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An Advance in Metrology & Manufacture - The Engineered Surface

By

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Abstract

In recent years considerable progress has been made in the nature of manufacture and characterisation of surface finish in three dimensions. Recently in the latter field particular progress has been made in the development of protocols and parameters which can be used for international standardisation. These developments have embraced stylus devices, laser based optical systems and scanning probe methods. But the subjects of manufacture and surface characterisation as they have currently developed have much further to go if the process of surface characterisation is to impact on manufacturing process control. Engineers and researchers are beginning to realise that if the new tools available are to have a great impact on manufacturing industries, surface characterisation as a subject must be broadened to include measures of surface integrity and be related to the functional demands imposed on the surface in service. If these three factors are considered together, surface characterisation, surface integrity and function then a new and important subject is born, **Engineered Surfaces**.

This paper draws together the elements which go to create the subject the ‘Engineered Surface’ and in particular relate to surface integrity, surface topography and the bulk properties of the materials used to create the product. The paper presents a method by which this important subject can be developed to the benefit of the demands placed on the manufacturing industries in the early years of the new millennium.

A Philosophy of Manufacture.

In recent years considerable progress has been made in the characterisation of surface finish. This is essential since engineers, conscious of the importance that the surface character has on the functional performance of the component, have strived to improve their understanding. One factor has become abundantly clear during the evaluation of three dimensional surface topography, although this is an important feature of the performance of a component or product, many other factors are also of equal importance. In recent studies, it has become recognised that the functional situation in which surfaces are employed should also be fundamentally investigated (ref. 1.)

What is it then that makes a functionally successful surface? It is a combination of the surface topography, the material selection which provides the underlying bulk properties of the selected material, the properties of the near surface layers, and the control of the manufacturing process by which the final surface is generated and as a consequence fine tune the properties of the surface layers produced.

Traditionally the majority of manufacturing processes (metal removal) which were specified for producing a wide variety of engineering components, defined the means of achieving the desired geometry through selection of the appropriate machining conditions. The nature of a typical machined surface and resultant sub surface layers normally consists of;-

- An oxide layer
- A plastically deformed layer
- A metallurgically affected layer
- The bulk material
- The topographic boundary between the workpiece and the environment

The surface that results has in many cases needs to be further modified by subsequent surface treatments (heat treatment, coatings, chemical treatment, mechanical treatment) to enable them to be more suited to the function for which they are intended. The purpose of this subsequent treatment, often referred to as surface engineering, is to modify the upper layers of the surface to impart specific properties such as wear resistance or fatigue resistance to improve functional suitability.

The importance and scope of this subject was demonstrated in an international survey of Surface Engineering, particularly directed to surface coatings, which was conducted at the University of Hull (UK), (ref. 2.). The findings of the report produced as a result of the survey indicated that in the UK alone the expenditure in this area would reach at least £5.5b by the year 2005. Clearly a large section of this expenditure would be related to re-engineering a variety of surfaces for function.

A third material modification process which must be added to the above group is component creation by forming. A technique where the material is physically deformed or moulded to create the desired shape and strength characteristics. These processes by their very nature invoke surface modifications which have an impact on their functional suitability.

Table 1 provides a typical list of processes, related to selected product precision which are created by either removal, addition or forming.

It is suggested that by the correct selection of the manufacturing process and the specific manufacturing conditions the expenditure which relates to post creation surface treatment might be largely eliminated by *'engineering the surface'* appropriately during the final stages of machining or forming if the process parameters had been selected with understanding and care. Under such care it would be possible to create the surface features required of a surface rather that just to allow them to arise as a function of the process itself. Figure 1 presents typical features of an engineered surface.

SURFACE CREATION

Table 1 A surface is created by a combination of one or more formative processes

Creation / Material	Conventional $(10^{-3} – 10^{-4})$m	Precision $(10^{-4} – 10^{-7})$m	Nano-Processing $(10^{-7} – 10^{-10})$m
Removal	Turning Milling Boring	Grinding Honing Lapping	Diamond Machining Etching Lithography
Addition	Painting Galvanising Plastic coating	Plating Mirroring Deposition	Plasma Atomic placement Vapour Deposition
Forming	Rolling Bending Forging	Extrusion Peening Moulding	Ultra Precision Moulding

