BULK AND PAPER UNIFORMITY

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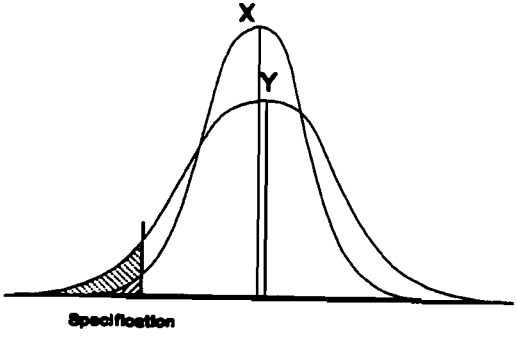
1 Introduction

1.1 The Importance of uniformity - the quality issue

Uniformity has become a topical subject as industry has focused on 'quality issues'. The underlying theme behind 'quality thinking' is that product variability can have a significant effect on the product (and therefore perceived quality).

Figure 1 demonstrates that a paper sample (A) that is nominally stronger (ie has a higher mean) can fail more often than a supposedly weaker sample (B) due to its larger inherent variability.

Figure 1 **Strength variability dictates functional performance**



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In many processes the variability of a property has a greater influence on the functional performance of that material than its magnitude

For example, a printer has latitude to vary the settings on his press to 'correct for small deficiencies' in the material he is using. Once he has set his job however, there is only a small 'property window' in which the material will produce an acceptable result.

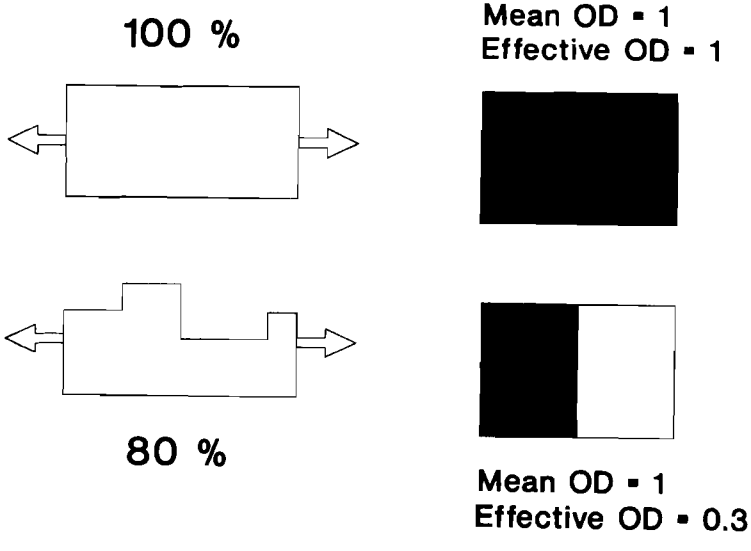
The process cannot tolerate any in-batch change in the property. It is therefore the variability in the product that determines, above all, its quality to the printer.

1.2 Uniformity and its effect on product performance

It is intuitively known, and easily demonstrated, that non uniformity detracts from the majority of paper properties.

Figure 2 shows (at a simplistic level) the relationship between structural uniformity and functional performance for strength and optical properties.

Figure 2 **Simplistic view of property degradation through non uniformity**



1.2.1 Uniformity and Strength

"A chain is only as strong as its weakest link". This commonly used phrase is also true of paper. The current range of strength properties being tested are dependent on the load bearing ability of the structure; its ability to distribute and absorb energy.

Consider a uniform homogeneous material, and the effect of subjecting it to a tensile force until it breaks, Figure 2.

For simplicity, it fails at 100 units of force. The sample is said to have a tensile strength of 100 units.

Consider the same material in a non uniform structure subjected to a similar force.

It is discovered that it fails at a lower level, 80 units perhaps. Nothing has changed, only the distribution of the material in the sample.

From this observation it can be stated that the structure has a 'Strength Efficiency' of 0.8.

(This of course is a gross simplification of the mechanisms that occur in a fibrous network.)

1.2.2 Uniformity and Optical Properties

The brightness, colour and opacity of paper are dependent on the absorption and scattering power of the material.

The uniformity of these properties is affected by the material distribution and the bonding between the fibres.

Consider the optical uniformity of the material to be characterised by the uniformity of its optical density in transmission.

The mean and effective optical densities can be written as:

$$OD\ (mean) = 1/n\ Sum(\ OD(i))$$
$$OD\ (effective) = -\log\ (1/n\ Sum\ (10^{-OD(i)}))$$

Therefore the 'optical efficiency' can be written as:

'Optical Efficiency' = OD(effective)/OD(mean)

A uniform sheet of material with an optical density of 1 will have an 'Optical Efficiency' of 1.0, Figure 2.

If that sheet is then folded in two the result can be considered as 50% of the area with an optical density of 2 and 50% with an optical density of 0. The mean optical density is still 1 but the effective optical density falls to 0.3. The structure can be said to have an 'Optical Efficiency' of 0.3.

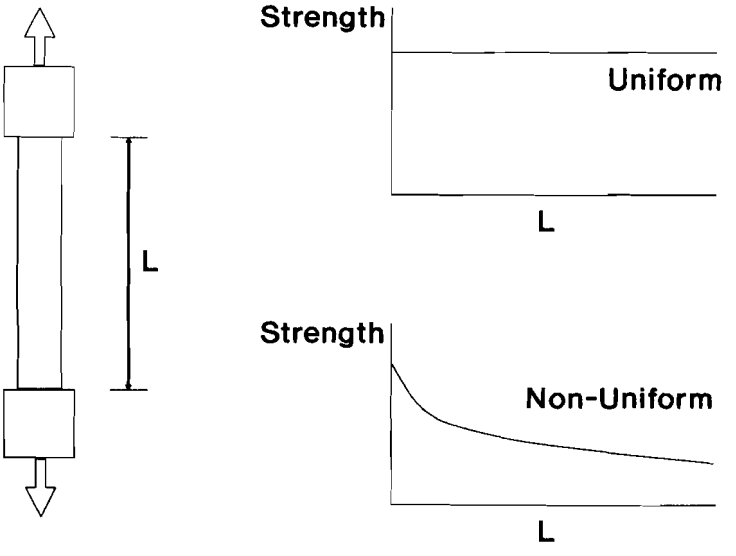
Again this is a gross simplification, but shows in principle how non uniformity can influence the properties of a paper sheet; and serves to introduce the concept of 'structural efficiency'.

