Nigel Rose, Rhopoint Instruments, discusses the use of phase stepped deflectometry, a measurement technique to assess surface quality defects

Advanced characterisation of surface appearance

In today's globalised, competitive world the achievement of high quality standards at all stages of manufacture is essential. Rapid advances in technology have resulted in products with complex designs, superior quality and higher performance. With ever-increasing productivity, greater demands are put on process control and the inspection methods used. Inconsistencies in manufactured components can have a dramatic effect on the overall appearance of a finished product. It is, therefore, no longer practical to simply rely on subjective visual comparisons for final product or component part verification. Measurements must be performed to quantitatively characterise each part throughout the entire process to achieve consistency in quality to the required standards. The correct selection of materials, processes and surface coatings used in the design and manufacture of a product is, therefore, critical in attaining consistent quality standards. If not correctly controlled during the manufacturing cycle issues will develop.

During the machining process, tool wear, for instance, can have a major impact on the quality of the finished component if not properly monitored, effects like chatter marks and machining lines cause visible differences between component parts that are produced. Similarly during the coating process, a variety of problems can occur if the substrate is not correctly prepared or the coating is incorrectly applied.

To overcome these problems and to provide a way in which surface condition can be more closely monitored, a variety of techniques are available to measure quality and fit into two categories, contact (tactile) measurement and non-contact (optical) measurement. Some of these techniques are well established, while others are relatively new.

MEASUREMENT METHODS

A surface can be imagined as consisting of three basic components: Form, Roughness (Texture) and Waviness.

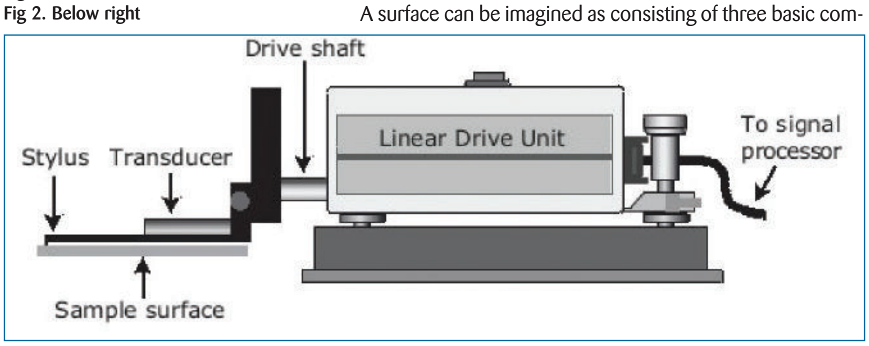
The Form of a component or product is directly controlled by the manufacturing process itself being largely governed by the dimensional tolerances applied, the use of accurate dimensional measuring instruments quickly verifies that these tolerances are being achieved and if not, corrective actions applied to the process.

Roughness (Texture) and Waviness can be affected by various stages of the manufacturing and finishing process.

The profilometer, a widely used contact-based instrument, uses a diamond stylus to measure irregularities in the surface. The stylus arm, containing the stylus and a transducer, is supported on the surface by a skid, a curved support having a radius much greater than the roughness spacing, projecting from the underside of the arm near to the stylus (**figure 1**). As the stylus arm moves across the surface movements of the stylus relative to the skid, are recorded and converted into an electrical signal over a selectable sampling length or cut-off.

As surface roughness is caused by different factors depending on the manufacturing process used, it is common to separate them out during analysis. This separation is achieved by the selection of filter cut-off settings allowing the operator to select the degree of filtering that is applied to the measured profile. The irregularities of the surface consist of high and low points created by the manufacturing process. These peaks and valleys are measured and used to define the conditions and sometimes the performance of the surface. There are a number of ways in which the information recorded from the surface can be processed and the results reported. Usually one or more of a number of roughness parameters are used depending on the requirement (**figure 2**).