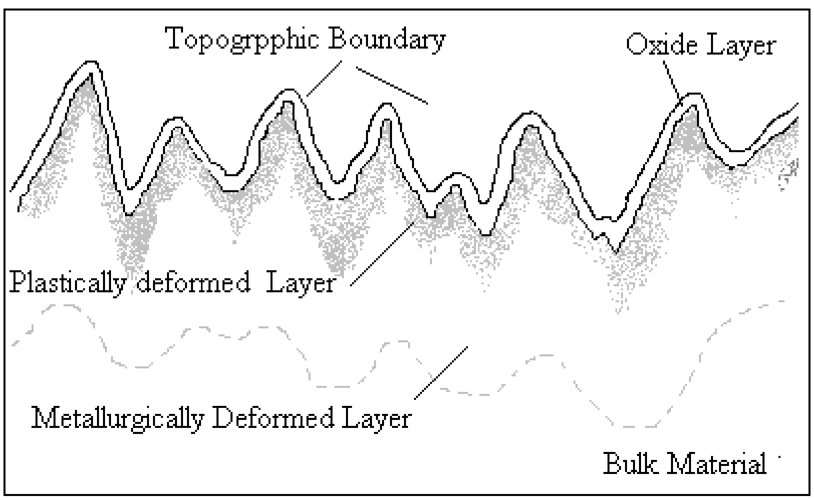

Fig. 1 The Features of an Engineered Surface

The Engineered Surface

The concept of ‘engineered surfaces’ implies that instead of creating a product using some form of machining, forming, casting or fabrication process, then modifying the surface produced to change its properties, a more analytical approach should be taken. This is usually undertaken in an attempt to improve functional performance. In fact it may be preferable and even cheaper in the long term, to begin to understand the consequences of the process of manufacture itself. This might be achieved by being able to carefully control the effects of the process or processes by which the component is produced to induce the desired physical properties of the surface layers.

Control of the physical properties of the surface may be possible by specifying the final processing conditions which yield the desired surface topography and corresponding mechanical properties of the surface and sub-surface layers. Thus this better specification would result in a surface highly suited for its intended functional performance.

This philosophy is not completely new. Whitehouse (ref. 3.) showed that the current understanding of the surface generation of most machining processes was minimal, but in his paper he demonstrated that it was feasible to rationally examine the topography of a surface and consequently the physical properties of the surface, its integrity to begin to understand the consequences of any machining or fabrication process. He also showed that as engineering requirements become more precise and manufacturers are forced to bring down their manufacturing costs it is imperative to understand the implications that the selected manufacturing processes yield. He argued that in most well controlled past and present material processing the workpiece was defined by a small number of simple parameters and from these definitions the component was manufactured. For the current manufacturing situation, these steps are diagramatically shown in figure 2 below.

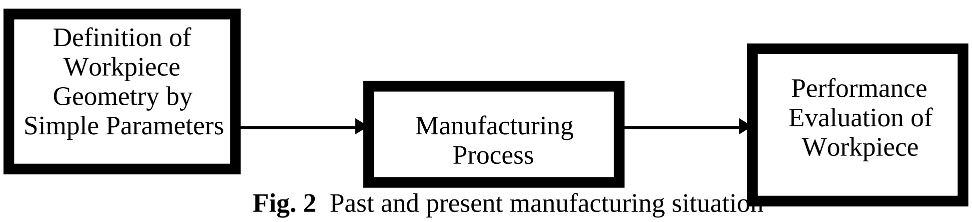

Fig. 2 Past and present manufacturing situation

A second and probably more scientific approach, is to develop a theoretical basis for the surface interaction and to explore that basis in relation to careful measurements of the component surface. Such a process has been suggested by Whitehouse (ref. 4.) in his definitive book on Surface Characterisation. Whitehouse suggested that in an ‘enlightened future’ the process of manufacture will require more comprehensive component specification; and as a consequence more complex workpiece geometry descriptions. This implies that the individual characteristics of the machine itself could all have a profound effect on the integrity of the surface produced.

As a consequence the process control parameters are likely in future to include specified limitations on tool wear, cutting speeds and feeds, tool dressing specifications accompanied by the selection and flow rate of the most appropriate coolant to be used during the cutting operation as well as the definition of parameters to be measured to ensure satisfactory compliance to specification. This will imply that a greater emphasis will need to be given to functional testing of components and products in order for manufacture to conform to international quality standards as well as product reliability and both current and future liability legislation.

The approach suggested above relates to the need for a well organised programme of investigation into the factors which affect the functional behaviour of production surfaces. What is important in such an approach is that the data produced during such research is documented and made available to a wide range of interested users and manufacturers. In the twenty first century we can expect to see industry move to higher precision manufacture for much of its production. For example the expected growth in both ultra precision manufacture and nano technology (ref. 5.) and the growing requirement for smaller sizes, tolerances and improved compliance in precision products which will be demanded to meet the more stringent functional requirements of many products.