1.3 Consideration of Scale

Non uniformity in paper materials is present over different scales, from long term machine direction drifts to differences at a fibre diameter scale.

One experiment that demonstrates the effect of scale (and the detrimental effect of non uniformity) is tensile testing over different spans (Figure 3).

Figure 3 **Tensile strengths over differing spans**

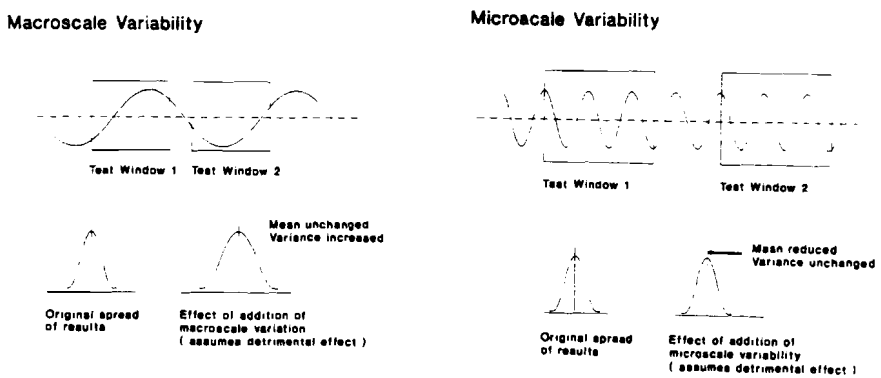


As the span increases the measured strength decreases (as the statistical probability of including areas of low strength increases). The difference between the value at zero span and the plateau indicates the reduction in strength caused by structural non uniformity (this observation has to be treated carefully as at zero span the fibre strength is being preferentially tested). The shape of the curve tells us something about the scale of non uniformity, though the complexity of strength phenomena prevents detailed investigation.

Previous workers have defined ranges for categorising variability into 'micro' and 'macro' scale. For our work we shall define 'microscale' as wavelengths that fall into a given test area and 'macroscale' for those wavelengths that fall out side.

Figure 4 shows the effects that these categories of non uniformity have on a given property.

Figure 4 **Effect of scale observed effects of variability**



1.3.1 Microscale

If the wavelength of the variability falls within a test area, then the resulting measurement will, in most cases, be adversely affected. Due to the scale of the variability this reduction in the observed value of the property will be the same for all subsequent tests. Therefore this form of variability will tend to reduce the mean value of a batch of test results, but not affect the associated variance.

1.3.2 Macroscale

If the wavelength of the variability is greater than the inspection area, then each measurement of the property will be affected differently depending on whether the test area falls on a trough or a peak. In this instance the mean value of the batch of tests will be unaffected, while the associated variance will be increased.

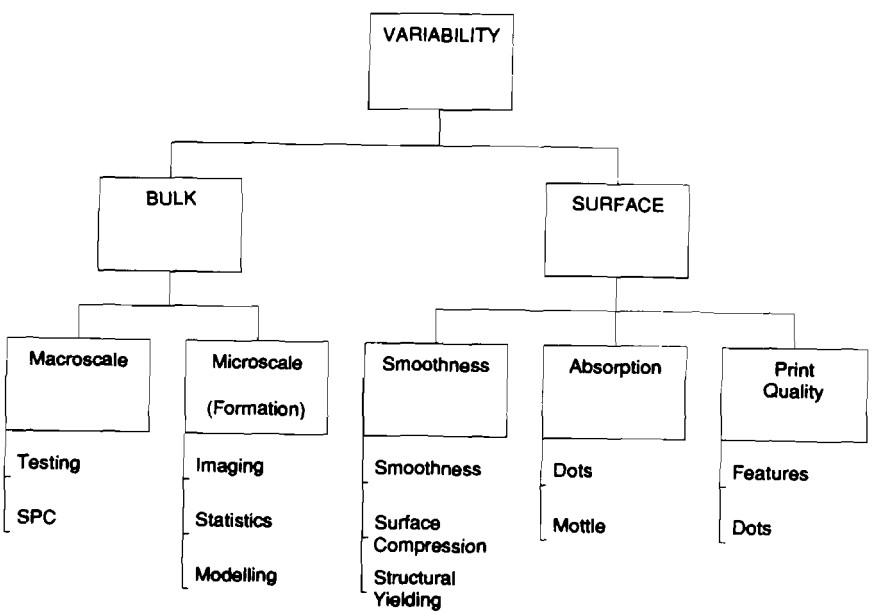
Although the above argument is simplistic in its approach (ie that variability reduces the magnitude of a measurement and assuming a definite cut off from micro to macroscale) it suggests that macroscale variance can be quantified through consideration of the variance observed in testing data.

1.4 Scope of the study

Pira's study of the influence of variability on product performance is summarised in Figure 5.

This paper will detail some of the results of a portion of the study. Information is presented on microscale variability, formation smoothness, absorbency and print quality.

