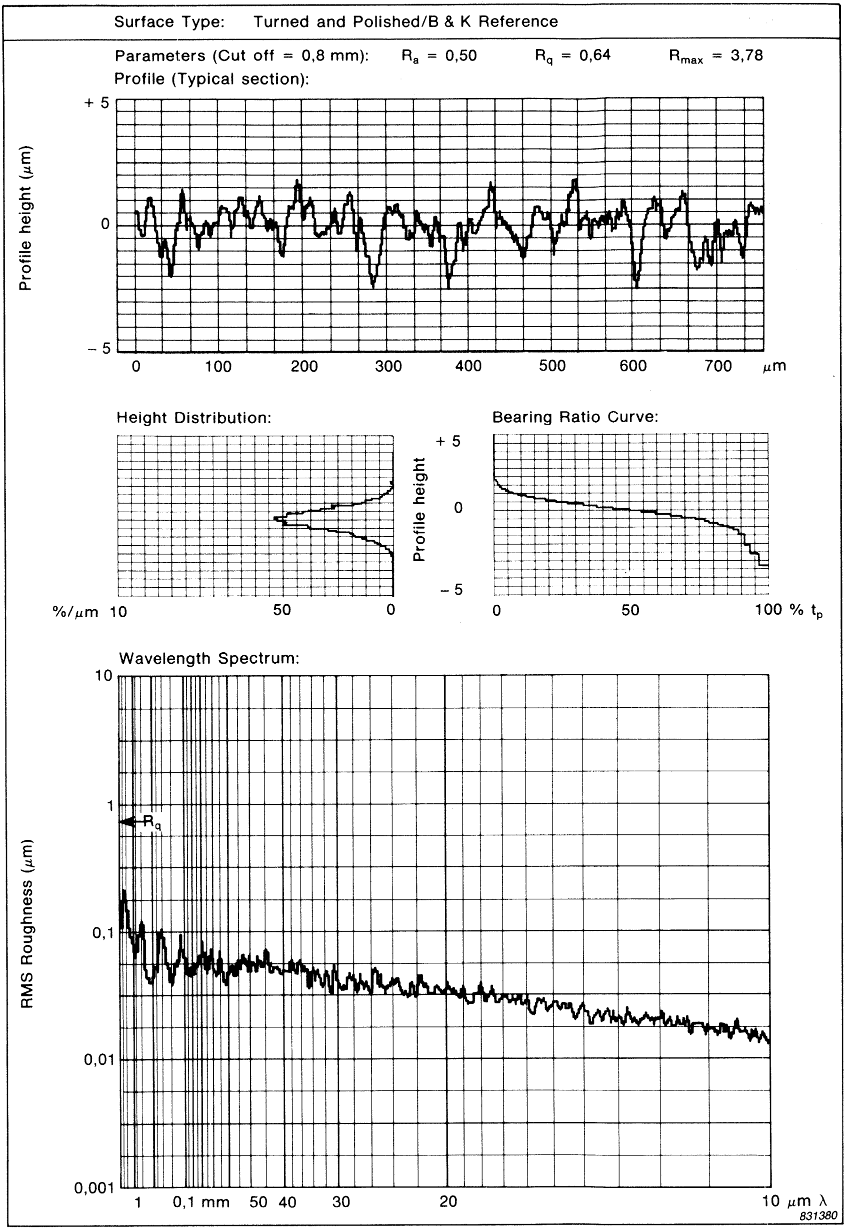


Fig. 15. Characteristics of turned and polished surfaces

Even from the relatively few examples, the amount of information about a surface structure yielded by spectral analysis can be appreciated. In many cases information can be obtained, which is not apparent when using the more conventional parameters and analysis methods. In general, it can be concluded, that the advantage of spectral analysis is that the most relevant information in a two-dimensional profile can be presented in a *quantified* and *condensed* manner. Furthermore, by direct averaging of spectra of a representative surface area, data reduction is also possible. From the wavelength spectrum, periodic phenomena, such as feed marks and tool irregularities, can be immediately isolated from overlapping random roughness caused by totally different factors.

Applications of Spectral Analysis of Surface Roughness

Although there are several applications of spectral analysis of surface roughness only a few important ones will be given in the following. For workers having analysis problems in the field of roughness measurements, spectral analysis might be a solution, while for others, it would complement their conventional measurements, making them more reliable.

Production test

The turned and polished surface shown in Fig.15 is actually a Brüel & Kjær production reference surface. Figs.16 and 17 show the surface characteristics of two differently produced parts, which should, within certain limits, have the same surface as the reference. Function tests showed that the surface in Fig.16 fulfilled the specifications while the surface in Fig.17 could not be used — solely for the reason that it looked totally different.

With respect to the three parameters, R_a, R_q and R_{max}, none of the two produced parts varied significantly from the reference. The profiles are not only difficult to specify but also difficult to compare, and since a profile cannot be averaged, a long profile must be examined to obtain a good representation of the surface. However, the profile in Fig.17 seems to be “a little more” periodic than the reference profile. Furthermore, neither the height distribution functions nor bearing ratio curves of the produced parts are significantly different from the reference. Only the spectrum of the unusable surface in Fig.17 deviates significantly from the spectrum in Fig.16 which is only slightly different from the reference spectrum of Fig.15. The ratios between the spectra in Figs.16 and 17 relative to the reference spectrum, are shown in Figs.18

