

DUAL FUNCTION – SURFACE METROLOGY

D.J. Whitehouse

Metrology Consultant Taylor Hobson and University of Warwick
 Department of Engineering, Coventry CV4 7AL, UK

Abstract: The role of surface metrology with respect to manufacture and performance is explained. How the rule has changed over the years and how it is likely to develop is discussed. It is shown how the classification of workpiece performance is related to surface typology and manufacturing control.

Keywords: Surface texture, Surface instrumentation, Tribology, Nanotechnology

1 WHY MEASURE SURFACES

In recent years surface texture has been recognized as being significant in many fields. In particular the surface roughness is an important factor in determining the satisfactory performance of the workpiece, in tribology for example or in coatings. Also in engineering applications the surface roughness has been found useful in machine tool monitoring. It is, however, pertinent to consider how the importance of surface roughness is changing with the passage of time, and how the importance of roughness depends on the actual scale of size of the work-piece and the process used to make it.

In very general terms the requirements for energy transfer and information transfer and storage have dominated the development of technology. This will no doubt also be true in the future but the factors governing such transfer depend themselves on size. As objects get smaller changes take place which highlight the importance of the surface. The energy and force equations experience a change of balance, Figure 1(a) as the scale of size of the moving object reduces.

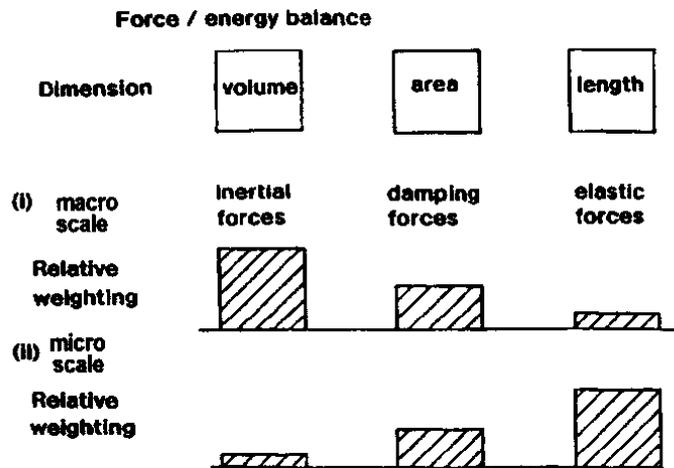


Fig. 1b. Information storage / transfer

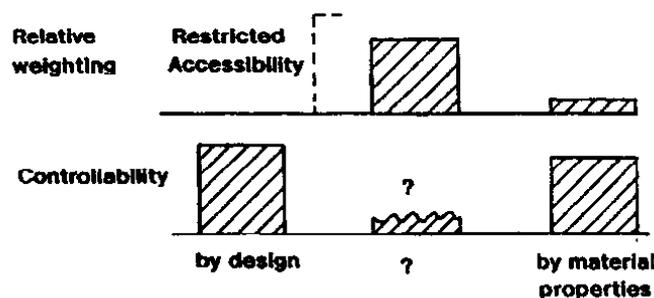


Figure 1. Importance of Surface Properties with Scales of Size.

Information storage in 3D is possible but still very difficult to achieve, also data retrieval is a major problem. On the other hand storage of data on surfaces is still actively being extended. This capability is obviously a function of the surface area. There is no problem with accessibility of the stored data as there is with volume storage. Notice that information storage trends tend to have the opposite sign to the energy equations with respect of the effect of the scale of size, Figure 1(b). In both situations the critical regime is that of area. Consider Figure 1(a). In the force diagram momentum effects quickly decrease as size is reduced, in fact by a factor of L^3 . Damping is proportional to area and reduces as L^2 . Elastic forces only reduce as a linear factor of L so that they become progressively more important than the others as the scale of size reduces. In rotational situations the dependence on scale is even more pronounced. For example moment of inertia reduces by a factor of L^5 .

Of the above factors elastic properties can be controlled by the properties of materials, which are well understood, and inertial forces can be controlled by design. This leaves areal or damping forces which cannot be well controlled. Energy losses and energy transfer; information storage and transfer, are all sensitive to uncontrolled areal properties and the areal property which is most likely to be influential is the surface roughness. It is also the least understood and manageable. Hence the greater emphasis being placed on its measurement in recent years. The pressure to do so is due to the search for a better quality of goods and also to achieve better manufacturing control. The term areal is used here in place of the often used but misleading 3D [1].

2 SURFACES IN MANUFACTURE

There are two basic ingredients involved in manufacturing a workpiece, the manufacturing process and the machine tool or production technique. How they relate to surface measurement is shown in Figure 2. At one time measurement of the surface was considered largely irrelevant but it soon became apparent that the finish on the surface was extremely sensitive to any changes in the process. Hence it became logical to assume that measurement of the surface could be used to control the manufacture. Any change in the surface parameter should initiate a review of the process parameters. In the UK and USA R_a the average roughness was used as the control parameter whereas in Germany and Soviet Union peak parameters were used [2]. The UK approach was pragmatic in the sense that the parameter specified on the drawing had to be measurable. In Germany the approach was to use parameters such as R_y the maximum peak to valley height on the surface in an attempt to impose functional constraints on the surface as well as manufacturing control. The peak parameters, however, are inherently divergent – they get larger as the sample size increases. Also, sometimes, the maximum values of a parameter are difficult to find over a large area of the surface. Extreme peak-valley measures soon degenerated into measurements of average peak-valley heights R_{TM} , R_z etc. simply to make them stable.

Although the variations of a single parameter of the surface roughness could be used to indicate a change in the manufacturing process, it is not sufficiently discriminating to pinpoint where the changes in the process have occurred. Even using a number of simple parameters rather than just one fails to provide the necessary discrimination. It is only recently that surface metrology has become comprehensive enough to be used a diagnostic tool. This capability arose because of the advent of random process analysis. That is, the use of auto-correlation, power spectra and probability density functions.