Figure 5 **Scope of the study**



2 Macroscale variability in paper

Macroscale variability is the variability in paper product that it is possible to resolve with conventional test equipment. It is therefore the variability that is the most visible, and of general concern.

Although the value of controlling this variability has always been appreciated, the use of Statistical Process Control (SPC) practices has brought this to the fore.

Before the nature and magnitude of variability can be measured, it is important to appreciate the effect of sampling, as all measurements of variability are dependent on the inspection area and validity of the sampling strategy.

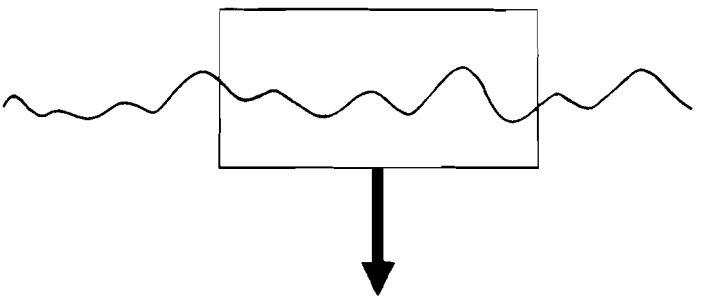
Variability exists at all scales in paper; from a molecular level to kilometres. Macroscale variability is distinguished through consideration of this scale. In this study it is defined as that variability that occurs at wavelengths above that of the inspection area of a given test. Therefore the definition is not based on absolute values, but is dependent on the nature of the test.

As an indication of the expected effect of macroscale variability, and therefore how to quantify it, the following theory is presented.

2.1 The effect of inspection area and windowing function

Imagine a continuous trace of the values of a property in a sheet of paper. For the simplicity of the next stage, this continuous trace is considered to be made up of discrete points at the limit of resolution. A measurement can be considered to be a function of the points within the test area, or 'window'. If this window is d data points long, then the measurement will be a function of the value of the data points (the property) over d values, Figure 6.

Figure 6 *Macro-scale uniformity windowing*



$$M(d,p) = F(v(p),v(p+1)...v(p+d))$$

M (d,p) = F(v(p), v(p+1), v(p+2).....v(p+d))

where:

M (d,p) is the value of a measurement over d data points starting at position p.

v(p) is the value of the property at position p.

The function F() depends on the nature of the property. For example, strength parameters may approximate to minimum function, opacity measurements would tend towards - log (1/d Sum $10^{-v(P)}$)) and many others may approximate to AVG().

As an example a 'filter' of 50 data points in length was applied to a random trace of 1000 data points. The resulting statistics are present in Table 1.

Table 1 **Effect of window filters (d = 50)**

	Maximum	Minimum	Mean	Variance
Trace	99	0	48	3083
Min filter	11	0	2	5
Average filter	59	39	46	2221
Maximum filter	99	91	93	9019

The nature of each of these filters is to weigh the results in a well defined way, and this alters the way the original distribution is interpreted.

The effect of changing the inspection window is summarised in Table 2 (for MEAN filter).

Table 2 **Effect of window size (filter = mean)**

Window size (d)	Maximum	Minimum	Mean	Variance
1	99	0	48	3084
2	87	3	48	2637
4	85	13	47	2430
8	80	25	47	2329
16	68	31	47	2263
32	60	34	46	2195
64	55	38	44	2094
128	54	41	41	1941

As the window is enlarged the variance and range observed in the trace is reduced.

These results were obtained by considering a random trace. When considering a property in paper, a degree of auto correlation is present. Thus, if measurements are taken over small intervals, these effects will be reduced. These observations provide us with an insight into the effects associated with inspection area. These observations are applicable to both on-machine monitoring and laboratory testing.

2.2 Analysis of test results

One complication in the analysis of testing results is that the measured variability is not a direct measure of the variability of the material tested (even after windowing effects have been considered).

The measured variability contains components due to the test method and sampling of the material, in addition to that of the material itself (Figure 7).

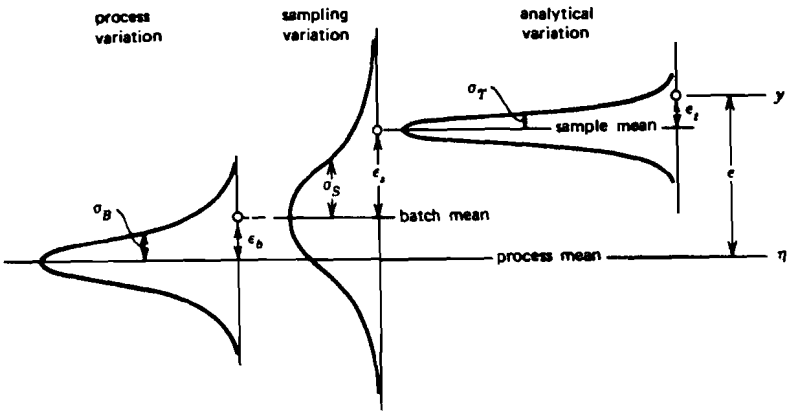
One statistical model of this can be simply written as:

$$E = Et + Es + Em$$

where:

E	is the total measured variation
Et	is the variation associated with the test
Es	is the variation associated with the sampling
Em	is the variation associated with the material.