There will be two overwhelming requirements by these precision industries. These are accuracy of manufacture and the suitability of the components and products for its intended function. Such requirements will imply considerable investment by industry in the understanding of the machining processes and their consequence in the operation of a surface in service.

The Complex Inter-Relationships in an Engineered Surface.

Before we can make much progress in this broadly based subject - the ‘engineered surface’. The complex inter-relationships which make up the engineered surface must be considered. They include;-

Bulk Material Properties - these have been carefully selected to provide the required component durability using the minimum of material and having the minimum weight. Much progress is currently being made in the automobile industry at the present time through laser welding of dissimilar metals and metals of various thickness. Further significant progress in design using modelling techniques such as FEA has enabled reduction in the bulk material. However these models only consider the bulk material properties and pay little attention to the subtle changes in surface properties induced by processing.

Surface Properties (either engineered or surface treated) - traditionally surface properties have been ‘adjusted’ by either thermal, chemical or mechanical treatments in order to impart some functional attribute. This, as indicated earlier has led to a large growth in surface modifying industries but by its very nature implies that the fabricated surface is not ideal for its intended application and to attain its functional properties further expensive processing is required.

Surface Interacting Conditions Their has been considerable activity in this broad area of engineering. For example there has been much progress in recent years in the improvement of lubricants. The greatest attention being paid to their wettability (their ability to wet and remain attached to the surface) and their design so that they remain effective as extremely thin films. This has been achieved by research into the effects of the inclusion of special additives to improve the tribological interaction. There has also been considerable improvements in surface prepared for both thermal conductivity, loading and electrical contact. Such applications require considerable attention to the creation of the shape of the surface to provide for large contact areas which either resist deformation (both elastic and plastic) or promote efficient electrical and thermal conductivity.

Surface Topography - currently a poorly understood subject in relation the functional use that surfaces are employed for. Depending upon the intended application, the required characteristics of the surface may need to differ. Currently progress is being made on characterisation methods but at this point in time they are more suited to the control of the manufacturing process. The progress which has been achieved is briefly outlined below. When these four areas are brought together a complete understanding of engineered surfaces is possible.

Surface Topographical Features and their effect on the Functional Performance of Surfaces.

Engineering surfaces can be divided into three groups based on their functionality, translational surfaces, static contact surfaces and non contacting surfaces. In addition to these three groups there is the category where surfaces are required to be specified comprehensively whose sole purpose is to create further topographies on secondary surfaces which then go into functional use.

Translational Surfaces are generally referred to a tribological surfaces and include bearings and slideways, surfaces experiencing friction, wear, galling or fretting. Clearly the amplitude of the roughness, its shape and the separation of the asperities and interconnecting valleys affect the interaction, the retention of the lubricant and affect the leakage of translational seals. The answer to operational performance is to identify the primary tribological interaction. Functional parameters such as valley volumes and valley interconnectability are of significance. A more comprehensive review, based on earlier work by Griffith (ref. 6.) in relation to static contact surfaces is presented in table 2 below. This figure (the first of four) indicates, as Griffith's suggested that there is evidence that the topography was indeed a contributory factor to operational performance. The way in which the information is presented illustrates the current degree of confidence in the correlation between surface finish and function.

TABLE 2 - TRANSLATIONAL SURFACES

Function	**Heights**	**Distribution and Shape**	**Slopes and Curvature**	**Lengths and Peak Space**	**Lay**	**Surface Volume Parameters**
Applications						
Bearings	●	●	◗	◗	●	●
Seals	●	●	●	◗	●	●
Sideways	●	●	◗	●	●	●
Mechanisms						
Friction	●	●	●	●	●	●
Wear	●	●	●	●	●	●
Galling	●	◗	●	O	O	●
Fretting	●	●	●	O	O	●

● Much Evidence ◗ Some Evidence O Little or Circumstantial Evidence

Static Contact involving joint stiffness, electrical or thermal contact, adhesion & bonding, fatigue, stress and fracture. This is a contact area related effect and therefore embraces both short wavelength and long wavelength effects. Under loading surface asperities deform both elastically and plastically. Clearly asperity heights, their shape and distribution, asperity slopes and curvatures are significant as is likely to be the peak spacing of asperities. The evidence of surface finish relationships in relation to function for the various types of static surface contact is presented in table 3 below. Much of this figure is again based on the work of Griffith (ref. 6.).

Clearly there may be more forms of description than have been so far defined and these will become apparent as further research is conducted, but the table below provides a useful starting point in the specification of surface parameters which will assist in developing an understanding of the consequences of surface topography on static contact surfaces.