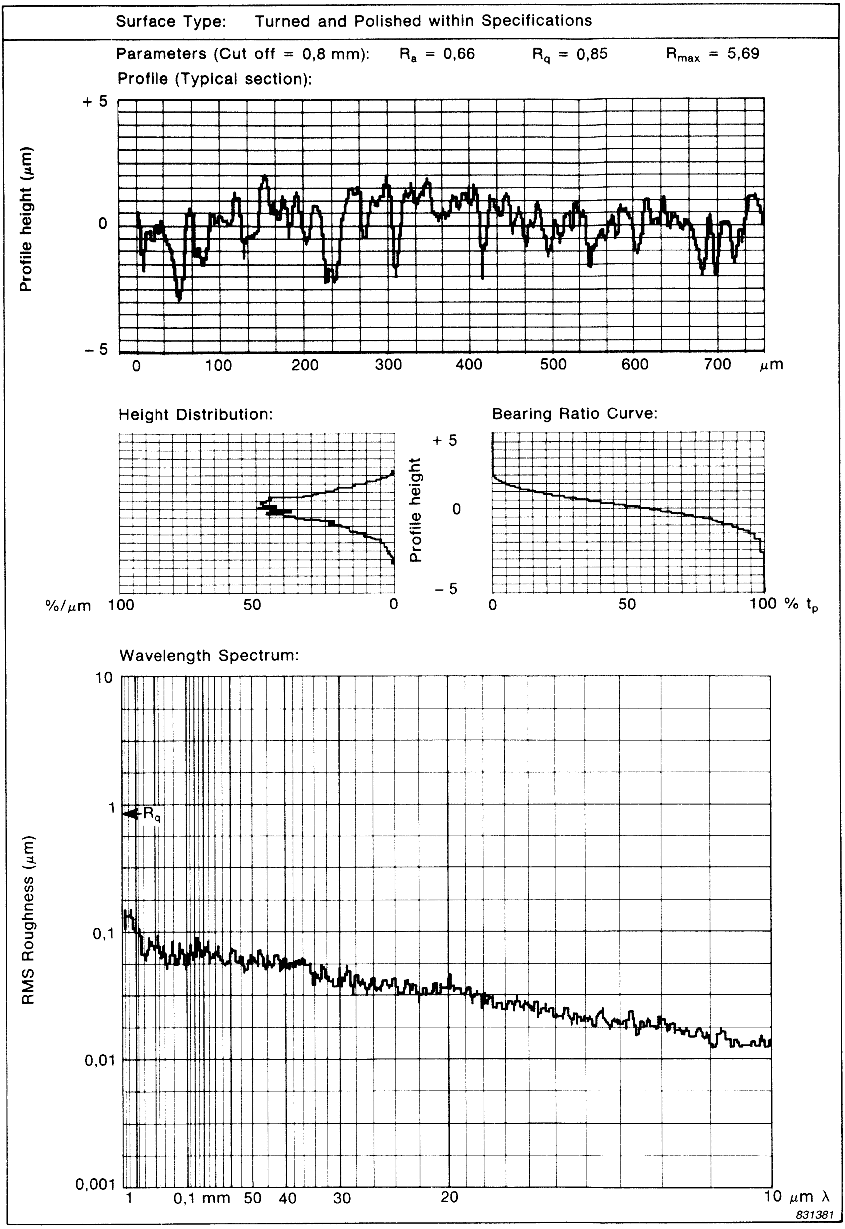


Fig. 16. Characteristics of a usable surface produced by turning followed by polishing

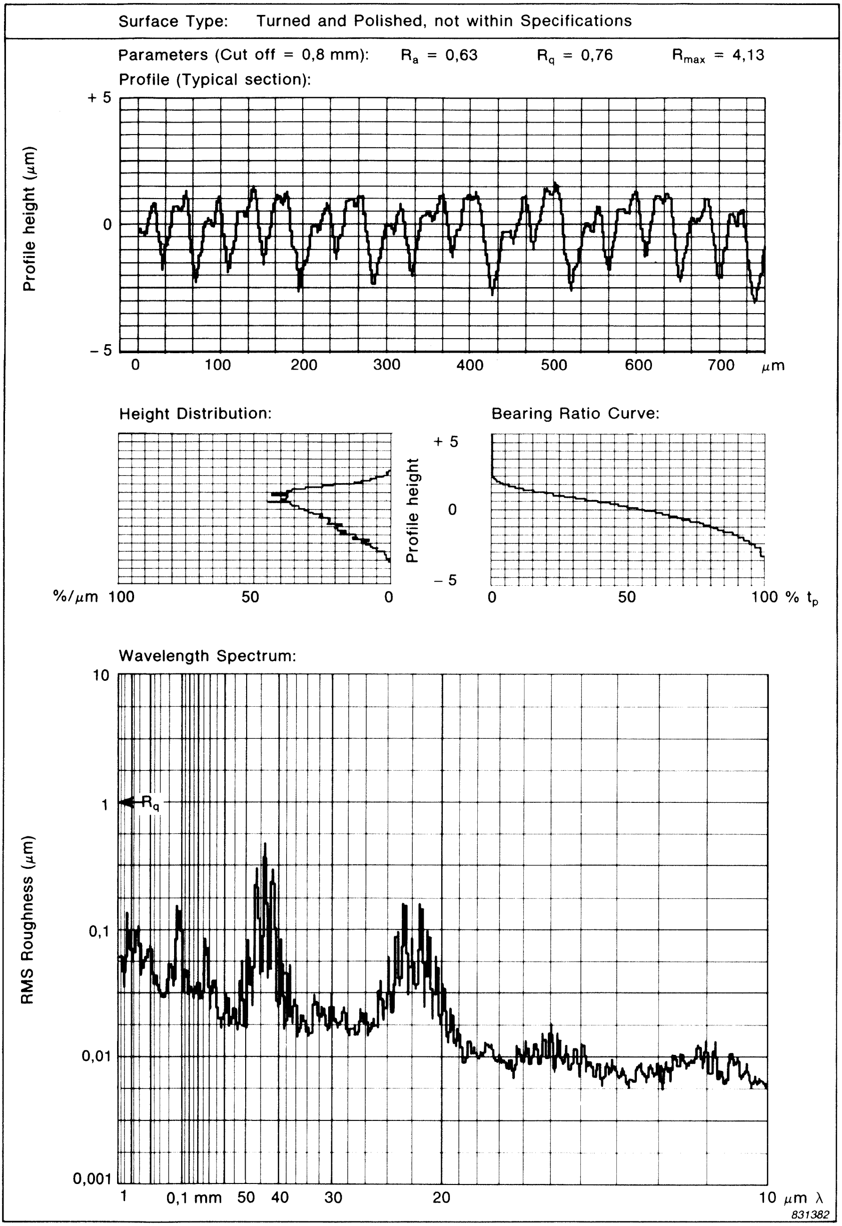


Fig. 17. Characteristics of an unusable surface produced by turning followed by polishing

and 19 where some usable limits are also indicated. Variation in roughness level at any wavelength within a factor of 2,5 is found to be suitable in practice. These ratio spectra with the indicated limits, are very useful for detecting if a surface fulfils some specifications. Thus by storing the reference spectra digitally, the detection process can be automated to make fast and reliable production tests by comparing the recorded spectra with the reference spectra. Furthermore, this method also involves an analysis technique which makes it possible to detect failures that are not detectable by conventional methods as shown by the last example.