Figure 7 **Macro-scale uniformity testing strategy**



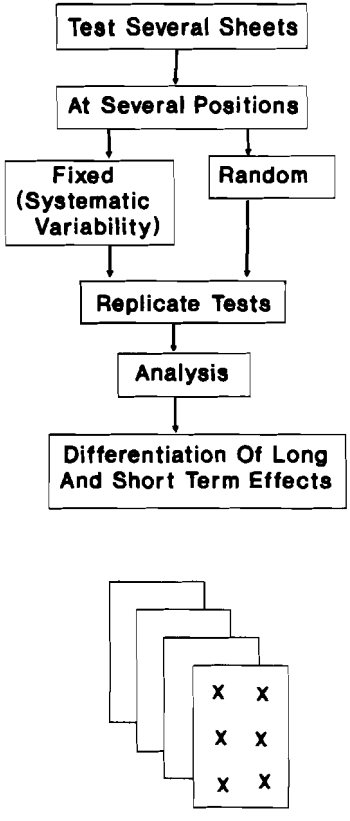
As an example, these errors can be quantified by testing a stack of papers. By replicating the tests, testing at various positions on the sheet and testing several sheets, analysis can provide measurement of variability associated with the test, within each sheet and between each sheet.

This analysis allows the scale at which variability is present in the material to be determined.

Point to point testing on a sheet provides information on the relative small scale macroscale variability that exists in the material (see Figure 8).

If functional characteristics such as jamming of office laser printer is considered, then it is the inter-sheet variability that is the determining factor. This inter-sheet variability originates in cross direction profiles and machine direction drifts but is randomised in slitting and sheeting operations.

Figure 8 **Macro-scale uniformity testing**

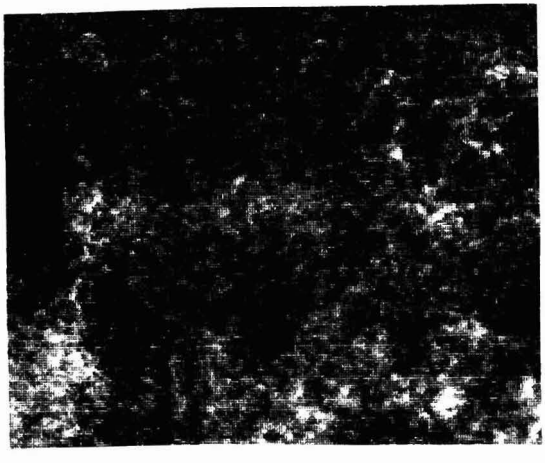


3 Microscale variability in paper

3.1 Microscale Bulk Uniformity (Formation)

The mass density distribution of paper is traditionally viewed as a two dimensional image, the intensity of which being related to the mass at any given point (Figure 9).

Figure 9 **Formation as viewed as mass density**



Although traditionally this has been analysed through visual assessment (by holding the sample up to a light source) modern practices require a more objective, numeric analysis.

3.1.2 Objective

The objective of Pira's work is to establish techniques that can directly measure the uniformity of the structure and generate likely 'Efficiency Indices'. This will assist manufactures to establish the effect that non uniformity is having on their product and provide a

tool to establish the effects of changes to the manufacturing process or raw materials. The outcome of this research is not detailed in this paper.

3.1.3 Imaging

Paper can be imaged by a number of techniques (Table 3). Each has its own associated advantages and disadvantages.

Table 3 **Imaging techniques**

Imaging Techniques
Beta Radiography
X Radiography
Electron Beam Imaging
Optical Imaging

Beta Radiography

Beta radiography as an imaging technique is the traditional technique used in the paper industry. Beta-ray transmission is determined by:

$$I = I_0 \cdot e^{(-Um.W)}$$

where:

I = Measured Intensity
I_0 = Original Intensity
Um = Mass Absorption Coefficient ($m^2.g$)
W = Mass Density ($g.m^{-2}$)

Beta radiography benefits from low internal scatter and a good correlation with the true mass density distribution.

One potential disadvantage of this technique is the lengthy exposure time required for high grammage sheets. The technique using a carbon 14 film source is limited to approximately 150 $g.m^{-2}$ where imaging takes several hours.

X Radiography
Soft X radiography offers the benefits of higher resolution than Beta ray systems. It also benefits from the ability to measure higher basis weights and shorter exposure times as the source potential can be varied to suit the material being imaged.

On the negative side however, the cost of the equipment is higher than for beta radiography and imaging is subject to spatial variations in intensity.

Electron Beam Imaging
The use of electron beams as an imaging source has been discussed. This techniques should provide higher resolution due to the parallel nature of the beams with a greater grammage range than beta radiography.

Optical Imaging
Optical techniques are still favoured due to the low cost and simplicity of the systems. Acquisition time is almost instantaneous, but the measurable grammage range is dependent on the nature of the material.

One feature that must be considered however is that (especially in white grades) the absorption of light is mostly due to scatter, and thus is not representative of the true mass density of the material.

The image analyser measures the amount of material in a sheet through a measurement of light transmittance. If we assume that a certain grammage of material transmits 50% of the incident light, then a sheet of twice that grammage will transmit 25% (50% of 50%), and four times 6.25%.

Obviously transmittance is not a good unit to measure the amount of material present.

The light transmittance of a non scattering material can be written as:

$$I = I_0 \cdot 10^{-OD}$$

Where:

I = Transmitted Light Intensity
I_0 = Incident Light Intensity
OD = Optical Density of the Material

The optical density of the material is the product of its grammage ($g.m^2$) and general absorption coefficient ($m^2.g$).

Therefore for a more meaningful measurement of the amount of material present in an image, the system can be calibrated to read directly in optical density units.

Now twice the material present will give twice the optical density.

This technique is well suited to the analysis of beta radiographs where the image has been produced by non optical means.

The problem with optical imaging techniques is that the optical density of paper does not vary proportionally with grammage.

For a material that both scatters and absorbs light, Kubelka-Munk theory predicts that the transmission can be described as:

$$T = \varnothing / (K+S) \cdot e^{(-\varnothing \cdot W)}$$

where:

$\varnothing = K \cdot (K + 2.S)^{0.5}$

S = Scattering coefficient, caused by refraction at the fibre:air interfaces ($m^2.g$).