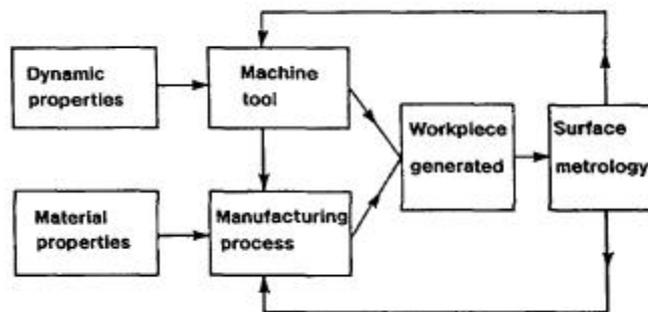


Figure 2. Surface Measurement and Manufacture

These are functions rather than numbers such as the R_a (average Roughness) of the profile and so can reveal much more of the underlying statistics of the surface. They are more reliable because in

the case of autocorrelation and power spectral density any random phase shifts between the sinusoidal components making up the profile are eliminated. The autocorrelation function is particularly useful for looking at random surfaces and the power spectrum is more useful for looking at periodic surfaces, as will be seen shortly. Neither are particularly difficult to generate. The autocorrelation function is simply a plot of the correlation coefficient between the surface profile and the same profile shifted in space by a set amount. The Power Spectrum is the Fourier Transform of this.

2.1 Autocorrelation and Manufacture

The reason why these statistical parameters are effective is because they provide a large enhancement of the signal over the noise introduced into the system. For example each point on the autocorrelation function of a profile taken off a surface is a result of a great deal of averaging. Small changes between surfaces became significant. As a general rule the autocorrelation function can best be used to reveal changes in random processes such as grinding whereas power spectral analysis can be used to best advantage in processes which are fundamentally periodic or repetitive as in turning or milling. Both the autocorrelation function and the power spectrum hunt for the unit machining event. In the case of grinding the unit event is the impression left on the surface by an average grain on the grinding wheel. In power spectral analysis it is the periodic signal left on the surface by a clean cutting tool on a perfect machine.

Take grinding for example as a case where autocorrelation is useful Figure 3(1a) shows the impression left on the surface by a sharp grain [3]. Figure 3(1b) is a typical profile and Figure 3(1c) is the correlation function. Notice that the correlation length (distance over which the correlation drops to nearly zero) is a direct measure of the effective grain hit width. For a grinding wheel in which the grains are blunt, Figure 3(2a) there is a considerable material pile-up as well as a chip formed. By examining the correlation function it is apparent that pile-up or ploughing is revealed by lobing in the autocorrelation function. The width of the central lobe is a measure of material removed. At a glance therefore the shape of the autocorrelation function reveals the efficiency of the grinding in all its aspects, Figure 3.3 Notice that this would not be revealed by looking at the profile or by using simple parameters. In Figure 3 any longer waves in the autocorrelation function of the surface show other problems such as the need to dress the wheel.

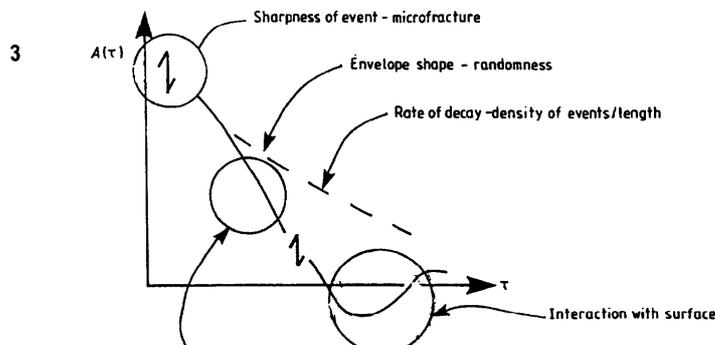
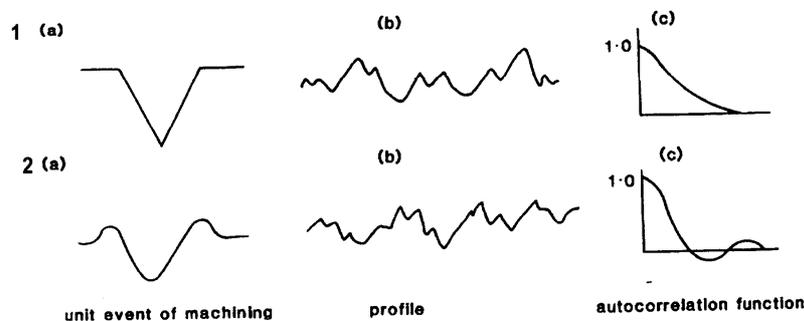


Figure 3. Autocorrelation Significance in Manufacture

2.2 Power Spectral Density in Manufacture

Another example shows how the power spectrum can be used to identify problems in turning. As the tool wears and the machine tool deteriorates significant changes occur in the spectrum of the surface as shown in Figures 4 and 5.

Figure 4 (1b) shows a profile of good turning produced by a good tool, Figure 4 (1a) together with its spectrum Figure 4 (1c). As would be expected for good turning the spectrum shows some line frequencies, the fundamental corresponding to the feed and a few harmonics due to the shape of the tool.

As the tool wears the ratio of the harmonic amplitudes to that of the fundamental increases. This is due to the imposition on the surface of the wear scars on the tool. Also on this right hand side of the fundamental spectrum the base line can rise, due to random effects of the chip formation and microfracture of the surface.