TABLE 3 - STATIC CONTACT SURFACES

Function	**Heights**	**Distribution and Shape**	**Slopes and Curvature**	**Lengths and Peak Space**	**Lay**	**Surface Volume Parameters**
Functions						

Joint Stiffness	●	●	◗	◗	◗	◗
Contacts (elec/therm)	●	●	●	●	O	O
Adhesion & Bonding	●	●	◗	◗	◗	●
Mechanisms						
Fatigue	●	◗	O	O	●	●
Stress	●	O	◗	O	●	●
Fracture	●	O	O	O	●	●
Reflectivity	●		●	●	●	●

● Much Evidence ◗ Some Evidence O Little or Circumstantial Evidence

Non Contact surface, often related to finishings include plating, painting, polishing, reflectivity and hygiene. Functionally relevant parameters include asperity heights, slopes curvature and asperity separation. Highly reflective surfaces such as optical mirrors and precision lenses, characterisation and counting of 'digs' and 'blemishes' are significant. Non contact and magnetic data storage surfaces usually require optical assessment, often performed by optical techniques, or scanning probe microscopy so that surfaces are not damaged during assessment. The relationships between surface finish and function for non contacting surfaces is presented in table 4 below.

Although table 4 below is useful it is likely that further forms of parameter specification will be introduced as further development is undertaken. Clearly as precision manufacture further develops and the need for greater surface discrimination increases, particularly in the domain of optical surfaces, more specific descriptors may be necessary.

TABLE 4 - NON CONTACT SURFACES

Function	**Heights**	**Distribution and Shape**	**Slopes and Curvature**	**Lengths and Peak Space**	**Lay**	**Surface Volume Parameters**
Plating	●	◗	◗	◗	O	◗
Painting	●	◗	◗	◗	O	●
Polishing	●	◗	●	●	◗	◗
Reflectivity	●	O	●	●	●	◗
Hygiene	●	◗	◗	O	O	●
Corrosion	●	●	●	O	O	●

● Much Evidence ◗ Some Evidence O Little or Circumstantial Evidence

Shaped Surface Creation (which can be considered a hybrid of translational and static contact). These surfaces produce secondary functional surfaces and include the following processes, forming, drawing, extrusion and rolling. The parameters which are relevant to these surfaces include asperity heights, their shape and curvatures as well as their peak spacing. Complex relationship exist when one surface in effect produces a secondary surface. As a consequence it is not just the primary surface functional requirements which must be taken into account, in addition the desired functional attributes of the developed surface is also of significant importance. Evidence of the relationship between surface finish and function is presented in table 5.

TABLE 5 - SHAPED SURFACE CREATION

Function	Heights	Distribution and Shape	Slopes and Curvature	Lengths and Peak Space	Lay	Surface Volume Parameters
Forming	●	◗	◗	●	◗	●
Drawing	●	◗	◗	●	O	●
Extrusion	●	◗	◗	O	●	●
Rolling	●	●	◗	◗	●	●

● Much Evidence ◗ Some Evidence O Little or Circumstantial Evidence

Surface Mechanical Features which Affect the Functional Performance of Surfaces. (Surface Integrity).

Surface Hardness which will normally vary to some extent across the surface is partially responsible for the durability of the surface and its resistance to wear, plastic and elastic deformation. If two adjacent surfaces come into contact in a functional sense then their relative harnesses affect their ability to operate as pairs.

Residual Stresses;**-** These are induced during machining or other processing of the surface and can either be tensile or compressive in nature. Essentially residual stresses describe the stress state of the material lattice. Compressive residual stresses are highly desirable in that they suppress crack growth as the inter atomic stress acts to blunt any cracks. This enhances the wear and fatigue properties of the surface and improves stress corrosion resistance. Tensile residual stresses on the other hand tend to promote crack growth and are consequently deleterious to the material surface properties.

Plasticity index is a measure of a surface’s ability to conform under loading. The complimentary effect is to assist the reduction of surface loading by spreading the load over an increased area. If there is substantial lubrication between the surface interface then little or no plastic or elastic deformation will occur as the lubricating fluid will integrate the loading by promoting a fluid pressure profile within the gap between the counter faces.

Sub-Surface Features which Affect the Functional Performance of Surfaces.

Sub-surface features which influence functional behaviour of a surface have also been suggested by Griffith (ref. 6.) and these include;-

Untempered martensite (UTM) - a state which is caused by thermally induced metallurgical transformations in steel and primarily induces tensile residual stress into the surface and sub-surface layers. The formation of untempered martensite has the effect of reducing fatigue life of materials increases the susceptibility to stress corrosion and cracking and reduces wear life. UTM is often induced by thermal energy resulting from high metal removal rates during machining.