K = Absorption coefficient, characteristic of the material ($m^2.g$).

W = Grammage ($g.m^{-2}$)

Therefore the optical density of the sample can be written as:

$$OD_S = 0.4343 \cdot \varnothing \cdot W - \log_{10} (\varnothing / (K + S))$$

It is evident that the optical density is not only dependent of the grammage of the material. Any assessment of the formation of the material by optical techniques will be effected by local differences in the scattering power, for example from fibre contact.

The consequence of this is that care must be exercised when analysing samples where the relative contribution of the internal scattering has changed, for example filler addition, calendering, waxing or dying.

3.1.4 Statistical Processing

There are many statistical methods for describing variability. The objective for selecting a descriptor is to reduce the amount of information required to describe the important feature of that data set. The value of that descriptor therefore is based on whether the "correct" information has been summarised.

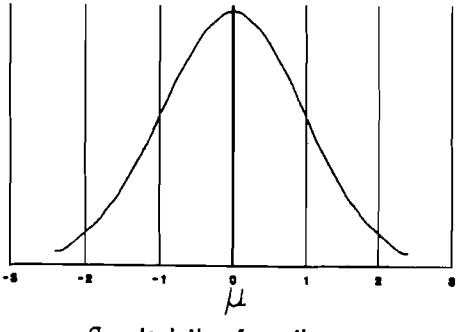
In our study the definition of "correct" is that information which defines the way in which the material behaves, both mechanically and optically.

To assess this, sheets are prepared with different levels of uniformity engineered into them. These are then tested for various physical properties and for uniformity. The correlation between these results is then analysed.

Stochastic Descriptors
Stochastic variability is assumed to have no systematic information.

Population Statistics
If the resulting pixel values are plotted as a frequency of occurrence chart (histogramming) then the nature of the population becomes apparent. Assumptions of normality in the distribution allows the generation of various descriptors of that population (Table 4).

Figure 10 **Normal distribution**



Results are typically quoted as a coefficient of variation where the standard deviation is normalised by dividing by the mean. This indicates how non uniform the material is - but gives no information on the nature of its distribution. It is known that variability present at certain wavelengths have a greater influence than others. More information is required to categorise this information.

Table 4 Population descriptors

Population Descriptors
Mean
Variance
Skew
Kurtosis

Deterministic Descriptors

Deterministic variability is assumed to have systematic information. The resulting processing techniques are either a direct frequency analysis (Fourier) or compute statistics that will be influenced by frequency components in the image.

Fourier Analysis

Fourier analysis is a mathematical technique to decompose a signal (or image) in to a set of sine waves (Figure 11). This procedure can be used to produce a two dimensional power spectra of the image. This plot contains information on the extent of systematic information and its directionality. Conventionally this spectra is transformed in to a wavelength spectra so that the systematic features can be related to objects in the image. Interpretation of the wavelength spectra is then carried out by integrating the curve over set limits, for example 1-2, 2-4, 4-8, 8-16 and 16-32 mm (Figure 12).