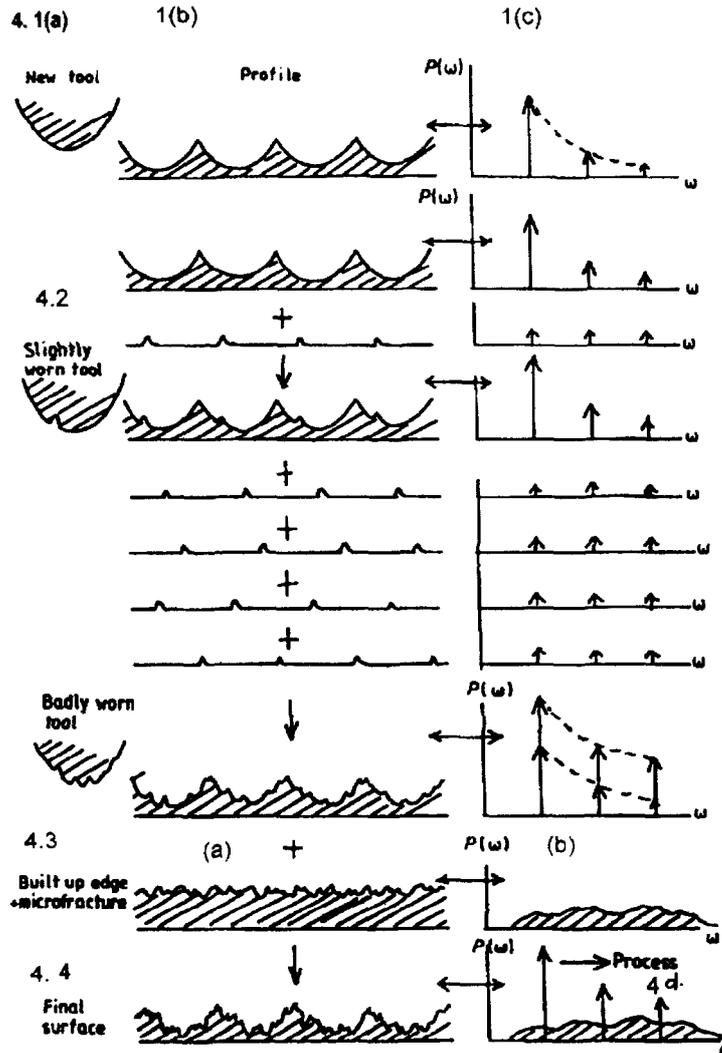


Figure 4. Power Spectral Analysis Harmonics

To the left of the fundamental wavelength periodicities appear whose wavelength is much greater than that of the fundamental. These are due to machine tool problems such as bearing wear, slideway error or even lack of stiffness in the machine tool itself which may cause chatter. Identifying these effects by using the surface texture is an important first step in remedying the problem.

The spectrum can therefore be split up into two parts, one to the right of the fundamental frequency and one to the left, Figure 5.1 - 5.5. On the right appears process problems and on the left, in the sub-harmonic region, machine tool problems. These advances in machine monitoring and diagnostics stem from the realization that the surface generated by the manufacturing process constitutes a very extensive data bank of information. The surface is in effect a fingerprint of manufacture.

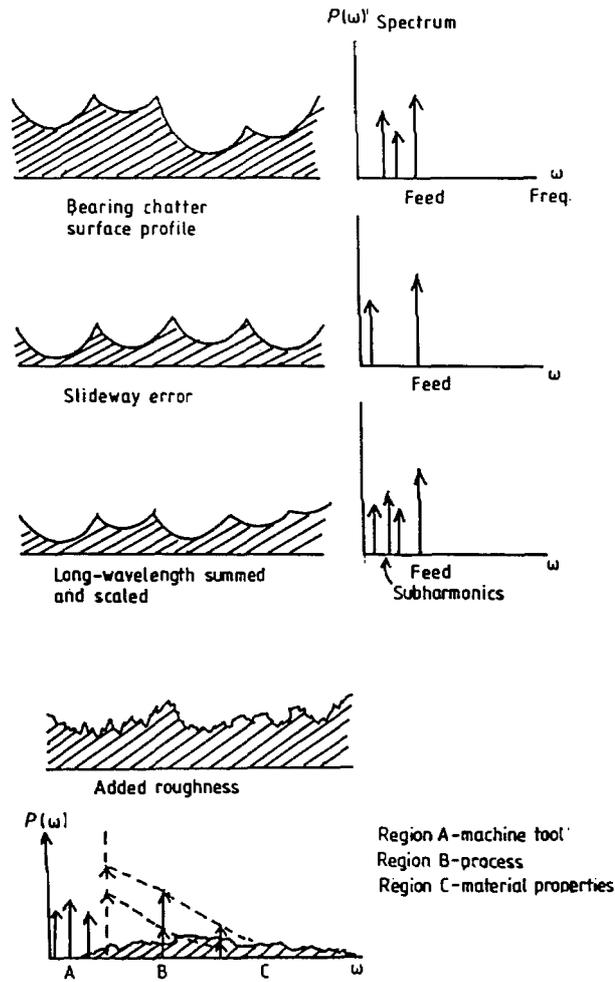


Figure 5. Spectral Analysis Sub-harmonic and Total Spectrum

2.3 Space-Frequency Functions

From what has been said above it could be argued that autocorrelation and power spectrum are sufficiently comprehensive to be able to cater for most eventualities in manufacture. Unfortunately this is not so. There are instances where subtle changes in the surface geometry can be very important in machine tool monitoring. For example the mode of vibration of a tool column determines the changes in statistics of the surface geometry. Using Power Spectrum or autocorrelation cannot detect changes in the statistics. Unfortunately changes in the nature of the surface often accompany the presence of defects, flaw etc. which are detrimental to the performance of the workpiece. Looking at the formulae for autocorrelation $C(t)$ or power spectrum $P(w)$

$$C(t) = \frac{1}{2L} \int_{-L/2}^{L/2} f(x)f^*(x+t)dx \tag{1}$$

$$P(w) = \left| \int_0^\infty f(x)\exp(-jwx)dx \right|^2 \tag{2}$$

show that the integral limits extends over all the signal $f(x)$. The whole signal is integrated. Any change within these limits in the nature of $f(x)$ will simply be averaged out.

This restrictive behaviour of the random process functions has been recognized for some time and measures have been taken to remedy the situation by modifying the definitions. There has to be a window function introduced in either time or frequency which localizes the extent of signal $f(-)$ which is being examined. The width and shape of the window function together with its position along the time or frequency axes provide adequate flexibility pinpoint and examine small detail in the signal [4, 5].

With this incorporation the 'time frequency' functions have evolved. In surface metrology the time variable is replaced by the spatial dimension x .

There are many forms of 'space-frequency' functions. These include Wigner, ambiguity, Gabor functions as well as Wavelet functions. In the first two the kernel inside the integral sign in equation 1 is modified.

