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Technological shifts in surface metrology

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ABSTRACT

This paper gives an overview of the progress which has been made in surface metrology over the past ten years. It updates the surface classification system, and discusses the practical and theoretical reasons for the technological shifts which have occurred. This includes the use of surfaces with predetermined features as an alternative to traditional machined surfaces, and the move from simple to freeform shapes. The paper discusses technological shifts in association, filtration, numeric parametric techniques, fractals associated with function and standardisation. Many examples are given in order to contextualise the significance of these technological changes. This paper should help to predict the direction of future developments in surface metrology, and therefore emphasise its importance in functional applications in advanced manufacture.

1. Introduction and fundamental shifts

The technological shifts which have occurred in surface metrology in the past ten years are inherently linked to the changes in advanced manufacturing, e.g. micromanufacture and nanotechnology [3,21,50,53,64,116,136] and mirror the changes to all attributes of geometrical components in this period.

The technical change in surface metrology has been primarily driven by the need to make manufacturing more efficient, economic and less environmentally sensitive while at the same time optimising performance; to give ‘added value’ to the workpiece. These are not really shifts in emphasis but rather common sense attempts to progress the technology in parallel to manufacturing practice. There have been however genuine shifts in the requirements of technology over the past decade or so; many more devices are based on planar technology due to semiconductor manufacturing progress and there is the inexorable trend towards miniaturisation.

Size has always been regarded as being the most important attribute with respect to function but recently, with the increase in planar technology and miniaturisation, this position is changing. Feature position and size within a planar area, as well as texture are growing in importance relative to volume and size [186]. What is critical here is the way in which the relative importance of these attributes has been and is changing with time, and more to the point, how their properties are changing with size!

Historically the first attempt to reduce the size element from a practical part goes back to the 1820s when Fresnel [47] approximated a lens by a set of prisms. He then replaced each prism by its change in shape from the previous one. It can be seen that he simply ignored the body of the lens and replaced it with the changes in shape at the various levels thus making a much lighter element and yet retaining many of the properties of the original lens. The need to reduce weight and the amount of material used in design is a major priority today, so that emphasis is being placed where this can be achieved. As a result of the new trends in geometry mentioned above there are an increasing number of cases where the actual size of the part can be subordinate to the shape and texture.

Even at the macro scale manufacturing emphasis is changing as can be seen in Fig. 1. Fig. 1a shows how in the early days, the part was made so that the size and shape conformed to the design specification; the surface texture was regarded as incidental. In fact attempts were made to make the surface as smooth as possible to get rid of it but it was soon realised, e.g. by the Bentley Car Company in the late 1920s that smooth cylinder bores did not make good racing car engines [92]! Fortunately, as there was a need to control manufacture from a process and machine tool point of view, it soon became apparent that one way to do this was by examining the surface geometry of the part being made because it was extremely sensitive to changes in both process and machine tool performance. It could be convincingly argued that the shorter wavelengths on the surface, the roughness, could be attributed to the marks left by the process. Any longer wavelengths, called the waviness could be attributed to errors in the path of the tool as prescribed by the machine tool. These concepts (Fig. 2), defined in wavelength bands, were standardised and widely accepted by industries up to the 1990s [7,70,71].

Over subsequent years, the texture also became to be utilised as a functional attribute but only secondary to size and shape, see Fig. 1b. This trend gradually evolved through the 1960s [131] to the 1990s until nowadays the situation has evolved to that shown in Fig. 1c in which the ‘value add’ of the workpiece in terms of performance benefit has moved to both the shape and texture. So surface geometry is now regarded as fundamental both in the control of manufacture and functional performance [14,27,40,117,178,189] and as such has to be taken into account by the design, production

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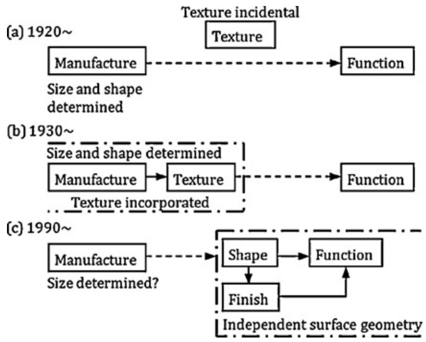

Fig. 1. Development of the role of Surface Geometry.

and quality control engineer. This is only part of the story because the very nature of surface texture and shape are changing; no longer are the shape and texture adjuncts to the generation of the size, they are becoming to be regarded as entities in their own right, having specific functional properties. This is mainly due to the growth of surface dominated functions in micro-machining and MEMS applications [21,64], which require sub mm in size and have texture feature sizes of a few tens/hundreds of micrometer but with often sub-micrometer roughness.