Figure 11 **Time series**

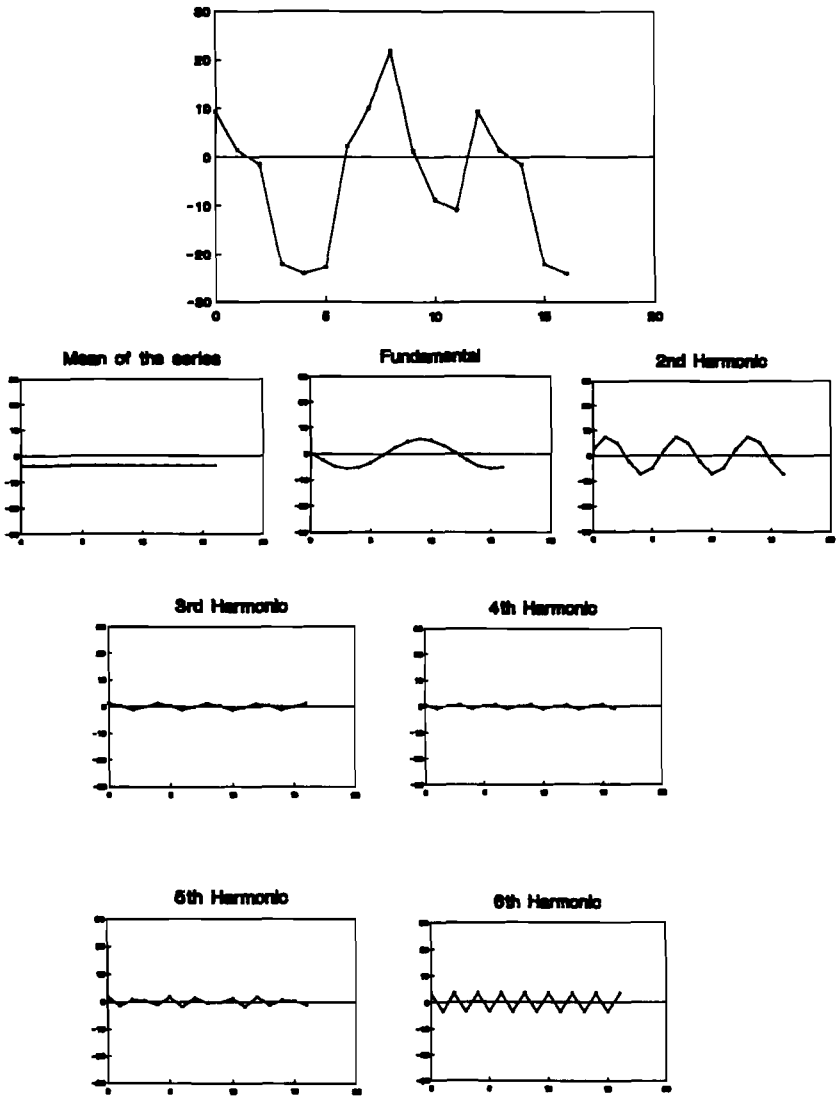
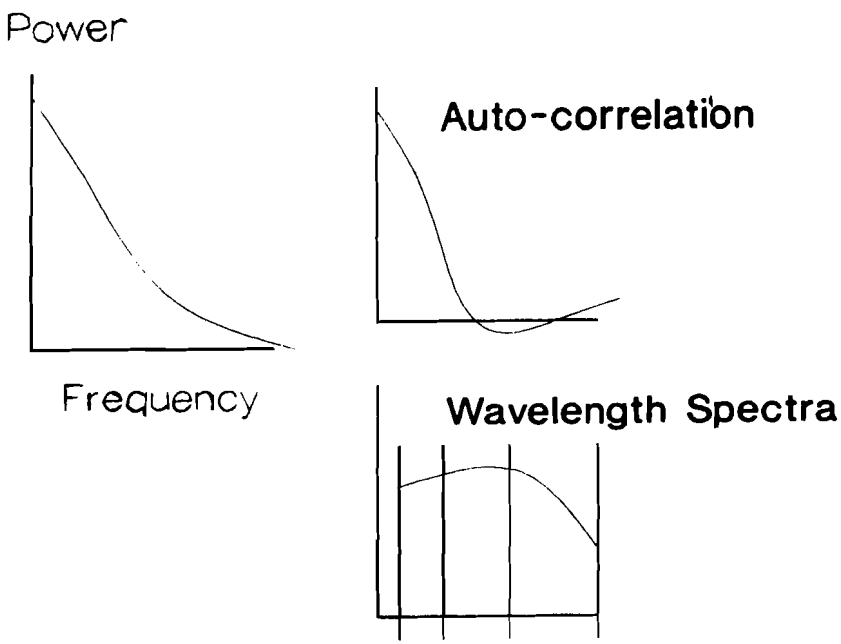
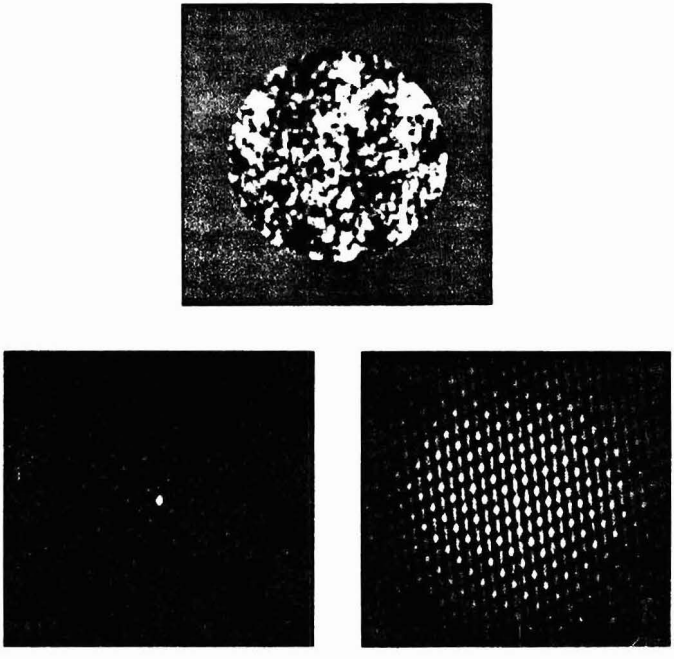


Figure 12 **Fourier analysis**



Other workers have produced the auto-correlation map of the image, which is an effective way of identifying patterns. We have developed this technique to analyse the periodicity of wire marking (Figure 13).

Figure 13 **Wiremark analysis**

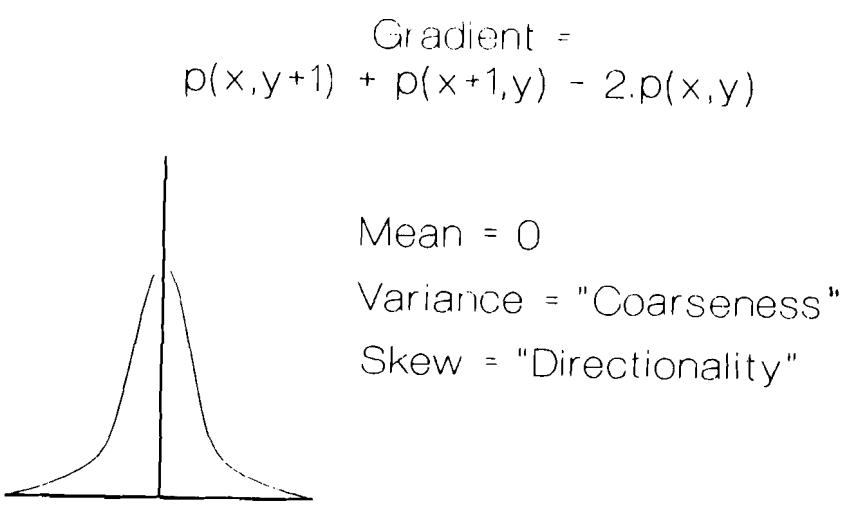


Gradient Analysis

Frequency information also becomes apparent in other techniques, such as gradient analysis.

For this analysis the image is differentiated to identify the slope of the gradients present in the original image (this is achieved using an edge detector algorithm) (Figure 14)). Histogramming this image produces a second image. A uniform image would produce a single vertical line at the origin. The widening of the curve indicates increasing non uniformity and the shape its frequency. Current work is being undertaken to produce a numerical description of this curve.