Using this kernel in equation 1 to provide a basis for non-stationary monitoring allows at least two possible options, both link spatial and spectral domains into one function. These two are the ambiguity function $A(c, \nu)$ defined as

$$A(c, \nu) = \int_{-\infty}^{\infty} f\left(x - \frac{c}{2}\right) \cdot f^*\left(x + \frac{c}{2}\right) \exp(-j\nu c) dx \quad (3)$$

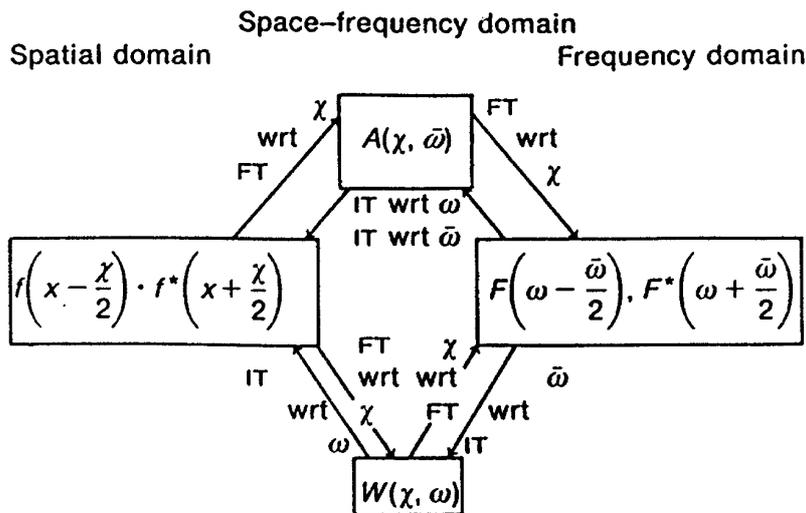
and the Wigner distribution $W(x, \omega)$ which is given by

$$W(x, \omega) = \int_{-\infty}^{\infty} f\left(x - \frac{c}{2}\right) \cdot f^*\left(x + \frac{c}{2}\right) \exp(-j\omega c) dx \quad (4)$$

It is clear that the ambiguity function and the Wigner distribution are related. In fact they are a Fourier transform cyclic relationship shown in Figure 6.

Figure 6 shows two things. First is that $W(x, \omega)$ and $A(c, \nu)$ are both in the space-frequency domain. Second is that they can both be equally well approached from the frequency or space domains. It is this latter property which makes them so useful and unique.

Because of the direct path within the space-frequency domain a double integral involving a Fourier transform and an inverse Fourier transform either way connects them.



Relationship between functions.

Figure 6. Relationship between Functions

All of these vibration modes are difficult to analyse using conventional random process analysis. Not included above is tool roll which is even more difficult to analyse. Wigner distribution analysis easily separates them [6].

Wigner distributions tend to be better at identifying the nature of the modulation, Ambiguity functions are good at showing where it occurs. Wavelet transforms are good at identifying flaws and defects rather than changes in the statistics as is Wigner [7, 8].

It is clear from above that formidable analytical tools can be used to extract manufacturing information from the surface. This means that the surface can be used in machine tool diagnostics as well as process control. However, neither of these applications is the important one. The fundamental reason for making the workpiece is to use it. It is in the use of the workpiece where the surface is most important and this will be explored next. The situation is shown in Figure 9. It shows where surface metrology fits relative to the function of the workpiece.

Figure 8 shows a simplified effect of tool vibration on surface profile.

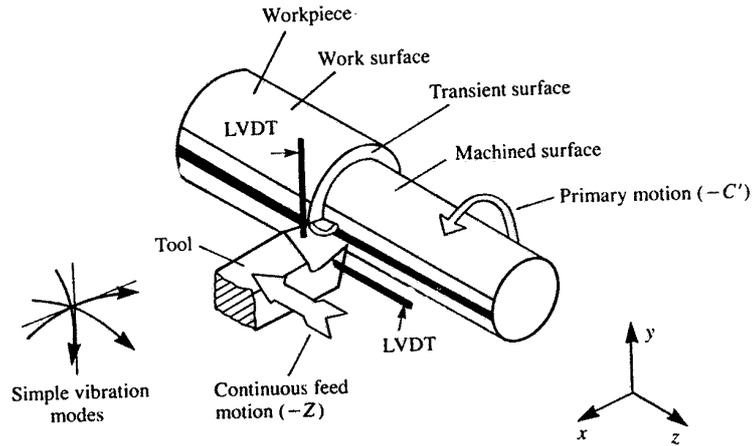


Figure 7. The position of the cutting tool and its vibration modes relative to the workpiece

