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The evolution of surfaces and their measurement

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**Abstract**

Surfaces and their interactions are at the heart of living systems and all moving objects. They have fascinated man from the ancient Egyptians, through Leonardo Da Vinci in the Renaissance period, to nanotechnologists of today. This paper elucidates the science of surfaces and their interactions, covering the importance of surfaces and how they influence us all in terms of energy, environment and quality of life. It attempts to uncover the story of mankind's deepening understanding of surfaces and their measurement, and to provide an overview of surface measurement and shows how current thinking has evolved from a complicated historical background.

**Keywords:** Surfaces, surface measurement

## 1. Introduction

*What is a surface*? In applied science, a surface can be defined as *an interface limiting a body and separating it from the surrounding medium*. The desert is a surface (Fig. 1), it is an interface limiting sand and separating it from the atmosphere. If we take a surface section from this desert, you find that the cluster of grains of sand represents roughness; the ripples are waviness and the undulating nature of the land is the form or curvature. The *roughness*, *waviness* and *form* are the three basic components of a surface. Figure 2 shows four surfaces from engineering and geography. It shows that landscapes and surface texture have similar topography, such as similar summits/valleys and slopes, but the scales are completely different.

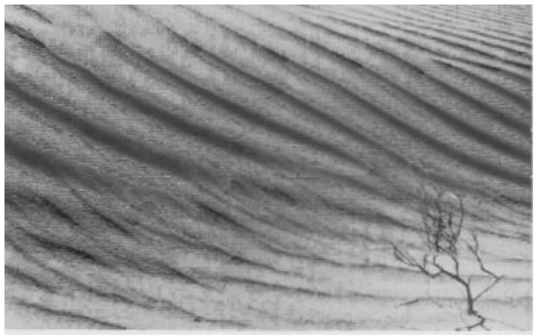

Fig. 1. Desert sand as a surface.

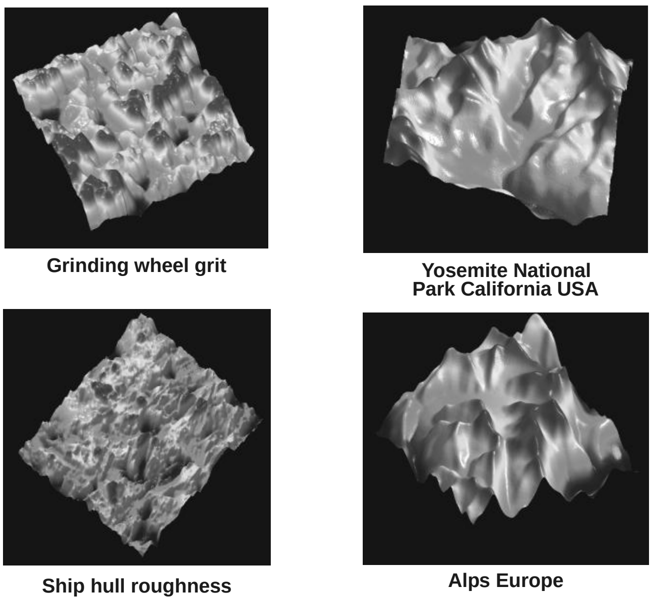


Fig. 2. Landscape v surface texture.

*Why are we interested in surfaces*? *Why is surface important*? The answer is that surfaces and their interactions are at the heart of living systems and all moving objects. Surfaces affect qualities and efficiencies in our life. For example, energy transfer, force transfer and information transfer.

## 2. The genesis of the surfaces and their measurement

Fig. 3. Rhind mathematical papyrus.

Surfaces where first measured by early civilizations for example the ancient Egyptians. After the annual floods from the river Nile, this left deposit of good soil on the land. To re-establish the field systems, they had to survey the land that is to measure the landscape. The Rhind mathematical papyrus (Fig. 3 [1]) dates back to about 1650 BC and gives mathematical exercises, some relate to measuring landscape. These papyruses also mention two ancient Egyptian words, SEKED means *slope* and PESU means *quality* and together means quality of a slope; so the Egyptians already had the words for the quality of surfaces as demonstrated by the fit of two stones accurately and the construction of the pyramids.