Another advantage of spectral analysis in product testing is that the spectrum also indicates which part of the production line has failed. Abnormal machine vibrations, worn tools, wrong adjustments etc., almost all types of failures can be detected by the spectrum, as shown in the previous sections. In the case of the rejected surface shown in Fig.17, the spectrum indicates that there are at least two sources of errors:

1. The polishing process has been incomplete as the peaks in the spectrum from the turning process are still clearly visible.

2. The malfunction of the turning process is evident from the discrete line pattern in the spectrum which is different from the pattern that can be recognized in the spectrum of the reference surface (Fig.15). One can furthermore detect that the adjustment of the lathe is incorrect, and also that it is not constant (indicated by several discrete peaks in the spectrum in Fig.17). This is probably due to a defect in the lathe.

Thus, spectral analysis for product testing not only gives a unique surface control check, but is also widely used for machine health monitoring — a fact which should be borne in mind.

Lubricant test

Application of spectral analysis in lubricant tests has been developed in the Department of Mechanical Technology at the Technical University of Denmark and described in Ref.[2]. Here, only the principle of this application will be touched upon.

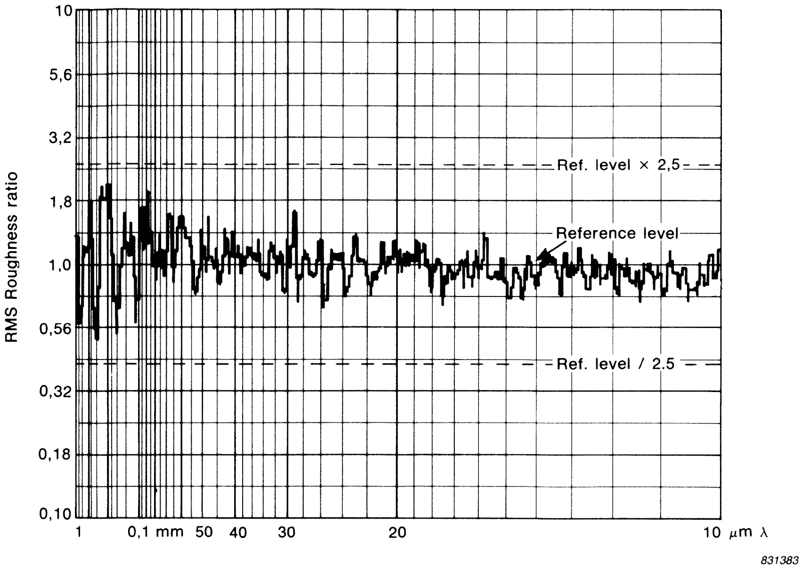


Fig. 18. Ratio between the spectra in Figs.16 and 15

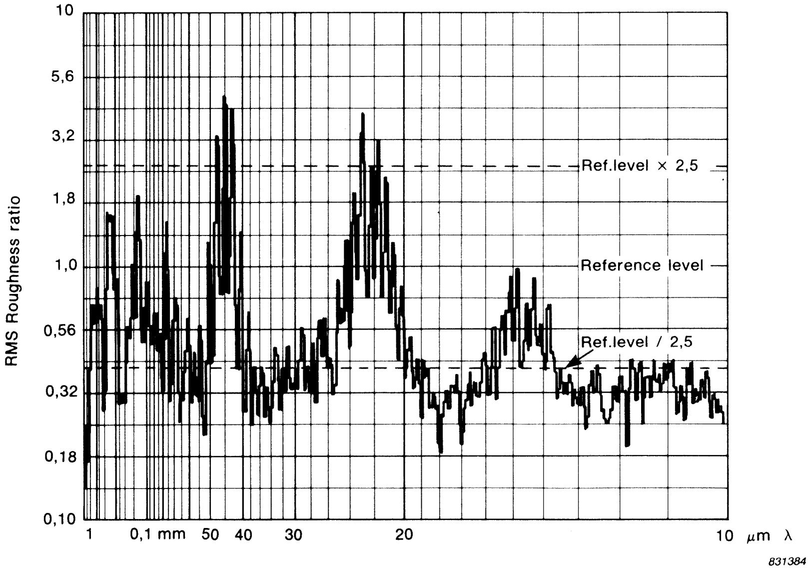


Fig. 19. Ratio between the spectra in Figs.17 and 15

When different lubricants were used in a shaping process, no significant differences were found using conventional parameters. This was because the feed marks dominated the micro-structure as mentioned above. With spectral analysis, the random roughness in the surface can be measured, and thereby it is possible to detect the effects of rather small amounts of additives in lubricants. An example is illustrated in Fig.20 where the spectrum on the left obtained from dry cutting of aluminium can be compared to the spectrum on the right obtained from cutting in alcohol. It should be noted that for these two spectra a linear scale for roughness level has been used. The random roughness level is found to be approximately 5 times lower when cutting in alcohol, however, much smaller deviations have been registered between different lubricants. It appears from the above article that the effect of some additives can be registered only at very short wavelengths (5 to 10 microns). In this range conventional measurements are not practicable. In fact, the parameter measurements in some cases gave directly misleading results.