Overtempered martensite (OTM) - is found beneath the UTM and is softer than the bulk material due to over tempering. The presence of OTM reduces the bulk material mechanical properties.

Plastic deformation of the surface layers which is usually identified by heavy plastically flowed layers which often appear featureless under the microscope and are termed 'white layers'. Such layers produce compressive residual stress in the surface which assist fatigue life, increase the resistance to corrosion cracking, improve wear properties and surface hardness and assist mechanical properties in general. Machining processes such as honing, light grinding, lapping and forming induce plastic deformation at surfaces and consequentially benefit material properties.

Some Examples of Engineered Surfaces.

Processes which have been commonly used and are related to the concept of "The Engineered Surface" whose key process constraint is controlled plastic deformation of the surface layers are described. Surprisingly these are not new processes. Many of them have been employed for almost a century to improve the integrity of the surface, but their specific understanding is limited and today they are mainly regarded as a 'black art' employed by skill workers and craftsmen who have learned to understand, in general how the process is to be employed and controlled.

Ballising. The process of driving a precision sphere through a machined hole or bore to improve the surface finish, to impart negative residual stresses into that surface to improve surface wear resistance and fatigue resistance. There are a number of applications where such a process is invaluable in increasing, in particular, fatigue life and fatigue resistance, and many of these components are to be found in the aerospace industry and in automobile manufacture.

Barrel Finishing This well established technique is used to improve the finish of a variety of ferrous, non ferrous and plastic components (ref. 7.). Parts slide or float in the medium used so fragile parts can be tumbled as well as heavier sections and the method can be used to improve surface finish without destroying the geometric surface and solid design specifications often required in high technology application. One application where the method is used to improve performance is in the manufacture of compressor blades for gas turbines. It is known that gas turbines, both aero and industrial, require turbo machinery components offering the highest possible efficiency (ref. 8.) and that gas turbines for mechanical drives require increasingly large power blocks and higher thermal efficiencies (ref. 9.). Sophisticated 3D CFD design methods are used to improve design performance and the advantages gained are matched with improvements in manufacturing tolerances. Similar gains are made from improved blade finish. Barrel finishing improves the 'as cast' surface from 63 μ inches to 20 μ inches.

Shot Peening This is a further process where the surface properties, in particular the residual stress of the surface layers are modified by impinging the surface with particles, normally lead shot, at relatively high velocity. The kinetic energy imparted by the lead collisions with the surface induces plastic deformation which in turn induces negative residual stresses into upper surface layers, which improves the performance of the component.

Sheet Texturing This is a relatively new process which has been introduced as part of the final rolling sequence for producing sheet steel and other sheet materials. A defined topography is deliberately imparted onto the finishing rolls which is then transferred to the sheet metal. This process has been introduced to create a defined roughness so that the sheet is able to contain lubricant in the valleys of the micro topography. This is done to reduce friction and avoid the risk of galling during for example, sheet forming. Such texturing can also improve the paintability of sheet materials and as a consequence it produces a surface which has visual improvement. Sheet texturing is conducted in one of two ways. Either EDT texturing or laser texturing of finishing rolls for sheet steel rolling and then transferring the topography to the sheet steel itself by rolling.

Honing This is a widely used process which engineers the surface. In this machining process the surface is deliberately engineered to produced a stratified surface which retains lubricant to ensure a long service life. The process is particularly well developed in the automotive industry in the production of engine bores. More recently however a development of the process, the plateau honing process provides a surface which provides the characteristics of the run-in engine. Such conditions prevent early running failure and minimise engine emissions which is the subject of considerable international legislation. In recent times there has been the development of other forms of specialised surfaces by other more exotic processes to engineer engine bores. The objective of the new processes are to create surfaces with greater consistency and which yield lower harmful engine emissions.

There are a number of other processes which fall into the category as those defined above. They all amount to processes which are introduced to deliberately "engineer the surface" to assist in improving the functional performance of the finished component through controlled plastic deformation. Engineering surfaces can be described as a technique which the surface is 'functionally finished' for the desired application.

Future Approach to the Engineered Surface.

For the Engineered Surface to become a broadly understood and scientific approach to surface production, much is needed to be known about the nature of material working and the physical effects that the finishing process has on the surface layers and near surface layers of the material. At present, although there is some understanding of the effects of the processes which work the surface as they are sized and shaped, there is little quantified information to aid the understanding. The modern surface specification and design philosophy is specified in figure 3.