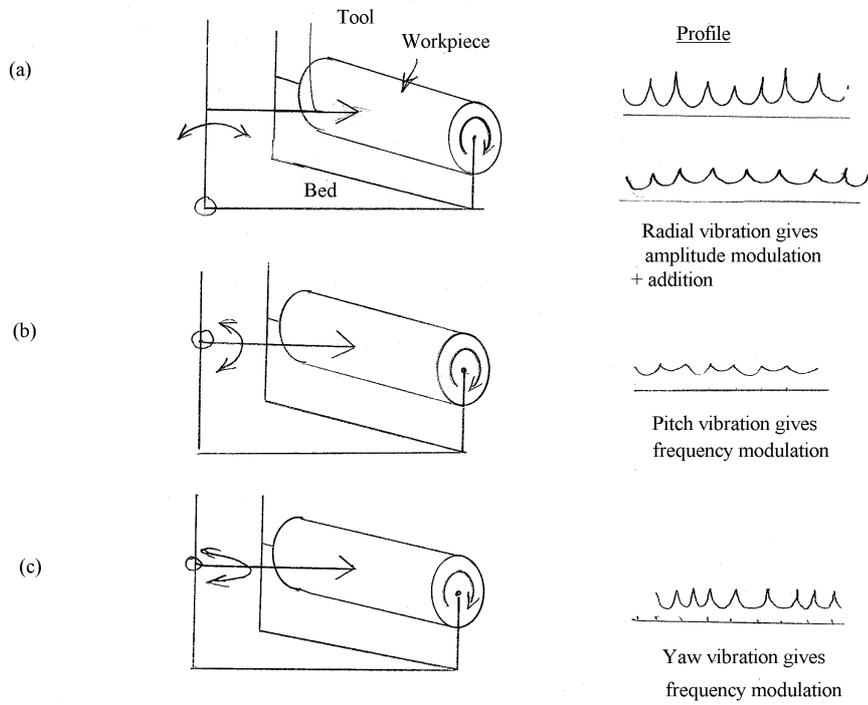


Figure 8. Tool Vibration Modes

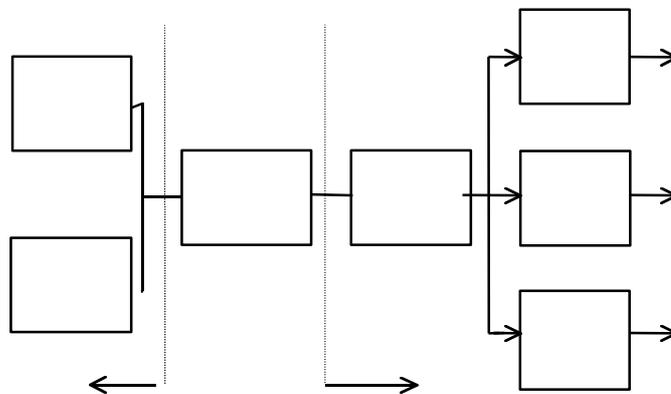


Figure 9. Role of Surface Geometry

Most of the uses above involve contact and as will be seen even the sophisticated methods mentioned above are found lacking.

3 THE SURFACE AND FUNCTION

The surface is obviously important in many practical situations. This has been known for years. The problem is how important? For many years very simple parameters were used to describe the surface and hopefully its properties. Note. It is not the variation in the parameter which is most important as in manufacture, it is the actual values. These included R_a the average value, R_q the rms value and various peak height estimates. Investigators in Germany and Russia used peak measurements rather than average because they argued that peak measurements correlated more with tribological situations than average values [9]. Also the peak measurements of roughness could be measured equally well with optical and stylus methods. This philosophy proved to be practically unsound.

The notion of being able to predict the performance of a work-piece from the geometry of the surface has been attractive for some time. Early investigators used simple models of the surface. These usually involved modelling peaks on the surface as hemispherical spheres scattered on a plane. Then these hemispheres or 'bosses' were assumed to be distributed in a random Gaussian way in height [10].

This development was closer to real surfaces than previous ones but it had the disadvantages that two surface descriptions were needed, one deterministic to describe the shape and size of the hemispherical 'peaks' and one statistical to describe their distribution in space [11].

This confusing model was eventually replaced by the random process model mentioned earlier which was based totally on communication theory [12]. This enabled all salient features of the surface to be described with one model. This random process model was and still is considered to be a big breakthrough in surface characterization.

However, current thinking indicates that even this model needs modifying to better reflect the mechanical situation that occurs, for example, in contact where the surfaces contact top down on each other. Another problem which has to be considered is that contact occurs in a parallel mode rather than a serial one. The conclusion has been reached that random process analysis is adequate for monitoring the manufacturing process, but is inadequate for some cases of functional prediction.

The reason is that the foregoing theory was developed for communication and not for tribology. Take for example the simple case of loading a peak, shown in Figure 10. Random process analysis can give an idea of the density of peaks and to some extent the heights, but cannot as a rule determine which peaks deform under load.

In the figure it is seen that some peaks deflect even though they are not contacted. The point is that at a contact factors other than geometry have to be considered for example the elasticity of the material. It is true that the curvature of the peak is important but so also is the presence of chemical films such as oxides or sulphides on the surface which are vitally important in for example, electrical conductivity. Neither random process analysis nor space frequency functions help.

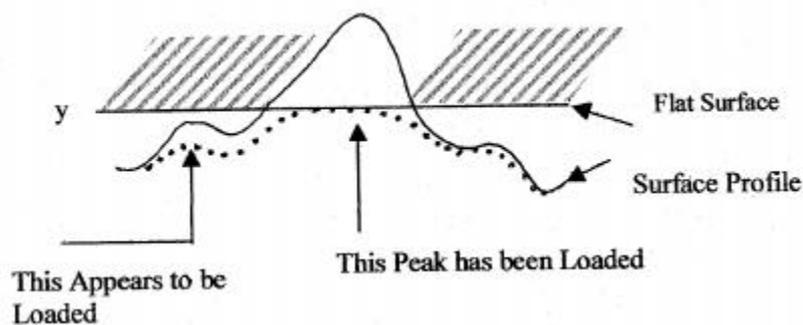


Figure 10. Apparent Peak Loading

There are two considerations for contact. One (Ref. 13) is the nature of a typical contact – which has been addressed above. The other is how these contacts are distributed in space. Surface geometry contributes to determining a contact but other factors such as material elasticity also contribute. However, the surface geometry is absolutely crucial in determining the contact distribution. Material properties do not get involved. These two aspects, the unit of behaviour e.g. the contact, and their distribution are common to most tribological situations. These factors involve specifying the whole surface: in fact two surfaces for contact not just the profile. A number of attempts have been

made which will be discussed briefly below. The problem is where to stop! Areal characteristics (sometimes wrongly called 3D) are much more than an extension of profile parameters. Areal assessment of surfaces needs more than profile parameters. Perhaps the most comprehensive attempt so far has been carried out by Stout et al [14]. Some of these parameters are listed in Table 1.

Notice that there are 17 parameters split into two groups. One group is conventional comprising of extensions of profile parameters such as S_q the areal equivalent of R_q . The symbol S is used here to represent the surface rather than the profile parameters which use the letter R. The height parameters are straightforward as are the hybrid parameters. It is in the spatial parameters where area has to be taken into account. These attempt to describe the 'lay' of the surface.