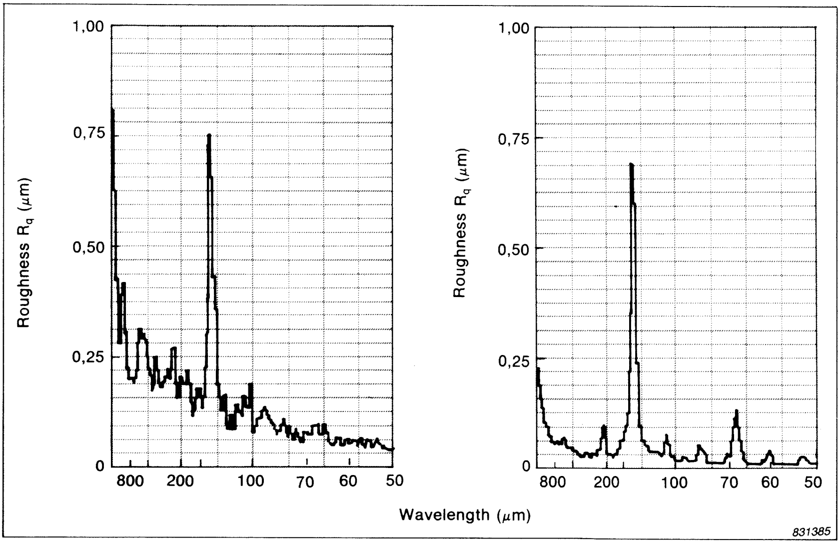
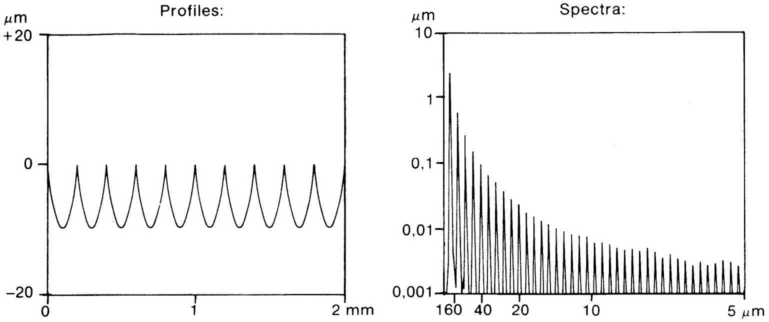
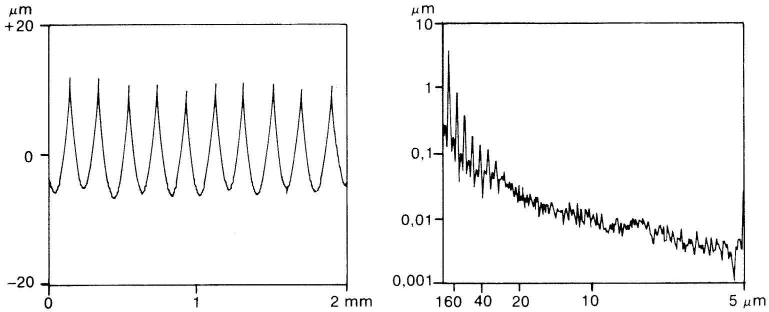


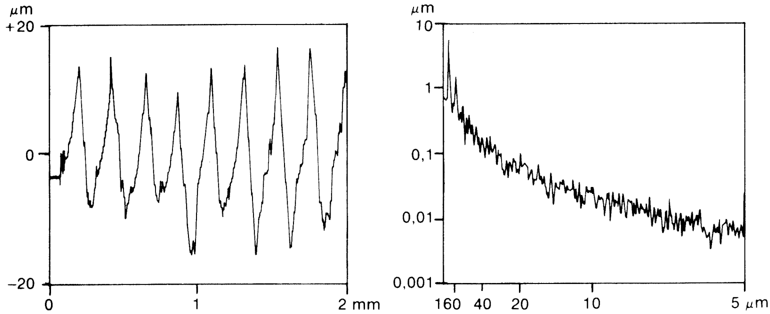
Fig. 20. Comparison between spectrum obtained by dry cutting of aluminium (left) and spectrum obtained by cutting with alcohol as lubricant (right)



Ideal surface produced by turning.



Surface produced by turning at cutting speed 200 m/min.



Surface produced by turning at cutting speed 50 m/min.

831406

Fig. 21. Profiles and spectra of an ideal surface (top) and the real surfaces with two different cutting speeds (middle/bottom)

Process optimization

This application has also been developed by the Department of Mechanical Technology at The Technical University of Denmark. The basic idea of this application is the same. However, in this case, the roughness of a turned steel surface is investigated as a function of the cutting speed. As the feed marks again dominate the roughness, conventional parameter calculations are not meaningful. From the adjustment of the feed mechanism and the radius of the cutting tool, it is possible to calculate the ideal surface profile and obtain an ideal spectrum from its transform. These are shown at the top of Fig.21. In the middle and the bottom of the same figure, the profiles and spectra of real surfaces produced at 200 m/min and 50 m/min cutting speed are shown.

With the spectral method, it is easy to distinguish between the two real surfaces and to measure directly how well the surfaces approximate the ideal profile, as well as to measure the random roughness level. For the given case, a cutting speed of 200 m/min is optimal: the first seven peaks in the spectrum are all clearly visible and identical to the peaks in the ideal spectrum. At the same time, the random roughness level is far below the top of the peaks. For a cutting speed of 50 m/min, the profile is very distorted relative to the ideal, and the random roughness level is high.

Parameter and cutoff selection

Spectral analysis can be of significant help in deciding whether a parameter measurement is sufficient. It also helps in the selection of the optimal cutoff filter for a given measurement. In general, it can be stated that a parameter measurement might be sufficient, if only information of the highest feed mark peak is essential. A simple amplitude parameter can then be chosen, e.g. R_a or R_q. If the random roughness level in the surface is high compared to the top of the peaks, a parameter like R_{max} or R_z should also be measured. For surfaces with no periodicity, a combination of R_a or R_q, and R_{max} or R_z, or equivalent must be chosen.

Fig.22 illustrates the use of the spectrum for cutoff filter selection. As the spectrum in Fig.22 is zoomed 10 times compared to the other spectra shown, the lowest wavelength is 0,1 mm in this case.

Fig.22 shows the spectrum of the milled surface of Fig.11, as well as the amplitude transfer characteristics of three standardized cutoff filters. It can be seen that the choice of the most commonly used 0,8 mm filter

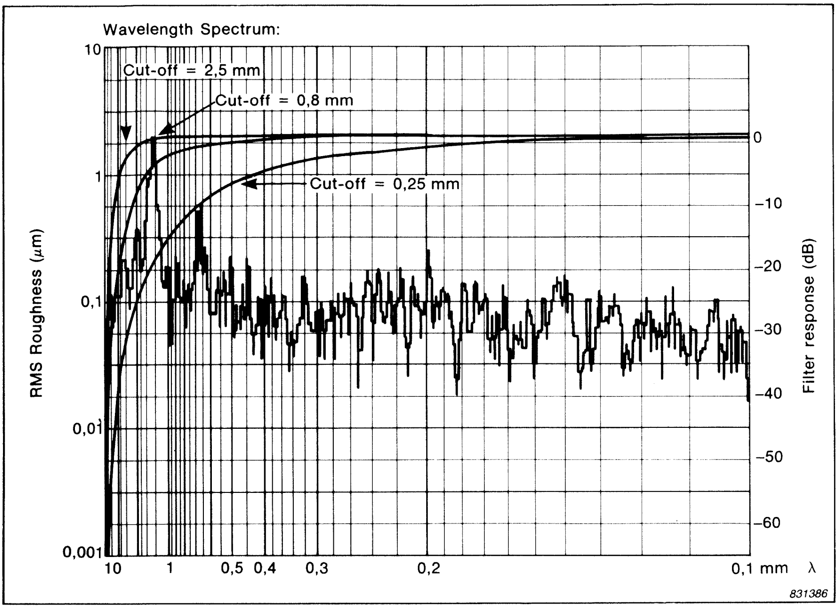


Fig. 22. Zoomed spectrum of the milled surface from Fig.11 with three cutoff filter amplitude characteristics