De Vinci was an artist, scientist, engineer, Renaissance man; who designed many marvelous machines, including a thread cutting machine (Fig. 4 [2-3]). Because of this, he became very interested in the friction of surfaces. He discovered one of the basic laws: *Friction is independent of the area of contact*. This is a very surprising result and only understood when the true nature of surfaces was revealed in the 20th century.

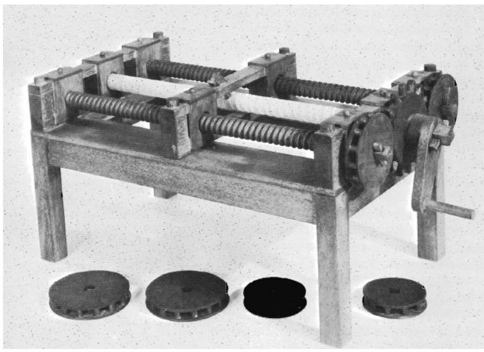

Fig. 4. De Vinci's thread cutting machine.

In England, one historical interest in the quality of surfaces was the need to make accurate cannon and low friction pulley blocks for 'ships of the line' of the Royal Navy in the sixteenth and seventeenth centuries. The cannon ball comes out very fast and precisely from accurate cannon and low friction pulley blocks means the sails can go up and down very quickly, and turn ship around much more easily

Another general interest in the quality of surfaces was the use of surfaces for optics. Haytham, often regarded as the "father of optics". He formulated the first comprehensive and systematic optical theories and techniques. The earliest pictorial evidence for the use of eyeglasses is the 1352 picture of the cardinal Hugh reading. Newton was a science hero in England and he invented the reflecting telescope which just requires a good quality polished surface with the correct form, to replace previous glass based telescopes. In the 1840s at Birr, Ireland, the 3$^{rd}$ Earl of Ross built a 72-inch (1.83m) telescope mirror. This was the largest telescope until the 20th century making many discoveries including the true nature of galaxies.

Surfaces played their full part in the industrial revolution. At that time, scientific Instrument makers (such as Jesse Ramsden 1735-1800 [2]) produced ever accurate instruments and precision surfaces for scientific advance. He is famous for his circular dividing engines for grating manufacture and measurement. Another critical figure is James Watt; he invented a fuel efficient steam engine [4]. The engine has two surfaces characters: The first, the cylinder was produced by using accurate canon manufacture techniques from the Royal Navy, such that you could not fit the width of a sixpence between the cylinder and the piston. Secondly, accurate cylinder surfaces make the Watt engine operated smoothly enough to convert linear motion into rotary power. The increased efficiency of the Watt engine finally led to the general acceptance and use of steam power in industry.

Babbage was an English mathematician, philosopher, and mechanical engineer; he sought a method that mathematical tables could be calculated mechanically to remove the high rate of human error. He originated the idea of a programmable computer. Parts of his unfinished engines are displayed in the London Science Museum [3]. In 1991, a perfectly difference engine was constructed from Babbage's original plans. The success of the finished engine indicated that Babbage's machine has very accurate form and roughness of the surfaces, which gives it the capability to carry out very complex calculations and it also represents the highest precision of the late nineteenth century.

## 3. The early instruments where invented to discover the nature of surfaces

The development of instruments for assessment of surfaces began in the late 1910's. In 1919, Tomlinson at the National Physical Laboratory devised an early stylus instrument. This is a pure mechanic system. Tomlinson amplified vertical movement of the stylus mechanically by a group of levers causing a continuous scratch on a smoked glass plate, approximately 30 times magnification.

By 1939, it was being realized, particularly, in the aircraft industry, that finish or texture of machined surfaces was as important as dimensions. Richard Reason of Taylor, Taylor Hobson invented the Talysurf 1 (Fig. 5 [5]). It was the first truly commercial instrument with electronic meter and chart. One of earliest instruments was sold to Rolls-Royce for quality control of the engine for the super-marine spitfire in 1941. In the early surface instruments, engineers used two methods to quantify surface texture. One was to use a single number representing surface profile, with a scale corresponding to 'good' to 'bad' surfaces. This number was the average deviation of the profile, Ra, and it can be easily calculated using simple analogue devices. The second method was the chart record. This method uses a magnified representation of the surface. The important thing for the chart record is to select the correct magnifications.