Table 1. Primary set of 3D Surface Roughness Parameters

Amplitude Parameters
Root-mean square deviation of the surface (μm)
Ten point height of the surface (μm)
Skewness of the surface
Kurtosis of the surface
Spatial Parameters
Density of summits of the surface (mm^{-2})
Texture aspect ratio of the surface
Fastest decay autocorrelation length (mm)
Texture Direction of the surface (deg)
Hybrid Parameters
Root-mean square slope of the surface ($\mu\text{m}/\mu\text{m}$)
Arithmetic mean summit curvature (μm^{-1})
Developed surface area ratio (%)
Functional Parameters Characterizing Bearing and Oil Retention Properties
Surface bearing index
Core Oil Retention Index
Valley Oil Retention Index
Material volume ($\mu\text{m}^3/\text{mm}^2$)
Core valley volume ($\mu\text{m}^3/\text{mm}^2$)
Deep valley volume ($\mu\text{m}^3/\text{mm}^2$)

Texture aspect ratio for example is the ratio of the shortest correlation length on the surface to the longest. Here the correlation length is taken as that length over which the autocorrelation function falls to an agreed low value, usually $1/e$ but sometimes 10%. This parameter has no equivalent in the profile. The direction in which the correlation length is a minimum is usually taken as zero angle. This has to be referred to some arbitrary angle reference on the workpiece.

The second group are called functional parameters and are unashamedly contrived to satisfy some functional need e.g. oil retention or load carrying capacity.

The actual definitions of these parameters are usually linked to the material ratio parameters They can be obtained from the literature [15] reference to Euro report 15178 EN but it has to be emphasized that these functional parameters and the areal (3D) ones are not standards, they are suggestions.

So far the set includes 17 parameters and this is low. Other parameters are possible. Some very interesting alternatives have been tried e.g. Scott [16] who explores different ways of splitting up the surface area based on what are called Maxwellian Hills and Vales. This method is an extension of the motif methods such as the E system proposed by Radhakrishnar and others [17].

The problem is that the number of parameters gets enormous. It is the 'parameter rash squared'. It is useful to reconsider the problem.

Surface characterization is used to describe the surface in a way which enhances signal and reduces noise. The question is what is the signal and what is the noise. A ground part 5 cms long and 1 cm radius has about one million independent bits of information. It could be argued that only one bit is needed. Is the workpiece good or bad? The question, as above, is which one?

Ideally the manufacture should match the functional use of the surface. Grain size should relate directly to contact size. Also tool path should determine the flow pattern in hydrodynamic bearings: the surface finish should, not enter into the argument except as a control.

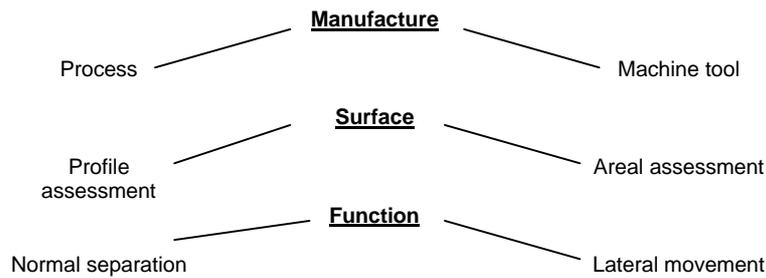


Figure 11. Basic Characterization

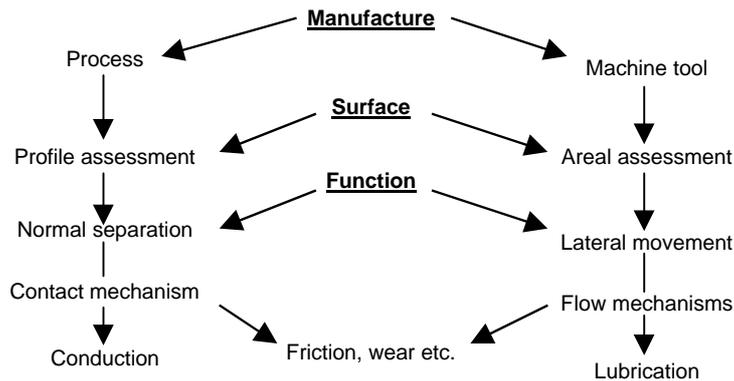


Figure 12 Elementary Links in Characterization

There are a number of issues which have been either neglected or avoided. The most important is the fact that it is impossible to match manufacture to metrology and to function unless all have been measured or estimated or characterized in a similar way. Manufacture can conveniently be split into process and machine tool – a very rudimentary classification but useful. Surface metrology can be roughly classified into profile height parameters and areal spacing parameters. What about the functional classification? This has been totally neglected. The functional requirements should be split into basic mechanisms. A useful first step is to consider normal separation of mating surfaces as one variable and lateral movement the other. This format allows convenient subdivision.

The simplest and yet most meaningful breakdown linking manufacturing to function is shown below in Figure 11. To some extent the basic characteristics can be linked as shown in Figure 12.

Obviously this is a considerable simplification but it does concentrate emphasis. Also, the surface metrology is fulfilling two different roles as far as a function is concerned. One is to ensure good performance and the other is to detect sources of failure. These two jobs require different aspects of the measurement. As a general rule surface metrology can be subdivided in a way shown below in Figure 13, into 'average' and 'extreme' characteristics.

Measurement, and hence control of average behaviour e.g. **Ra** ensures adequate performance whereas measuring extremes, whether high values of the surface statistics or just defects, detects likelihood of failure in performance.

Below in Figures 14, 15 and 16 the concept of function mapping and the associated template of surface parameters is shown. Functional performance can entail a 'unit event' and its distribution as in contact, the distribution of statistics as in optical reflection and so on.

Looking at the function map shows that for many functional applications two surfaces are involved not one. Single surface applications are covered in the case where $h \rightarrow \infty$. One example is in optical reflection. So to classify or characterize one surface to the n^{th} degree i.e. 17 parameters or thereabouts, seems to be an 'overkill' What is needed is less emphasis on one surface and more on two surfaces and in particular the gap between them.

The concept of a function map is new and is the first attempt to completely characterize the mechanisms of function Figure 16. This classification should be the starting point from where the designer sets the specification. This mechanism e.g. flow requirement, should filter back to the manufacture and not the other way around.