would be a poor one in this case, as the highest peak in the spectrum is neither cutoff totally, nor measured correctly. Even small changes in the wavelength of this peak will give totally different measurement results. The demands on the cutoff filter will also be high in this case. It is necessary either to cut away such a peak totally or to let it pass. In this example, this can be done using the 0,25 mm filter or the 2,5 mm filter respectively. However, when the spectrum consists of several closely spaced peaks, (of which many examples have been shown), the above rule can be difficult to follow. In each case, the spectrum can be used to evaluate if a proper cutoff filter can be selected and, if so, it would also help in pointing out the optimal filter.

Measuring equipment test

Spectral analysis can also be used for calibration and testing of roughness measuring equipment which is obviously of great importance. Figs.23 and 24 show the zoomed spectra of the reference calibration surface of Fig.7. In Fig.23, the traverse speed has been constant while in Fig.24 it was varying due to error in the traverse unit.

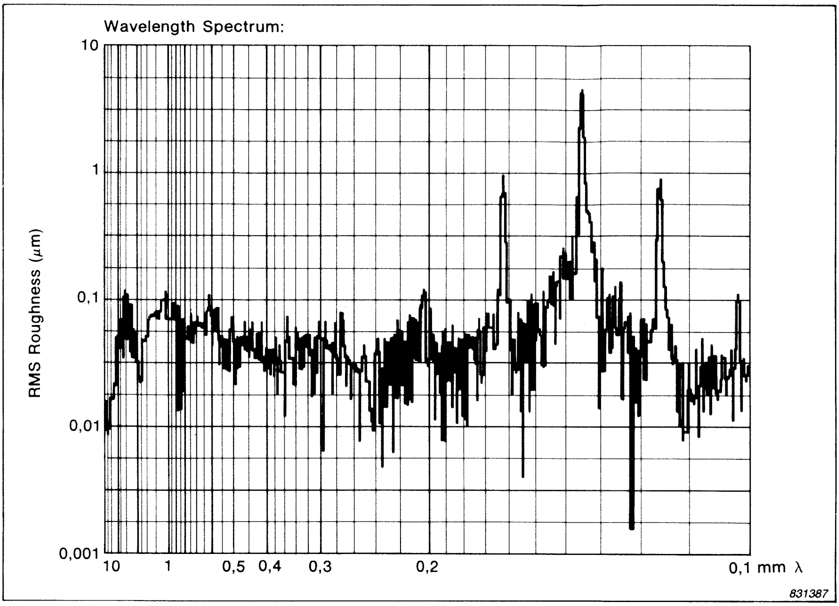


Fig. 23. Zoomed spectrum of reference surface from Fig.7 measured with constant traverse speed

It can be seen that the dominating peak at 0,135 mm is spread out in Fig.24 indicating the varying traverse speed. For checking the traverse speed this method is very accurate and fast.

It is also important to check the radius of the pickup tip. Normally special (expensive) references with specific steep steps are traversed, and the profiles are investigated. However, any change in the radius and shape of the pickup tip will also be detected in the spectrum when a known periodic reference is measured. It is well known that the finite radius of the pickup tip distorts a periodic profile. The distortion components appear in the spectrum at frequencies that are integer multiples of the fundamental frequency, the harmonics. This harmonic distortion can be theoretically determined, and approximate expressions for the two first harmonics, d_2 and d_3, are given below. r is the pickup tip radius, a is the amplitude of the surface and k is the wavenumber (i.e. wavelength × 2π/length unit). d_2 and d_3 are the ratios between the fundamental frequency and the second and third harmonic respectively.

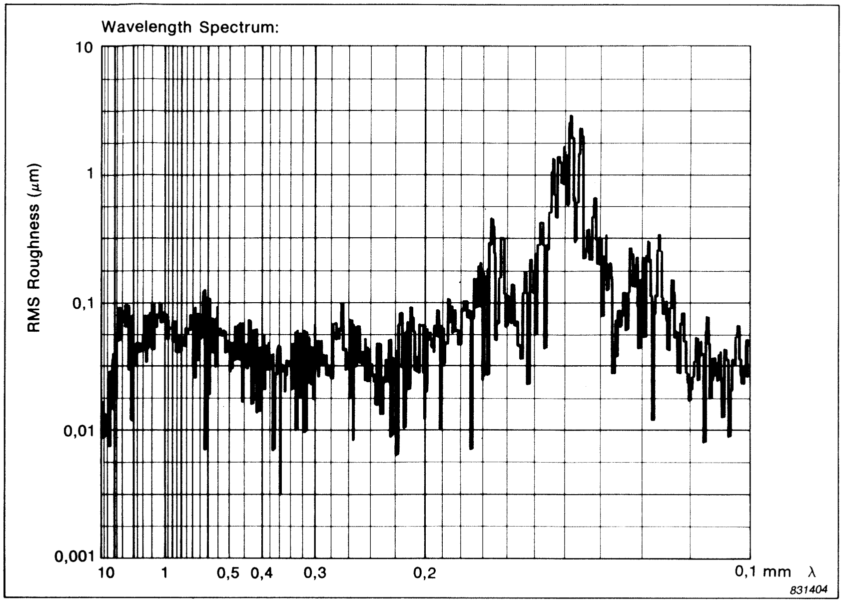


Fig. 24. Zoomed spectrum of reference surface from Fig.7 measured with varying traverse speed

$$d_2 \cong \frac{1}{4} kr\, ka$$

$$d_3 \cong \frac{1}{8} (kr)^2 (ka)^2$$

The radius of a pickup tip can be checked by measuring the spectrum of a reference surface, and comparing it to the spectrum of the same reference surface obtained using a pickup in good condition. The spectrum ratio feature described earlier can be advantageously used for this purpose. The amplifier gain and the filter characteristics of a roughness measuring instrument can also be easily checked and adjusted with the help of the spectrum. Additionally, the spectrum yields information of possible noise sources in the instrument as well as vibration of the measured object which helps in tracing the causes of failure. Thus, by measuring a single spectrum of a reference specimen it is possible to check almost all the relevant functions of roughness measuring equipment; traverse speed, pickup tip radius, amplifier gain, filter characteristics, and noise and vibration level.