Through early measurement the nature of surfaces were beginning to be understood for the first time. Surface interactions were found to be more complex phenomenon than originally thought. For example, there are many types of friction for example: boundary friction where the two surfaces are sliding against each other; mixed friction where the two surfaces are separated but still contact each other with some lubrication; and hydrodynamic lubrication where the two surfaces are totally separated with fully lubrication. The interaction of light with a surface was also a very complex phenomenon which is not only depends on surface geometry, but also material properties.

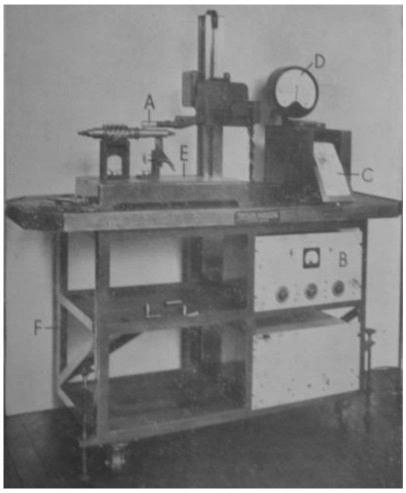

Fig. 5. Talysurf 1.

## 4. Surface instrumentation became computerized

In the1960s, the digital computer became widely available, surface instrumentation changed dramatically with the addition of computers. With digital method, surface instruments can be automatically controlled by a computer and an analogue surface signal converted to a digital signal and displayed in the screen. The more important thing is that digital method overcame the difficulty of "seeing" between two surfaces in contact by mapping the surfaces digitally and simulating contact using a computer. This was the first time that surface functional prediction was in place.

Meanwhile, scientists and engineers realized that many surfaces created from different manufacture have similar Ra values. For example, there are three surfaces produced by honing, turning and grinding (Fig. 6), they have completely different surface texture and surface functions, but they have almost the same Ra. So, Ra has very limited capabilities for a global description of surface properties. As a result, engineers and designers were looking for better ways to describe a surface. With computing capability, many different parameters were designed and even specified by many national standards. They were largely based upon custom and practice of surface descriptions used in the individual industries of their countries. Very quickly, over one hundred parameters were published, many did not give independent information about the surface and some had different names for the same evaluation. Overall, there was much confusion in industry and academia.

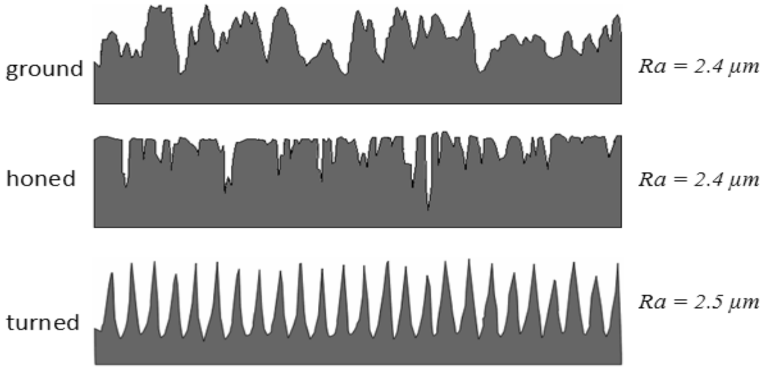


Fig. 6. Three surfaces with similar Ra.

At that time, a paper [6] by Whitehouse defined the "Parameter Rash" for the explosion of parameters. This shocked the researchers and industry who realized that a serious mistake had been made. This pushed the International standards organization into publishing a profile standard with a limited number of parameters.

## 5. Surface description needs to truly reveal the geometrical nature of a surface

The illustration is a profile from a ground surface and there are two deep valleys (Fig. 7). It is impossible to identify whether the valleys are from pits or troughs. However, if an areal surface is measured, you can easily identify these surface features, pits, troughs and their size. So, surface topography is three dimensional in nature. This problem was recognized by both of academia and industry in 1980s. In 1990, under the European framework 4-5, a basis for characterization of areal surface texture was well established [7-8].