Fig 1. Below
Fig 2. Below right



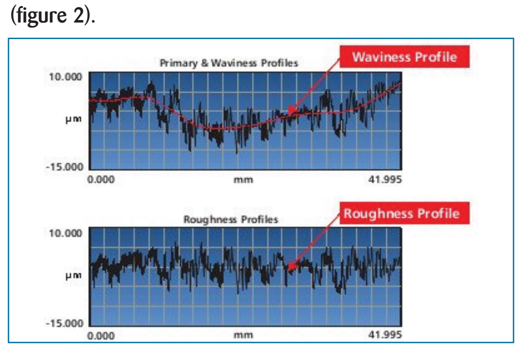


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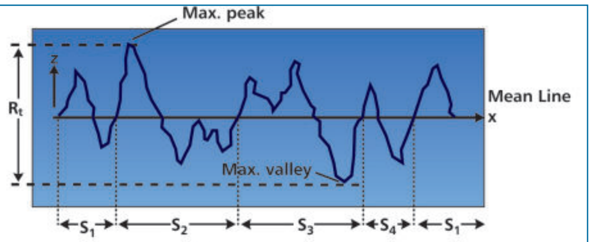
Fig 3. Graphical representation of surface roughness parameters Ra, Rt and Sm



$$S_m = \frac{1}{n}\sum_{i=1}^{i=n} S_i \qquad R_a = \frac{1}{L}\int_b^L [z(x)]\cdot dx$$

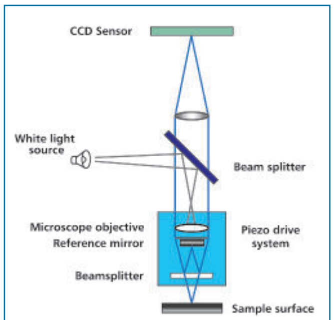


Fig 4.

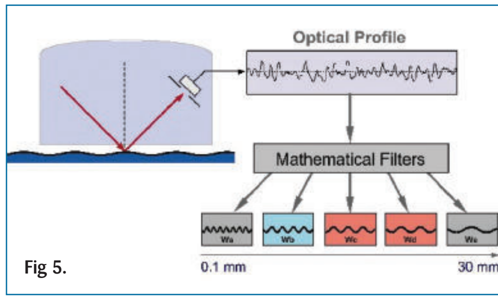


Fig 5.

The most universally recognised parameter Ra or Arithmetic Average Roughness, is the average height of roughness component variations from a mean line and provides a simple value for pass/fail assessments. Ra is a commonly quoted parameter on most manufacturing drawings (**figure 3**).

There are a number of instruments available for non-contact measurement of surface roughness utilising various techniques including scanning white light interferometry (SWLI), confocal microscopy and focus variation microscopy, to name but a few. SWLI, however, is the most commonly used method in 3D optical surface profiling systems that are available today. These systems combine an interferometer and a microscope into one system. The SWLI is a special type of Michelson Interferometer that scans the height of a test surface. It achieves this by using a beam splitter to divide the light coming from a white light source into two parts; a reference beam, which is reflected from a reference plane and a measurement beam, which is directed on to the test surface (**figure 4**).

When the vertical distance is changed between the sample and the interferometer optical interference, a fringe pattern occurs at every point of the surface where the optical path length of the two beams is exactly the same. During the vertical scan the interference patterns are captured by a CCD camera array to determine where the surface is located using the shape of the white light interferogram, the localised phase or a combination of both shape and phase and the data processed to create the topography of the surface. Highly accurate 2D and 3D images of the surface are produced to sub-micron resolution, allowing further analysis of texture and other structures that may be present.

PAINTED SURFACES

It is well known that the condition of an unpainted surface can have a noticeable impact on the finished product once the coating is applied. While the two instruments discussed earlier allow surface measurements to be made with a high degree of reliability, accuracy and repeatability, they are generally only used on unpainted surfaces. For the measurement of waviness in paints, particularly those used in automotive applications due to the wavelengths of the structures (0.1 - 30mm) and the size and shapes of the surfaces involved, it is impractical to use these instruments, therefore, other methods are preferred.