The Hilbert Transform

Another analysis technique that can be used in surface roughness measurements, is the Hilbert transform. While the Fourier transform shifts the independent variable of a signal from the time domain to the frequency domain or vice versa, the Hilbert transform leaves the signal in the same domain. Thus the Hilbert transform of a profile is actually another "profile". The Hilbert transform of a profile can be simply described as a shift of all wavelength components of the profile by 1/4 wavelength. The effect of this is very similar to an integration of the profile. Through the Hilbert transform, the profile signal can be interpreted as a complex signal where the real part of the signal is the original profile and the imaginary part of the signal is the Hilbert transformed profile.

Hence the magnitude of the complex profile signal is given by $\sqrt{\mathrm{Re}^2 + \mathrm{Im}^2}$ The magnitude describes the envelope of the profile, and as it is always a positive quantity, it can be displayed on a logarithmic axis also giving access to a large dynamic range for the profile plot. This facility has two possible applications:

1. The profile of a highly varying roughness can be displayed on a single plot. Fig.25 shows an example of a fine and a rough surface separated by a deep scratch. On the conventional plot, the structure of the fine surface can hardly be seen, but on the logarithmic plot, the structure of both surfaces are clearly visible. As the magnitude of the profile is equivalent to the R_q-value, its value can be read as an average magnitude over a certain region of the profile. It should be noted that the magnitude function is not the same as the original profile, however, the profile type can be recognized from the magnitude.

2. In the second approach, the profile prior to the transformation is offset so that it contains no zero crossings. In this case, the original profile shape will be preserved in the magnitude function, as the magnitude describes the envelope as mentioned above. Thus it is possible to plot the fine profile with a logarithmic amplitude scale and thereby achieve high resolution for some heights of the surface (for example, the upper part, which is normally the most important), at the expense of lower resolution for other heights of the surface. An example is illustrated in Fig.26.

The upper curve of this figure shows the normal profile plot which has been given a negative DC-offset to remove the zero crossings. Hereby,

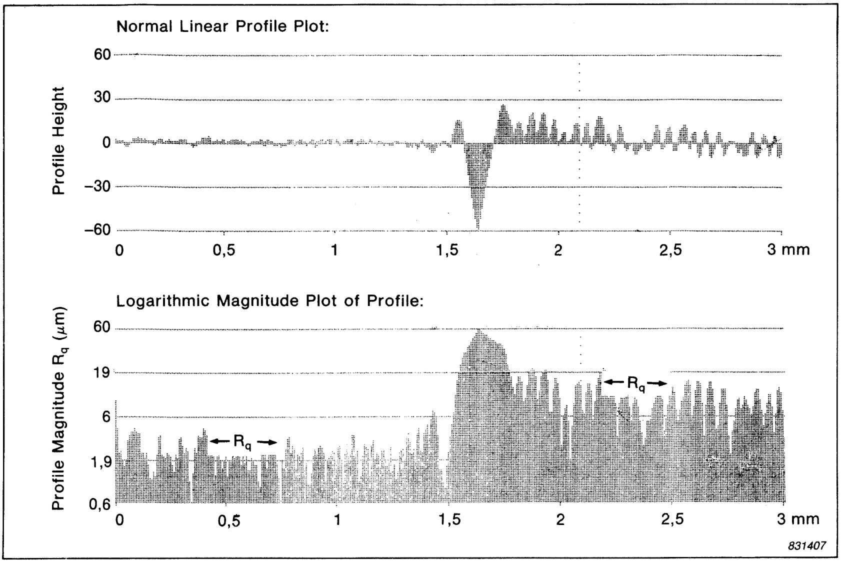


Fig. 25. Normal profile plot (top) and logarithmic magnitude plot (bottom) of a surface with varying roughness

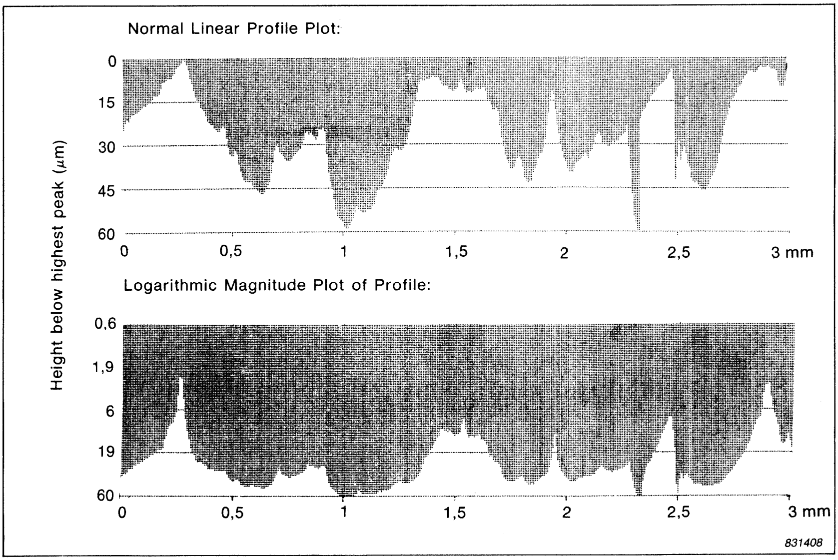


Fig. 26. Normal profile plot (top) and logarithmic magnitude plot (bottom) of a turned surface

the top of the profile becomes closest to the meanline. The closer to the meanline, the bigger the amplification, and this is why the top of the profile has the highest resolution in this case. It can be seen how the top of the original profile can be investigated with higher acccuracy on the logarithmic magnitude plot than on the conventional profile plot.

Instrumentation for Spectral Analysis of Surface Roughness

A roughness measuring system capable of calculating a surface spectrum, need only consist of two devices, a traverse unit and a Fourier analyzer. For the experiments in this article, a traverse unit Surtronic 3 from Rank Taylor-Hobson has been used, and a Brüel & Kjær 2033 Fourier analyzer. This analyzer fulfils the essential requirements that make an FFT-analyzer suitable for roughness analysis:

1. A long time buffer to store the profile (10 K samples is a convenient size)
2. Large display to investigate in detail the profile with different amplifications
3. Linear as well as logarithmic spectrum display
4. The ability to post-average spectra over a recorded profile
5. Non-destructive zoom analysis
6. The ability to compare two spectra and to calculate the ratio between them
7. Interface for a computer or desk-top calculator

The measurement results have been obtained on a Brüel & Kjær X-Y recorder on preprinted charts — one type of chart for the spectrum, another for the profile, and a third type for the height distribution function and bearing ratio curve. Furthermore, all the data profiles as well as spectra have been stored on digital cassette tape using the Brüel & Kjær Digital Cassette Recorder Type 7400. It is thus possible to make further analysis of the profiles, e.g. zoomed spectra or recall data for further processing.