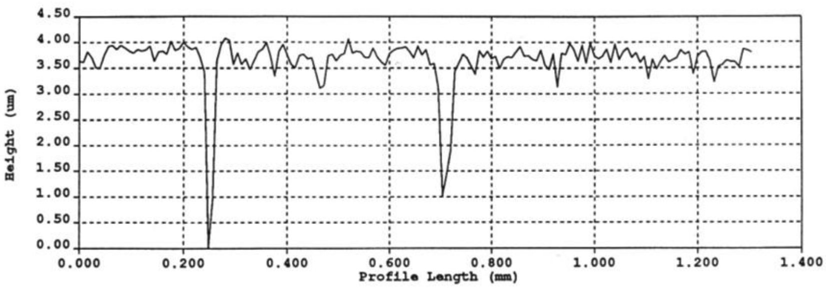


Fig. 7. Are the deep valleys Pits or Troughs?

Firstly, a classification scheme for surface instrumentation was developed that included: metrology characteristics, traceable measurement, and calibration methods. Now, instruments can cover surface measurements from 0.01 nanometres to 25 millimetres. For example, from the atomic force microscope that can measure atoms, through, white-light interferometer and phase-shifting interferometer for ultra precision surfaces, to a precision stylus instrument that can measure form and texture together.

Putting numbers to a surface was the main part of the EU research programme. In 1994, Stout and his Birmingham team [7] developed methods for characterization of roughness in three dimensions. The "*Birmingham 14 parameters*" resulted. These parameters were examined by European experts who found that things still needed to be cleared up further. A second EU Project followed, which was co-ordinated by Blunt [8]. Today, the parameters for areal surface texture are well established, and adopted by ISO 25178, which includes three groups of parameters. The S-parameters describe peak-valley heights, peak spacing, and surface slopes and V-parameters describe volumetric information related to oil retention and material wear properties.

A step change in modeling surfaces was led by Scott [9] and intended to put numbers to surface features. The main idea is to establish the fundamental elements of a surface with significant features of a surface retained and small elements moved out. Parameters can easily describe the feature themselves (height, volume etc) and the relationship between features (average spacing etc.). The feature parameter set is the third group of ISO parameters. With the established areal surface characterization techniques, industry can now diagnose their surface just like a medical doctor. These techniques give you information about how good the surface is and what is wrong, rather than just pass and fail. For example, you can diagnose manufacturing processes, you can model and predict surface function accurately, for example, identifying the grits in grinding wheels, and metallic crystal boundary structures as well as separating surface wavelengths with nano-scale accuracy to predict surface performance and wear properties.

## 6. Micro-scale dimensional geometry merges into surface texture

Looking at recent progress in precision optical components systems, you will find that high-tech products have developed very quickly. In 2000, high-tech products are PC cameras, CD ROMs using aspheric lenses. Today, high-tech products are bio-optics measurement systems, new power stations, and LED vehicle lights; they use micro lens arrays, freeform mirror arrays and freeform optics [10-11]. The components have become more complex, they merge micro-scale dimensional geometry into surface texture, in order for high-tech products to be more efficient and cheaper. This involved two surface evolutions.

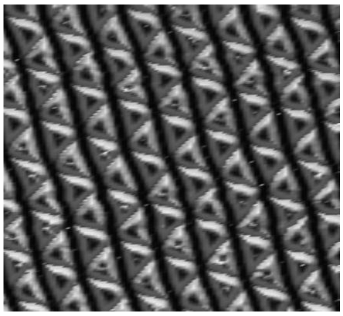

Fig. 8. 3M abrasive surface.

The first are surfaces with a deterministic structure, they are different to traditional stochastic surfaces because they have a repeated structure over the surface. For example this 3M abrasive surface (Fig. 8) consists of an array of triangular based pyramids with tens micrometer structure heights. The second is freeform and patterned surfaces. Freeform surfaces rely purely on the global complex geometry and they are smooth surfaces, for example, open ring reflector for operation theatre, F-theta lens for printers and scanners, high beam reflectors. Another type is surfaces that include steps, edges, facets and patterns; for example a Fresnel lens that is used to magnify the light in modern car headlights. The scale of steps and patterns are only a few micrometers high.

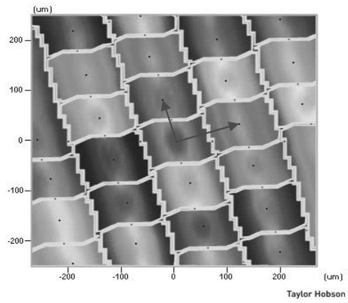


Fig. 9. Unit tile and two vectors for the tessellation for the 3M surface.