A commonly used instrument for this purpose, the Orange Peel or Waviness meter, uses a laser point light source at an angle of 60° and a detector at the same equal but opposite angle to illuminate and measure the light being reflected from the surface. The instrument is rolled across the surface over a fixed distance usually 10cm and the optical profile of the surface measured at each point.

Depending on the slope of structures present the detector measures changes in the reflected light intensity from the surface (**figure 5**).

Measurement data is then analysed according to the structure size by applying mathematical filtering of known pass bands in order to simulate the human eye's resolution at various distances as shown in **figure 6**.

The filtered measurement data forms a structure spectrum allowing detailed analysis of effects such as texture or 'orange peel' and the factors responsible, being either material or application.

For structure sizes less than 0.1mm the instrument uses a CCD camera and separate illumination at 20° to measure the amount of diffused light caused by these fine structures.

LIMITATIONS OF CURRENT TECHNOLOGY

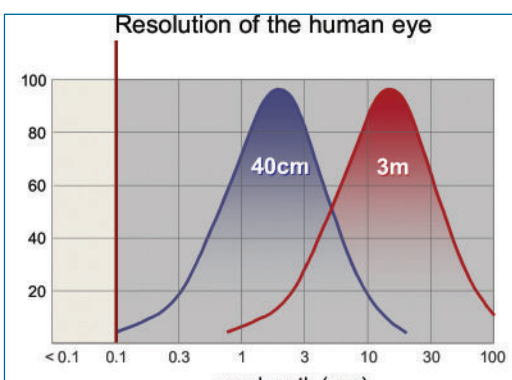
While many of the measurement techniques detailed provide a reliable method of quantifying surface appearance, they all suffer from disadvantages due to limitations and methodology of the technology being used.

One main disadvantage of the profilometer is that it needs to physically touch the surface being measured, which may cause contamination or damage to the component. The device is slow in operation, having to measure each location along a relatively small path length, which may not be representative of the total surface area, unless a number of multi-directional readings are taken.

The profilometer's accuracy is impacted when the size of the irregularities of the surface are close to or the same size as its stylus. Ra is also not a good parameter to use for different types of surfaces, as it is incapable of differentiating between scratched surfaces or surfaces containing defects, having the same average roughness. If incorrectly selected cut-off filtering can also impact the accuracy of results.

There are also limitations for non-contact instruments too. For example, instruments that rely on optical interference such as SWLI cannot resolve features that are less than a fraction of the frequency of their operating wavelength.

Fig 6.



Value	Wavelength
Wa	0.1 – 0.3mm
Wb	0.3 – 1.0mm
Wc	1.0 – 3.0mm
Wd	3.0 -10mm
We	10 – 30mm
SW	0.3 – 1.2mm
LW	1.2 – 12mm

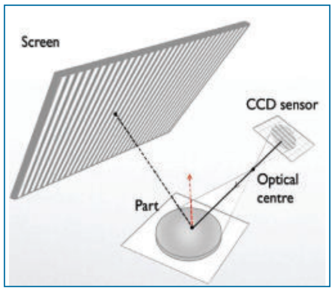


Fig 7. Above

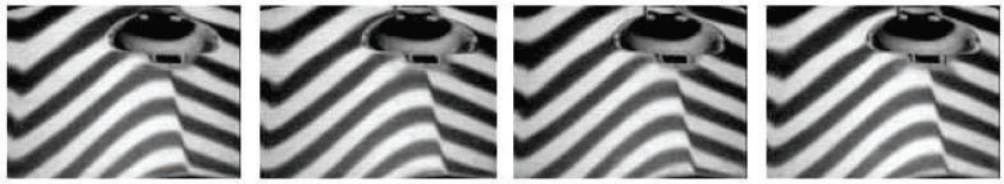


Fig 8. Above right: Images of phase stepping on the surface

This limitation can make it difficult to accurately measure roughness even on simple objects, since the features of interest may be well below the wavelength of light.