For calculation of the conventional parameters, the height distribution function and the bearing ratio curve, a desk-top calculator has been added to the system. Filtering of the profile is then performed in the calculator by a programmed digital filter. The calculator can also be used to remotely control the other instruments, facilitating the operation of the complete system. As the screen of the Brüel & Kjær Analyzer 2033 can be used to display all the data (including the statistical distribution functions), a calculator with built-in screen is not essential. The instrumentation set-up used is shown on Fig.27.

For the measurements in this article, an averaged spectrum over a total profile length of 20 mm has been calculated. Thereby, influence from small irregularities in the surface is avoided. As the traverse speed of the Surtronic 3 is 1 mm/s, and the frequency range of the pickup is much higher than 200 Hz — the selected upper frequency of the analyzer — it is possible to investigate wavelengths down to 5 microns. The sampling frequency of the analyzer in this case is 200 × 2,56 samples/sec, which gives a spacing of 1,95 microns between the samples. For accurate parameter calculations, the sample separation can be reduced, as the analyzer can sample up to 51 200 times per second! The tip radius of the pickup used was 5 microns, and here it is important to remember that the tip radius, the upper limiting frequency of the pickup, and the highest analyzed frequency, must be chosen to be compatible with each other.

The instrumentation in Fig.27 is fairly portable, and as the traverse unit can be connected by a simple analog cable to the rest of the system, it can be used remotely: an advantageous feature, for example, in product testing. It is also worth noting that the analyzer can be easily coupled to the profile output of *any* roughness meter, facilitating the difficult connection between a traverse unit and a computer or a desk-top calculator. It is thus possible to convert an old system into a modern one capable of spectral analysis and other computer programmed functions.

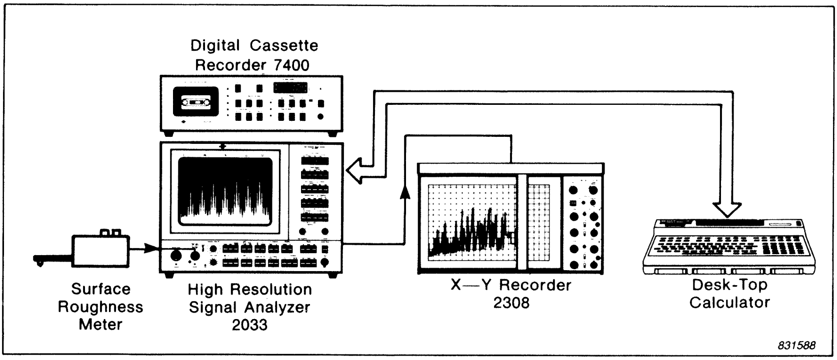


Fig. 27. Instrumentation set-up

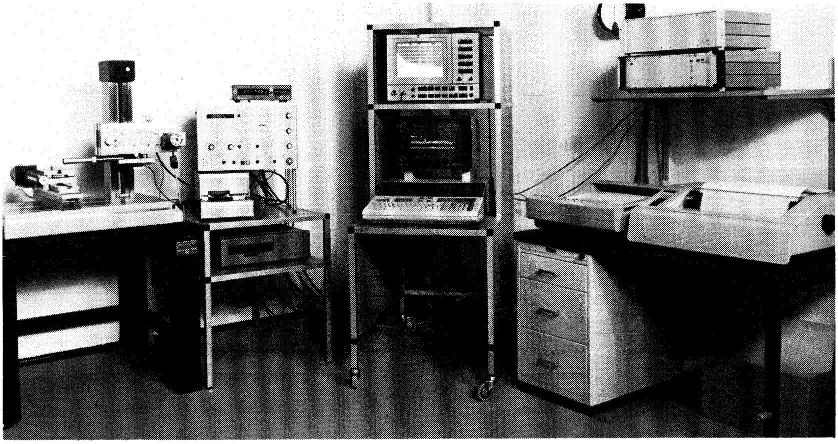


Fig. 28. Roughness measuring system in the Department of Mechanical Technology at the Technical University of Denmark

Fig.28 shows a roughness measuring system in the Department of Mechanical Technology at the Technical University of Denmark, where the Brüel & Kjær Fourier Analyzer Type 2033 is used for spectral analysis and as an interface between a traverse unit and a computer.

The system is capable of measuring both 2 and 3 dimensional surface roughness, and the sampling is position controlled instead of time controlled, to avoid the influence of varying traverse speed.

With the newly developed 2 Channel FFT Analyzer Types 2032 and 2034, the Hilbert transform and height distribution function can also be performed, and the display facilities of these analyzers are even wider than those of the 2033. Furthermore, the calibration procedure is very easy. Print-outs can be made on the X-Y Recorder Type 2308, and also on the new programmable Graphics Recorder, Type 2313, where the results can be very well documented. This recorder, with the 2032 analyzer, is capable of calculating and printing out a series of other functions — among them the height distribution function.

Conclusion

Fourier analysis is applicable to all types of surface roughness measurements. Its advantages in product testing, parameter selection and equipment control, as well as in more advanced analysis problems such as lubricant evaluation and process optimization have been illustrated. The wavelength spectrum yields easy to interpret information about the most relevant characteristics of a surface structure, and furthermore it is easy and quick to calculate in a Fourier Analyzer, where the profile can also be closely inspected. Besides, it gives information about the overall roughness level and differentiates between periodic and random roughness. As the spectrum also indicates the machining process that has been used to produce the measured surface, it helps to trace errors on the production line when failure occurs. Thus overall production monitoring can be performed by spectral analysis of surface roughness. In view of this, together with the fact that it facilitates optimization of production processes, considerable funds can be saved in mechanical industry.

It is therefore recommended that spectral analysis of surface roughness be introduced as soon as possible, and ultimately be standardized. It is believed that research and industry will be far better helped by spectral analysis as an analysis tool, than by efforts spent in developing new parameters, adding confusion to the already existing jungle of discrete parameters.