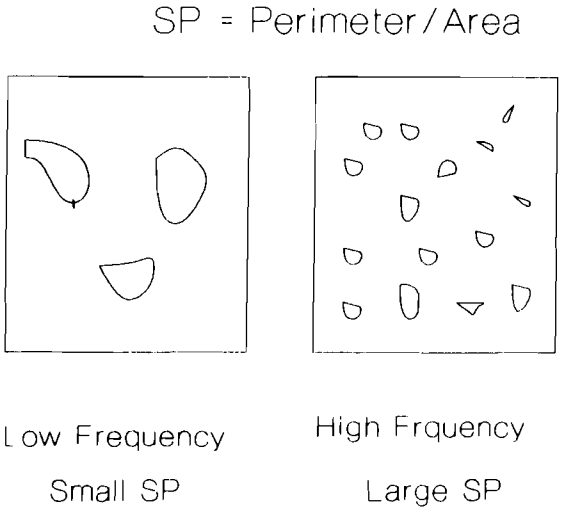
Figure 14 **Gradient analysis**



Specific Perimeter

Another technique used by workers to generate an index of the frequency information in an image is to calculate the specific perimeter. This is achieved by thresholding an image at the median grey level (all pixel values above the mean are set to white and below to black) and analysing the interface between the two phases. If high frequency information is present in the image then, for a given area of inspection, the measurement of the perimeter will be greater (Figure 15)).

Figure 15 **Specific perimeter**



Co-occurence Techniques

Workers in Japan have used Spatial Grey Level Dependency (SGLD) techniques to analyse the texture of the image (Figures 16 and 17). The co-occurence matrix is computed from a defined vector and a series of statistics calculated such as Uniformity, Entropy and Energy.

Figure 16 **Co-occurence techniques**

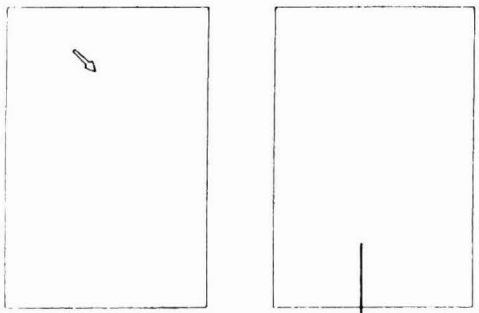
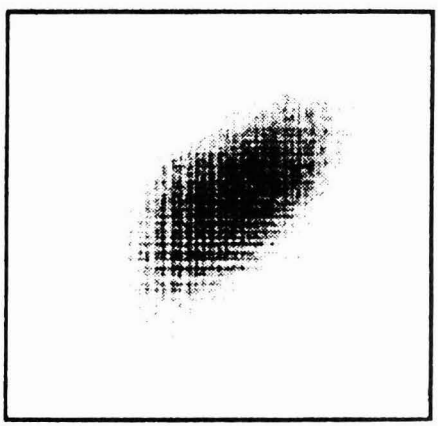
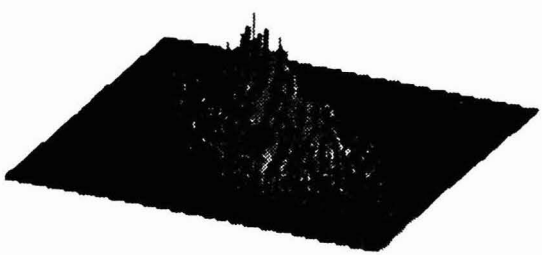


Figure 17 **Co-occurence image**





Each of these techniques have been implemented on an image analyser and are currently being used to generate "Structural Efficiency Indices" to describe the effect of uniformity on product performance.

3.2 Microscale surface uniformity (Smoothness)

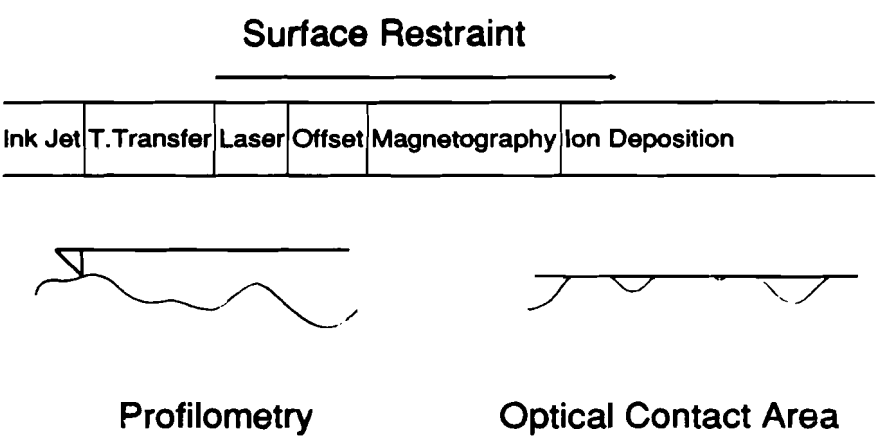
Smoothness measurements on paper products are typically made using air seepage techniques to provide a quick single value to characterise the paper in a quality control environment. While these test methods provide a good indication of changes in smoothness, they are too far removed from the functional requirements of the material to provide sensible diagnostic information.

It is important to appreciate that in many printing operations the surface of the material is under restraint during imaging, and therefore surface compressibility or conformability may play an important part.

Through consideration of the degree of restraint imposed in the imaging zone, the range of current printing techniques can be categorised.