SWLI also has a limited field of view and although a stitching procedure can be employed for larger measurement areas, involving the combination of a number of partially overlapping measurement areas into one surface profile, the overall measurement time increases because overlapping regions have to be measured more than once. SWLI systems are also expensive and require a high degree of user knowledge to operate them.

While the Waviness meter performs non-contact measurement of the painted surface profile, it does require physical movement over the surface in order to make its measurement. This movement could cause contamination or damage to the part by debris transfer from the instruments wheels on to the surface. The meter also requires a surface of suitably high reflectance in order to make a measurement; therefore, measurements on bare uncoated, electrocoated and primed surfaces can be problematic. Also its results, while widely accepted by industry, do not conform to any traceable SI unit of measure.

NEW MEASURING TECHNOLOGY

A new measurement technique, Phase Stepped Deflectometry (PSD) a white light optical technique that measures slopes, has been found particularly suitable for surface quality defect characterisation allowing objective, fast, full-field and non-contact surface inspection.

This technology uses a periodic pattern with a sinusoidal waveform (fringe pattern) projected from a high definition screen located remotely over the test surface and a high definition camera to capture the reflected image of the pattern (**figure 7**).

The sinusoidal waveform acts like a ruler over the surface allowing the relative ordinates of the light source points to be determined as they are proportional to the spatial phase of the sinusoidal pattern waveform. By using a standard technique known as 'phase stepping', **figure 8**, it allows an accurate measurement of each point across the surface through the corresponding point/pixel on the camera. Using the known geometric relationship between the display, the object surface and the camera light rays reflected from the surface are spatially modelled to calculate the direction of the normal at each point of the surface, thereby allowing the profile at that point to be obtained. By displaying the sinusoidal waveform in horizontal and vertical directions the surface slopes are determined in both orthogonal directions.

By differentiating the measurement data the curvature field can be calculated allowing accurate characterisation of surface profile. Using the sinusoidal pattern orthogonally across the surface allows multi-dimensional profile and curvature information to be obtained. By integrating this information it allows the original 3D surface topology to be reconstructed.

Fig 9. The Rhopint Optimap PSD

Unlike most existing slope and curvature measurement methods, PSD is a full-field technique, which does not require any mechanical movement or translation of either the sensor or the surface under test; all angular and positioning errors related to this translation are, therefore, avoided.

OPTIMAP PSD

Exploiting the benefits of PSD technology Rhopoint Instruments has developed an advanced portable handheld instrument, Optimap, capable of performing fast, full-field 3D surface profile measurements, **figure 9**.

The Optimap objectively measures and characterises many aspects of surface quality including texture, waviness and local defects including orange peel, inclusions, dents and scratches. Having a lateral resolution of 75μm and a fixed reference plane the device is able to detect surface defects that are invisible to the naked eye. The Optimap has a large area of measurement of 95mm x 70mm allowing the analysis of larger structure sizes that are visible from longer distances.

Unlike other instruments, the Optimap requires no movement over the surface, thus preventing any damage during operation. Although surface contact is required, the Optimap's measurement port is rubberised to protect it during measurement, which is performed entirely optically using PSD. Measurement results are displayed as graphical, image map and numeric format according to the measurement scale selected.