Acknowledgement
The author wishes to thank Leonardo de Chiffre (M.Sc.) at the Technical University of Denmark for valuable discussions.

References

[1]	RUPERT, M.P.	The importance of surface finish control. *Proc. of the 5th Int. Machine Tool Des. & Res. Conf.* Birmingham U.K. Sept. 1964. p 199–210.
[2]	DE CHIFFRE, L.	AMT, Technical University of Denmark, 2800 Lyngby, Denmark: Frequency Analysis of Surface Machined Using Different Lubricants *(paper presented at the 37th ASLE Annual Meeting).*
[3]	CETIM	Centre Technique des Industries Mécaniques, 10, rue Barrouin, 42029 Saint-Etienne, France: Le Rugosimetre Tridimensionnel Pour Une Meilleure Evaluation Des Etats de Surface.
[4]	RANDALL, R.B.	*Brüel & Kjær, USA:* Application of B & K Equipment to Frequency Analysis.

[5] VORBURGER, T.V., TEAGUE, E.C., and SCIRE, F.E. Mechanical Processes Division, A123 Metrology Building, 301/921-3838 Dimensions/NBS, November 1978: Fast Facility Available for Engineering Needs.

[6] TUMFART, S. *Feinwerktechnik & Meßtechnik* 85 (1977) pp. 308–312: Die Beschreibung der Rauhigkeit technischer Oberflächen mittels Wahrscheinlichkeitsdichte- und Korrelationsfunktion.

[7] KONCZAKOWSKI, ANDRZEJ Politechnika Gdańska, Poland. Mechanik No. 10, 1979, *Journ. of the Polish Society of Mechanical Production Engineering:* Research on the Influence of Turning Process on Geometrical Structure of Machines Surfaces Based on Spectral Analysis of the Surface Profiles.

[8] KONCZAKOWSKI, ANDRZEJ and PRZYBYLSKI, WLODZIMIERZ *Paper presented at Polish Academy of Science Winter Meeting,* Gdańsk, Poland, December 1981: The Rolling Process Effectivity Evaluation Method Conception Based on the Spectral Analysis of the Surface Geometrical Structure.

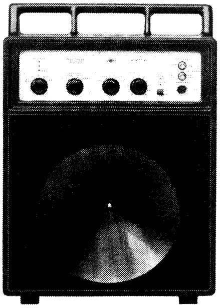
[9] KONCZAKOWSKI, ANDRZEJ and SHIRAISHI, M. Politechnika Gdańska, Poland and Faculty of Engineering Ibaraki University 4–12–1 Nakanarusawa, Hitachi, Japan 316. *Precision Engineering,* 0141-6359/82/030159, July 1982 Vol 4 No. 3: Sampling error in a/d conversion of the surface profile signal (pp. 159–161).

[10] Draft International Standard ISO/DIS 468: Surface roughness — Parameters, their values and general rules for specifying requirements.

[11] Americal National Standard, ANSI B46.1-1978 (Revision of B46.1-1962 (R-1971)): Surface Texture — Surface Roughness, Waviness and Lay.

News from the Factory

Sound Source Type 4224



The Sound Source Type 4224 is specifically designed for building acoustics measurements such as sound reduction index, facade insulation, reverberation time and absorption. The Type 4224 consists of a loudspeaker with built-in power amplifier and noise generator contained in a robust, moulded cabinet with an integral handle. It can deliver up to 115 dB sound power level from 100 Hz to 4 kHz when driven from its internal, rechargeable batteries or up to 118 dB sound power level when driven from a mains supply. In spite of its impressive performance the Type 4224 weighs only 18 kg (40 lbs).

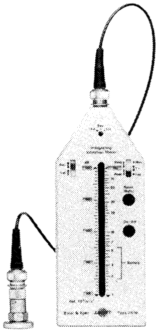
In its wide band mode, the Sound Source Type 4224 produces a pink noise signal from 100 Hz to 4 kHz. To produce bands of noise, this signal can be fed to an external $^1/_3$ or $^1/_1$ octave filter, before amplification and reproduction by the loudspeaker. Two special filter networks within the 4224 can be switched into the circuit to shape the noise signal to produce spectrum I and spectrum II in accordance with "Simple test method for measuring sound insulation" ASTM E 597-77 T.

The output level can be attenuated in steps of 10 dB over a 40 dB range, and varied continuously within each step. Lamps on the control panel indicate when the delivered sound power exceeds the maximum for continuous use ("Overload") and when it is within 3 dB of the overload condition ("Upper 3 dB").

When used in conjunction with the Building Acoustics Analyzer Type 4418 and a microphone, the 4224 constitutes a powerful and portable system for the automatic measurement and calculation of all the commonly used quantities in building acoustics according to both national and international standards.

The conical diffuser can be snap-locked onto the front of the cabinet, to improve the reproducibility of sound insulation measurements and to render the measured results less dependent on the position and the angle of inclination of the cabinet.

Integrating Vibration Meter Type 2516



The Integrating Vibration Meter Type 2516 has been developed to meet the demands from prospective users who prefer to measure in g's and in/s. In all other respects it is identical to Type 2513, which measures in S.I. units. Compact and light enough to be carried in the Document Folder supplied, the 2516 incorporates several advanced features, such as 60 s L_{eq} facility for taking the ambiguity out of the measurement of fluctuating vibration sources. The integrator which gives the 2513 its name calculates a true mean-square average of the vibration over a period of one minute. It displays the 60 s L_{eq} on a thermometer-type LED display, with a constant 6% resolution over its 100-to-1 range. The display adjusts its brightness automatically to compensate for ambient light conditions, and can also be set to read current or maximum values of true-RMS or true-Peak levels.

The 2516 can be set to measure either acceleration or velocity in the ranges 0,1 to 100 g and 0,01 to 10 in/s respectively. It has a flat frequency response from 10 Hz to 10 kHz, and includes weighting filters for measuring Vibration Severity and Hand-Arm Vibration to ISO 2954 and ISO/DP 5349 (1982-02-17) respectively. The vibration transducer supplied is a robust Piezoelectric Accelerometer, Type 4384, which comes with a specially designed mounting magnet for ease of attachment to the vibrating object.

Principal applications of the new Vibration Meter will be machine-condition monitoring for maintenance scheduling. However it is also expected to find many uses in general vibration measurement, especially in the quality control of manufactured products (where its Severity setting will be of benefit), and the Hand-Arm weighting will enable it to be used for evaluating the human factors of portable power-tools.