The first challenge is how to evaluate micro-structured surfaces? It is meaningless to calculate standard surface roughness for this type of surface because the parameters do not mean anything related to the control of manufacture and prediction of surface performance. A new method has been investigated, which establishes new mathematical theory to model the original structured surfaces as a tessellation [11]. According to this discovery the surface can be assessed by a unit tile (quadrilateral, hexagon) and two vectors (Fig. 9).

Originally, simple surfaces where measured, for example a plane, a cylinder, a sphere or a parabola. However, today surfaces can have any designed shape, for example from CAD data or a drawing. These surfaces with no symmetries are called freeform surfaces. High-tech freeform products often require sub-micrometer form accuracy and sub-nanometre surface texture. Consequently, the second challenge [11-12] is to fit the designed shape to the measured surface which is a lot more difficult than simple geometrical surface fitting. One needs to consider all six degrees of freedom. For example, you need to find the critical position on the surface and the correct orientation before fitting.

The third challenge is to how to evaluate micro-geometrical surfaces. For example, Lab-on-a-chip is MicroElectroMechanical devices that contain pumps, channels, mixers, and sensors; to move, mix, and analyze the fluids for chemical and biological applications. Surfaces are extremely important for these devices to work properly: Width and height of the channels, surface roughness, alignment accuracy etc. For example, the entrance to the reactor channels on the device shown has only 3um spacing, and is greatly influenced by the channel dimensions and any defect within the channels (Fig. 10 [12]). Today Lab-on-a-chip devices are still very simple devices. At the end of 2007 it was announced on the BBC website that "*antique engines inspire nano chip*", scientists have started to think about building novel computer engines according Babbage's plan on a nano chip [13]. Precision and surface scientists will face more challenges in how to manufacture and measure them.

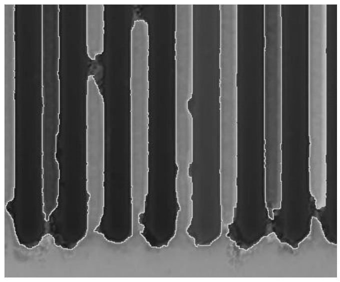

Fig. 10. Pattern analyses for Lab-on-a-chip showing blocked and free channels.

## 7. Leading surface applications in environment, energy generation and basic science

Nature provides good examples of complex surface properties. The leaves of many plants not only repel water, but also dirt, as water running off the surface takes dirt with it. The lotus flower is probably the best example. To use this effect, nano-technology methods have been developed to apply extremely fine nano-structured finishes to materials that simulate the surface of lotus leaves. So far, the lotus effect is being developed for self-cleaning glass. Another approach to self-cleaning glass uses chemistry method, for example, using UV rays in sunlight to break down organic dirt.

A very important future energy source is HiPER laser fusion energy [14-15] which uses sea water as a principle source of fuel. It is an attractive, environmentally clean power. HiPER uses many laser beams to implode targets of nuclear fuel to generate heat then convert it to electricity. In the HiPER system, huge ultra precision optics are required, which include 24 parabolic arrays with 10's nm surface form deviation and more than 2600 "perfect Optics" including optical lens, transport mirrors and gratings.

Euro 50 Ground Telescope is an Adaptive-Optics Extremely Large Telescope [16-17]. The telescope will allow astronomers to look back to the youngest galaxies. They will also likely detect the even earlier first lights of the universe, and search for signatures of other life forms. The large primary mirror will be developed from numerous freeform segments and has 42 m diameter with 906 freeform segments. The specifications for the segments are expected to be in the size range 1 – 2.5 metres with hexagonal shape, a few atoms surface roughness and less than 75 atoms form accuracy.

## 8. Conclusion

A brief overview of the evolution of surfaces and their measurement is presented. It shows how current thinking has evolved from a complicated historical background. It encapsulates the evolution progresses in technology which have resulted in tangible gains in capability being made and prepared the technology for the considerable challenges of the future [18].

This paper emphasises those technology shifts which will be needed for the major effort required now and in the future for measuring the new generation of surfaces. The paper reveals that surface texture is currently undergoing a huge technological shift by measuring over areas rather than lines, from random to predetermined engineered features, and from simple to complex geometrical shaped surfaces. The paper highlights the critical advances which have been made in the surfaces and their measurement.


## 9. Acknowledgements

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