A wide range of surface finishes can be measured from low gloss (2.0GU@60°) to mirror finish, allowing the complete characterisation of manufacturing processes from

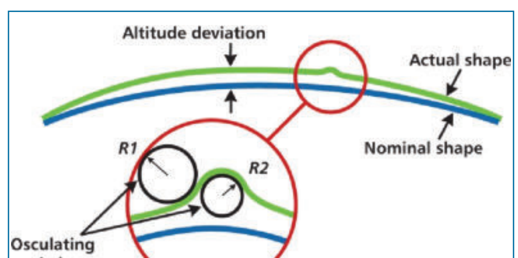
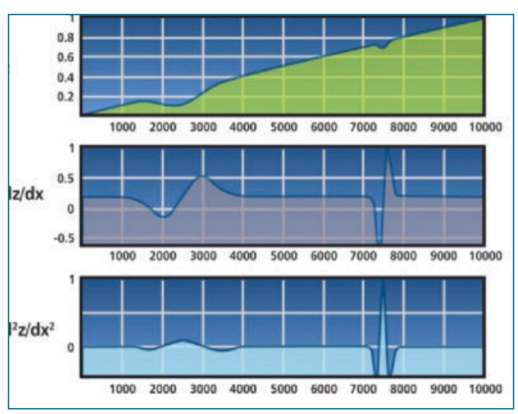


Fig 10a and Fig 10b below



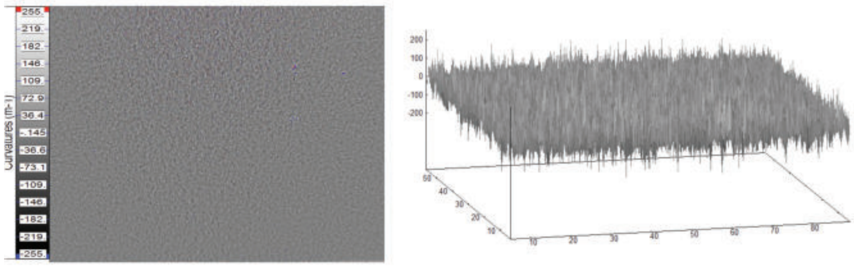


Fig 11.

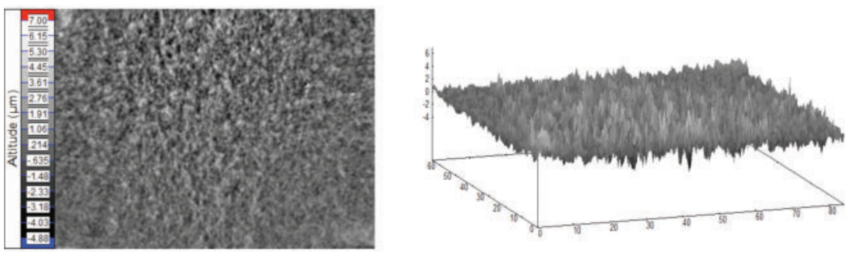


Fig 12.

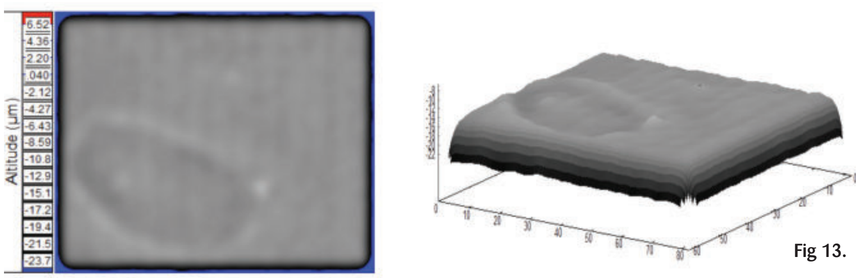


Fig 13.

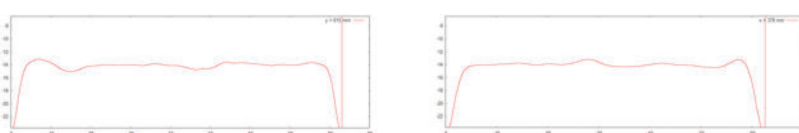


Fig 14.