There are two approaches;-

1. An experimental approach, whereby surfaces are produced under well defined machining or other finishing conditions and those surfaces are then subjected to functional tests, either in a well controlled programme on in 'real life' situations where there is sufficient control of the final product to obtain reliable feed back information. One such programme of this nature has been conducted at Chalmers University in collaboration with Volvo Cars (ref. 10.) with their Integrated Surface Modelling software for bores, gears and facia surfaces and Avesta Steel with their

Surface Database (ref. 11.) aimed at specifying the production of stainless steel sheet finishes. Both of these systems use processing parameters, metrology information and functional testing to allow the optimal process parameters to be set for given functional outcomes. The approach is to determine
an experimental rationale to explain the functional behaviour of the 'engineered surface'. This implies that the causes of the separate geometric components which are generated are identified. The topography provides, for example, the entire 'signature' of the machining operation within the surface asperities.

2. A second approach is to develop analytical models of the surface interactions during machining or fabrication, and through the results of these models, compare the predictions with the surfaces which have been produced. Such a model could take into account information on the influences of the machine tool itself, and this would include the effects of slideways, bearings and the machine stiffness on the resulting surface. Such inputs could contain direct information on the feed rate of the cutting tool, tool wear, coolant type and supply and other processing conditions. Such an analysis could embrace the effects of the material in-homogeneity itself. An illustration of a typical surface analysis and the way in which the signal can be interpreted is presented in figure 4.

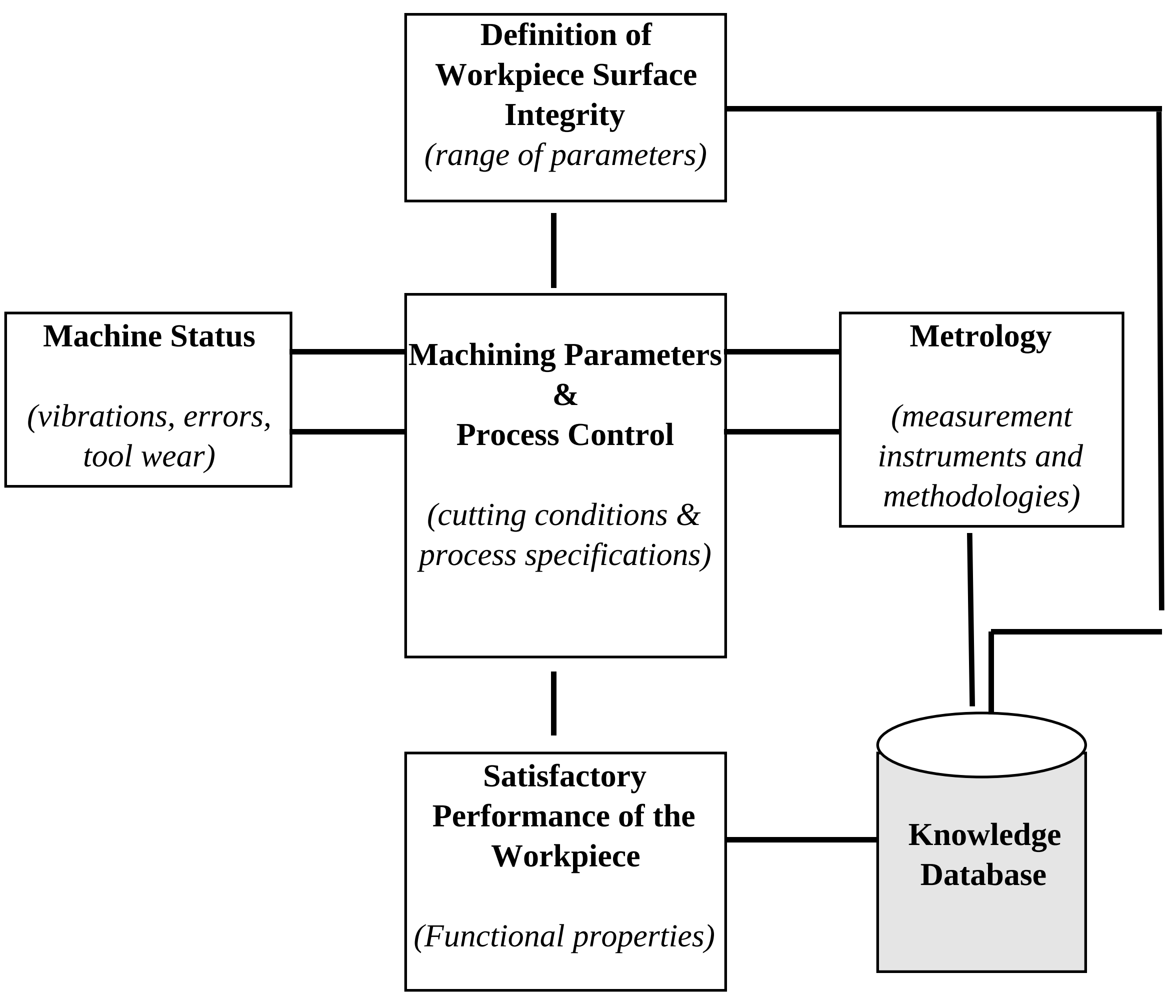

Figure 3 Modern surface specification and design philosophy

Comments.