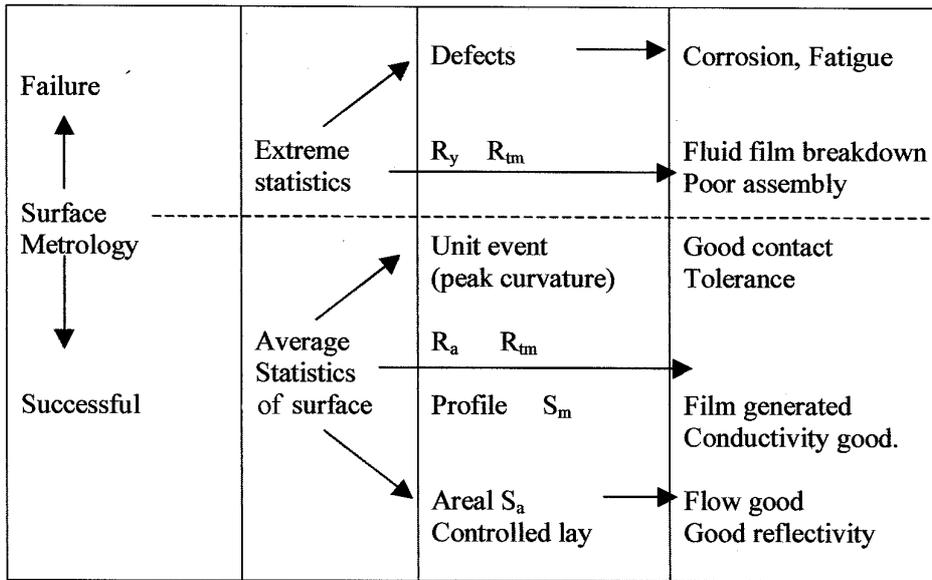


Figure 13. Dual Roles of Surface Metrology and Relationship to the Statistics

The interpretation of the axes of the function to map is flexible. The x axis could be designated 'dynamic' whereas the y axis is 'static'. Also, the map is not specifically to be used for surface metrology. For example the 'h' values of the ordinate axis are only directly related to surface geometry when $h \sim 0$ i.e. contact which is where the distributions of height of the two surfaces are comparable with the separation.