There is a complementary trend towards removing the shape from the size. This has already been shown in the use of Fresnel lenses in the 1820s but it is now being carried much further with the move towards freeform geometrical shapes to accomplish a specific functional need such as for optical imaging in heads-up displays. Complex waveforms needed to perform the objective can be calculated and a single element manufactured to accomplish the specification with the result that the size of the system previously needed is reduced significantly as shown schematically in Fig. 3. The advantages are optimal performance and a reduction in materials and weight.

Another phenomenon occurring in the development of precision and micro-/nano-technologies is that manufactured ultra-precision surfaces must not only be incredibly smooth, but also have form error of the shape reaching the level of atomic magnitude, e.g. optics in large ground/space-based telescopes, and in large inertial laser fusion facilities [148,154]; or the surfaces have large area substrates with ultra precision complex surface components (nanometre tolerance), e.g. optical surfaces in energy production systems [21,148].

There is however a downside to these interesting advances in surface texture which concerns manufacture and function. Some precision and ultra precision processes such as laser machining can introduce adverse functional properties into the subsurface, while freeform surfaces are sensitive to positioning and to shape tolerances. Both types of problems are not yet fully understood nor are they adequately catered for in terms of surface metrology and standardisation. These changes have brought into relief some characterisation problems and their modern solutions.

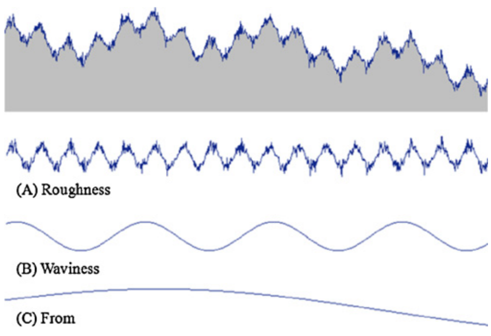

Fig. 2. Components of a surface profile.

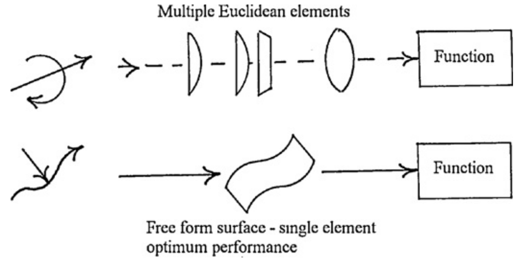

Fig. 3. Free form shape offers size reduction.

1.1. Scale-limited surface

As a consequence of manufacturing changes, the conventional surface characterisation framework has been proved to be inadequate. An important shift in ISO standardisation system is to embody a new concept called *a scale-limited surface*. It intends to provide a flexible way of identifying the various different scales of surface texture now required to be specified for manufacture.

An areal surface characterisation does not now require three different groups of surface texture parameters as in ISO 4287:1997 [70]. For example, in areal surface characterisation, *Sq* is only defined for the root mean square parameter rather than the primary surface *Pq*, Waviness *Wq* and roughness *Rq* in the profile system. The *Sq* parameter depends on the type of scale-limited surface defined in ISO 25178-Part 2 [76].

Under this definition, an SF surface is obtained in Fig. 4b, by using an S-filter and an F-operator (Fig. 4a), in combination, on a surface (e.g. for a Conventional machined surface). An SF surface means a primary surface, and an SL surface represents a roughness surface through the use of an L-Filter on an SF surface. Both an SF surface and an SL surface are called scale-limited surfaces. That indicates that a scale-limited surface actually depends on which filters or operator is used.

1.2. Feature-based surface attributes

Another critical change in surface texture is a feature-based attribute technique with which to solve the problems in multi-functional surface analysis including structured surface assessment. This technique was originally proposed by Scott in 1997 [141] and is now adopted by ISO. It states that a surface can be decomposed into basic point elements (e.g. peaks, pits, saddle points, shown in Fig. 5a) and line elements (e.g. course lines and ridge lines shown in Fig. 5b) by using Maxwell's method [143]. The key aspect of this technique is to build up a relationship of a surface

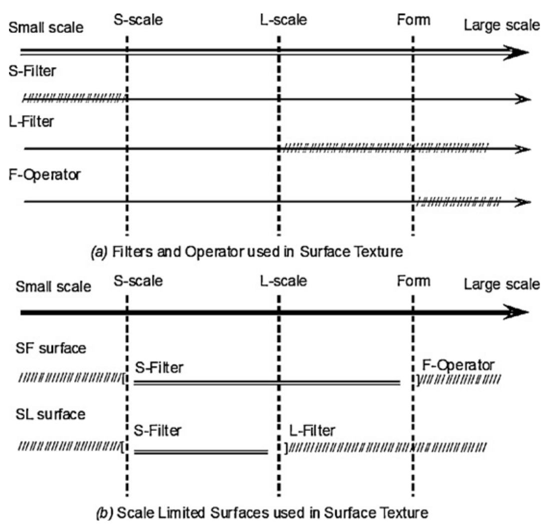

Fig. 4. Filters (S-filter or L-filter), operator (F-operator) and Scale-limited surfaces (SF surface or SL surface).