There are a number of other processes which can be investigated to determine the surface conditioning as a result of the specific process used. If all or most of the parameters are investigated which relate to process, it would be possible to produce a comprehensive 'Atlas' of the surfaces produced in association with a range of processes. The development of a range of Atlases would enable the functional process control parameters to be accurately set, which would ensure that the produced topography and its consequential condition of the surface and near surface physical layers, is compatible to the intended function for the surface.

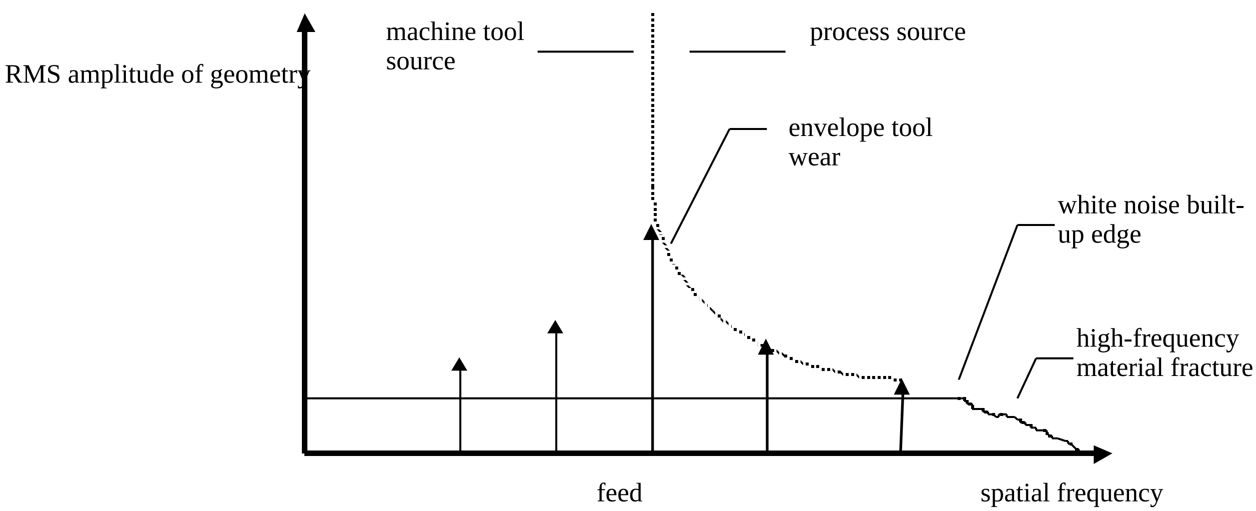

Fig. 4 Fingerprint of a single point cutting prcess. After Whitehouse (3)]

The industrial outcomes of 'engineering the surface' for its intended function include:- Increased product reliability and a reduction of the running-in time of tribological components. Reducing gas 'blow-by' in internal combustion engines to meet current and anticipated future legislation on gas and particle emissions from vehicle engines. The use of nanometre sized particles in the production of highly controlled porous materials, for example, to use for aerostatic bearing shells and high precision filters. The structuring of steel sheet and other metallic components for use in the automobile and other industries.

To support the proposals presented in this paper it is possible to state that there have been in recent times considerable developments in manufacturing processes. Also the development of new materials in recent years and the implications of surface topography combined with surface physics (the engineered surface) of these materials are particularly important in the following areas;-

a. increasing specification and use of multi-functional surfaces to reduce and hopefully running-in and increase both performance and service life of components and products.

b. The production of atomic scale finishes for use in the micro-circuit and micro-chip industries. This will imply energy beam processes and the use of atomic scale abrasives

c. The development of net shape fabrication processes in an effort to minimise post fabrication machining.

d. The need to develop more economical manufacturing methods. This will occur if the number of process in manufacture are reduced and the requirement to readjust the components after machining, shaping of fabrication is lessened.