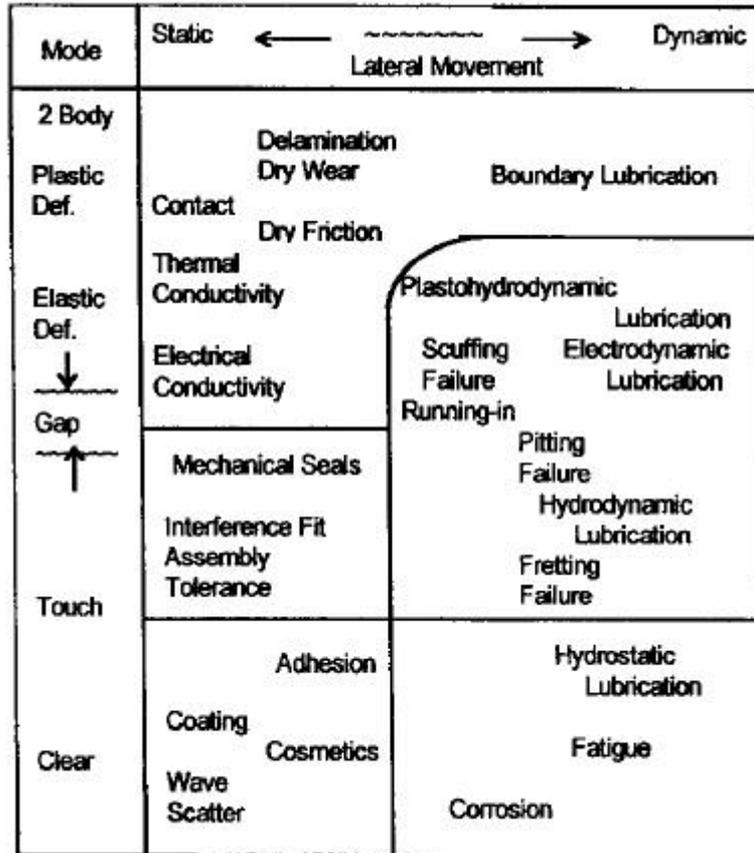


Figure 14. Function Map

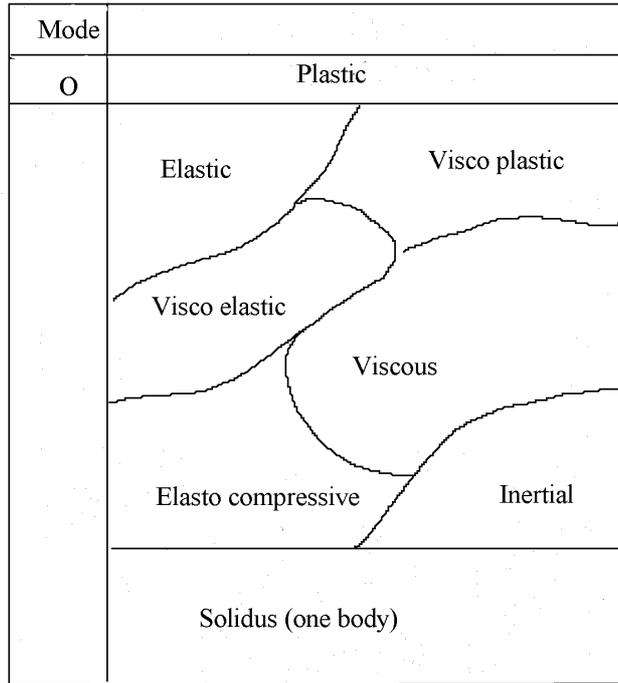


Figure 15 Function Mechanism

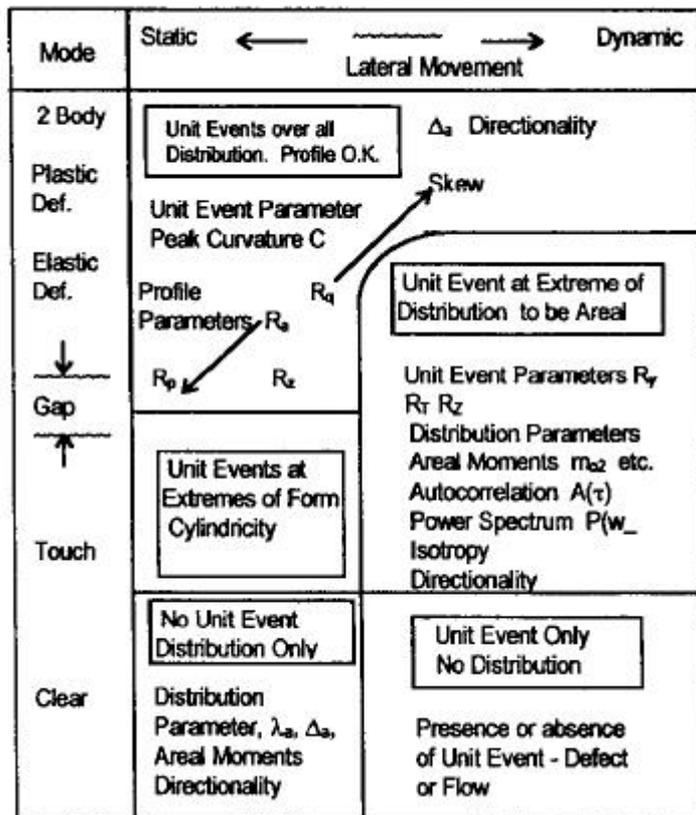


Figure 16. Surface Template

Summarizing, there is now a possibility of weaving a coherent thread linking manufacture metrology and function. This thread starts with the function map whose format is outlined above. Superimposed on this map is the surface metrology template (or dimensional template) whose axes are static parameters e.g. peaks usually from a profile, against 'dynamic parameters' which involve

slopes and curvatures and have to be areal. The manufacturing template has 'process' and machine tool as axes. This is superimposed onto the map and metrology template.

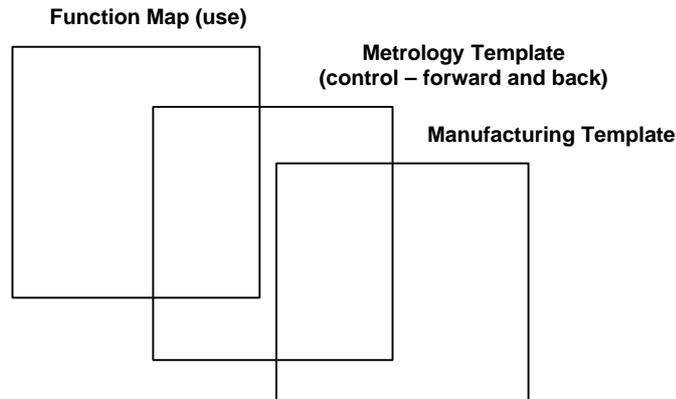


Figure 17. Arrangement of Templates – The Template Stack

Ideally reading through the template stack should give the best surface and manufacturing process for a particular function. This is shown pictorially above but would be carried out from stored computer data bases.

A further step which is even now a possibility is to forget the parameters of the surface and carry out a 'pilot' experiment in the computer to see if the workpieces work together. This involves areal mapping of both surfaces comprehensively using a tactile sensor and them literally making them contact and rub by simulation. It may be that this is the best way forward. Notice that the tactile sensor is suggested as the preferred instrument. The reason for this is that in the tradition of metrology the measurement should mimic as nearly as

possible the function. Because most applications involve contact and rubbing the tactile stylus method should be used. For non contact applications obviously optical or other methods are to be preferred.

4 CONCLUSIONS

This report has attempted to show how surfaces and in particular engineering surfaces and their measurement will progress.

The main point is that manufacture via metrology will become much closer to functional performance than at present. To do this surface metrology will have to get closer to both. Instruments will tend to imitate tool movement as well as link the sensor in scale of size to process marks. The present trend to anticipate functionality by a multiplicity of surface parameters will be replaced by a virtual functionality carried out by computer on high fidelity areal data obtained from the surfaces. Much more software flexibility will be required to enable interactive experimentation between the designer and the design specification.

REFERENCES

- [1] Whitehouse, D.J. (1994) Handbook of Surface Metrology, Institute of Physics Publishing Bristol and Philadelphia
- [2] Schlesinger, G. (1942) Surface Finish Institution of Production Engineers London
- [3] Whitehouse, D.J. Surfaces, a Link between Manufacture and Function Proceedings Institute of Mechanical Engineers **192** (1978) 179-188
- [4] Wigner, E. On the Quantum Correction for Thermodynamic Equilibrium Physics Review **140** (1932) 749-759
- [5] Woodward, P.M. (1953) Probability and Information Theory with Application to Radar Pergamon, New York
- [6] Zheng, K and Whitehouse, D.J. The Application of the Wigner Distribution to Machine Tool Monitoring. Proceedings Institute of Mechanical Engineers **206** (1992) 249-264
- [7] Daubechies, I The Wavelet Time-frequency Localisation and Signal Analysis IEEE Transactions on Information Theory 36 (1990) 961-1005
- [8] Strang, G. And Nguyen, T. (1996) Wavelet and Filter Bands Wellesley Cambridge Press
- [9] Perthen, J. (1947) Prüfen und Messen der Oberflächengestalt Carl Hanser Munich

XVI IMEKO World Congress

Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

- [10] Greenwood, J.A. and Williamson J.B.P. (1964) The contact of Nominally Flat Surfaces Burndy Research Report 15
- [11] Archard, J.F. Elastic Deformation and the Laws of Friction Proceedings Royal Society London A **243** (1957) 190-205
- [12] Whitehouse, D.J. and Archard, J.F. Discrete Properties of Random Surfaces of Significance in their Contact Proceedings Royal Society London A **316** (1970) 97
- [13] Whitehouse, D.J. Some Theoretical Aspects of Surface Peak Parameters. Precision Engineering **23** (1999) 94-102
- [14] Stout, K.G. Development of a Basis for 3D Surface Roughness Standards EC Contract No. SMT4-CT98-2256
- [15] Euro Report 15178EN
- [16] Scott, P. Areal Topological Characterization for a Functional Description of Surfaces. European Surfaces Workshop Corps 1a Salette June 1998
- [17] Radhakrishnan, V. On an Appropriate Radius for the Enveloping Circle for Roughness measurement in the E System Annals CIRP **20** No. 1 (1971)

AUTHOR: D.J. WHITEHOUSE, Ph.D. D.Sc., Metrology Consultant Taylor Hobson and Professor of Engineering, Department of Engineering, University of Warwick, Coventry CV4 7AL, UK