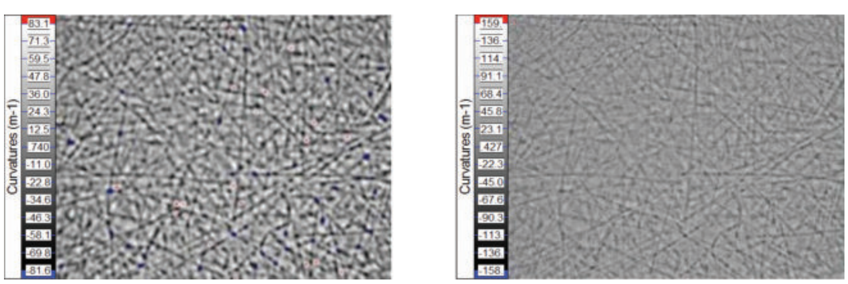


Fig 15.

machining, moulding and forming, through to surface preparation and final coating.

CURVATURE

An appearance or a shape defect can be defined as a fast variation in a surface profile across a short distance being dependant on its amplitude and wavelength, **figure 10a** and **b**.

For example, a 20µm amplitude deviation, spread over a length of 60mm, will be less visible to the naked eye than a 10µm deviation spread over a length of 20mm. So curvature, which is the first derivative of the slope and second derivative of the amplitude, combines both parameters to produce a more adapted quantity capable of being expressed in traceable SI units as m^{-1}.

This dimensionable characteristic (m^{-1}) of curvature data (K), therefore, provides a more representative method of reporting surface profile. As a totally flat surface would have no variation in curvature, higher curvature values indicate that there are more structures present on the surface at that particular wavelength range.

By filtering the curvature information in accordance with the wavelength ranges as shown previously, corresponding curvature parameters (Ka – Ke, KS – KL) can be used to represent the SD (sigma) of surface curvatures for each wavelength range. As an overall rating, Total curvature (K), is used to represent the SD (sigma) of curvatures falling within the range 0.1-30mm.

To correlate to the industry accepted Waviness scale standardised equations can be applied to the curvature values to produce a texture (T) scaling. In this scale total texture (T), is used to represent the SD (sigma) of surface textures with the seven additional texture bands Ta - Te, TS - TL used to represent the SD (sigma) of correlated surface textures Wa - We, WS - WL. This correlation provides a best fit interpretation from the dimensionless, single or multiple scan waviness measuring scale to a dimensioned, full-field, texture measurement scale.

DEFECT CHARACTERISATION

It can, therefore, be seen that slope and curvature measurement methods are particularly suited for surface analysis as they produce greater sensitivity to local slope variations, an accurate slope measurement over a short distance corresponds to an extremely accurate altitude deviation measurement. Slope and curvature are, therefore, more representative parameters for the characterisation of surface defects. See **figures, 11-14**.

By using the PSD measurement data, highly accurate 3D imagemaps can be constructed of the surface topology allowing the detection and analysis of any defects that may be present. By using a fixed reference plane of measurement, such as that incorporated in the Optimap it also allows the topology to be accurately dimensioned in microns.

Inclusions, scratches and other such defects can be perfectly characterised in terms of size, position, aspect ratio etc on the measurement surface.

As PSD can be used on a wide range of surface reflectivities, it is capable of performing measurements on a number of different surface types. Bare substrates either machined, moulded or formed, primed, plated and painted surfaces can all be measured using this technology, allowing a complete analysis of the surface finishing process and any problem areas identified at each stage.

As an example the imagemaps, **figure 15**, of a painted composite yacht panel clearly show how the fibres are oriented in the material according to their size, therefore, providing invaluable information on the substrate condition and preparation prior to painting.

CONCLUSION

The use of PSD for appearance characterisation provides a practical non-contact optical solution for objective full-field surface measurement. Due to its flexibility of use on a variety of surfaces, having a wide range of reflectivity, it provides a realistic cost-effective solution for appearance measurement during the many stages involved in the surface finishing process, providing traceable standardised data for quality control records.