Component Function Map

A way of characterising a component more comprehensively is through the creation of Component Function Maps, one of which is presented in figure 5 to illustrate the scope of the map. In the component function map many factors are interrelated, mode of function, the functional situation (either static, hybrid or dynamic application) and the scale of clearance or overlap required by the interaction with the mating part. In addition these inter relationships have been identified in terms of the functional application and the degree of precision required.

MODE	STATIC	FUNCTIONAL SITUATION HYBRID	DYNAMIC

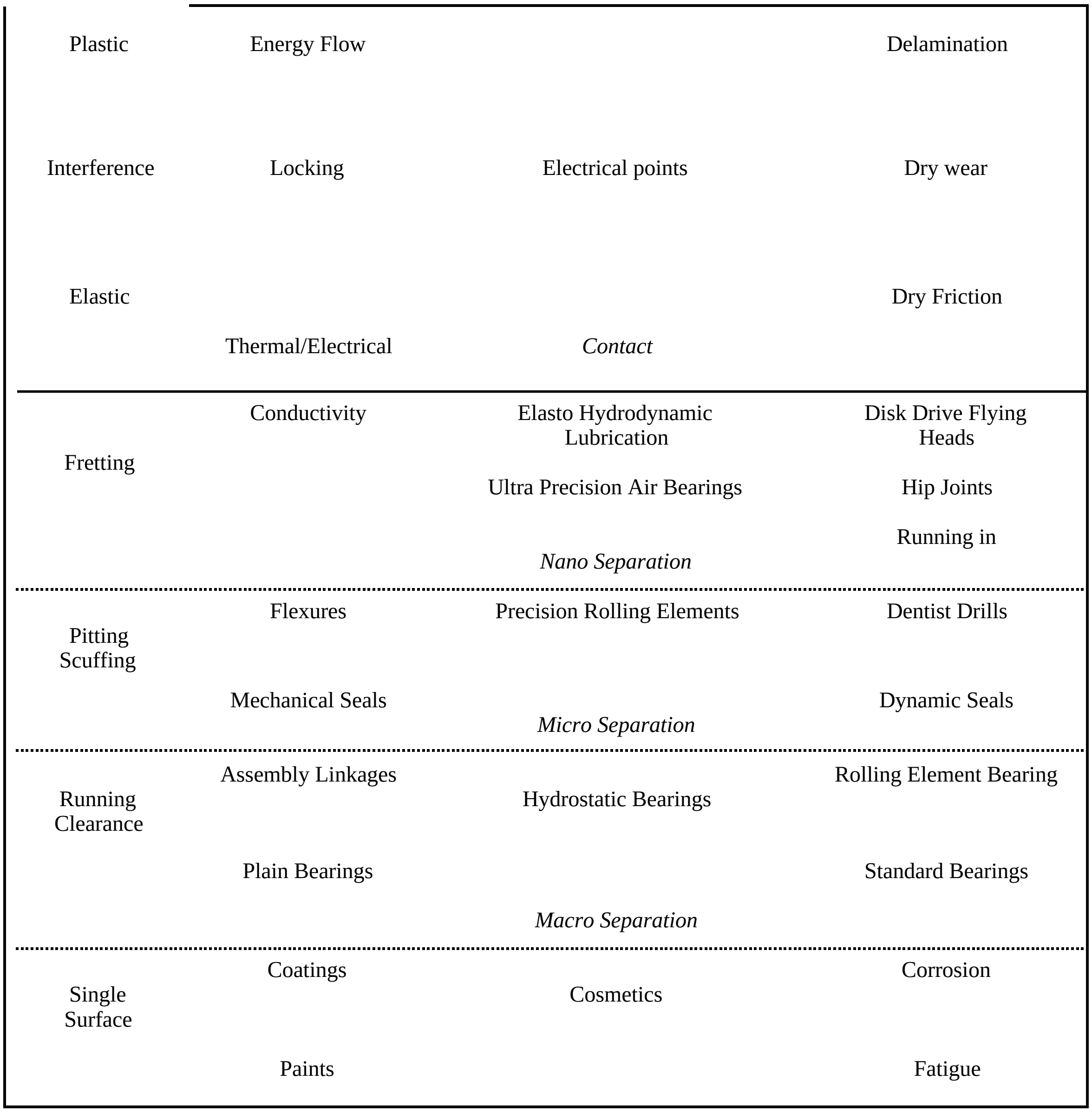

Fig. 5. Component Function Map

Concluding Comments.

It is these trends which will lead to more surfaces being *engineered* in the final processing of components to meet their long term functional requirements. It is believed that the recent interest in the 'engineered surface' has come to the forefront as greater demands for economy and functionality have been sought.

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