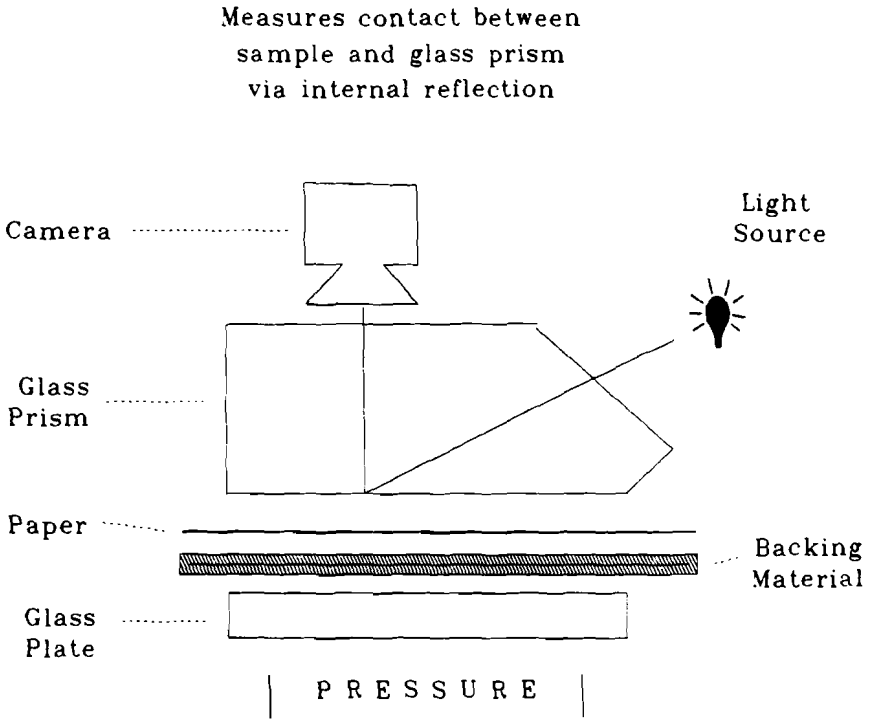
Figure 18 shows a scale of restraint and indicates that for those printing techniques that apply little surface restraint surface profilometry is a sensible measurement technique. The current range of surface profileometry equipment includes mechanical and laser based systems and several machines provide an option for 3d surface reconstruction.

Figure 18 **Surface restraint**



The majority of printing techniques do however impose a significant degree of restraint. To investigate smoothness for these processes a Chapman based instrument has been modified, Figure 19 The Chapman principle measures contact between a paper surface and a glass prism via total internal reflection, Figure 20. Although developed in the 1950's its use has been restricted by the complexity of the analysis of the resulting image, Figure 21. This has been overcome by the use of image analysis.

Figure 19 **Pira smoothness tester**



Variables : Pressure
Backing material

Analysis : Image Analyser

Figure 20 **The Chapman principle**

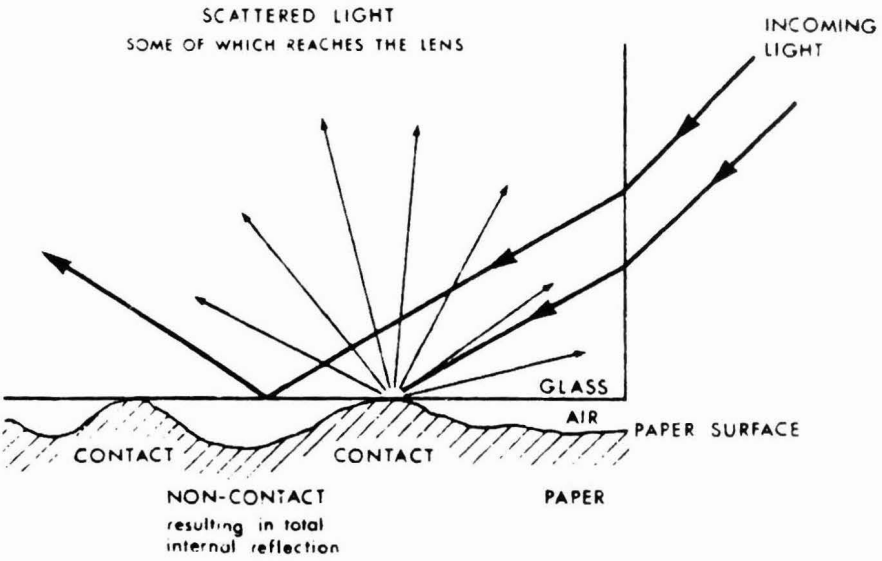


Figure 21 **Surface compressability map**

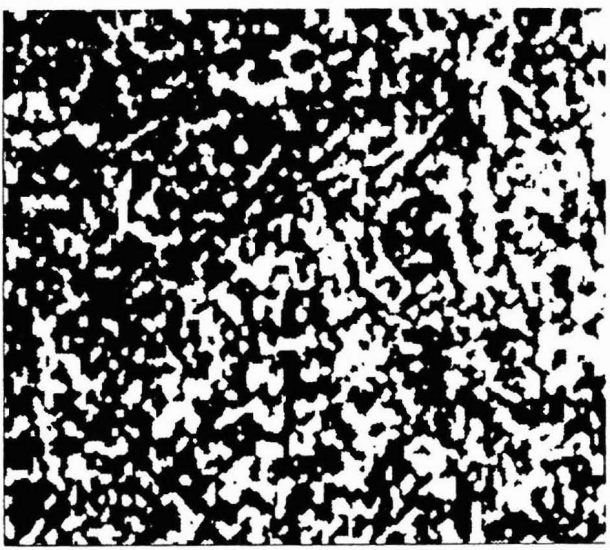


Figure 22 shows the effect of changing the pressure between the paper and the prism. As the pressure is increased the white areas grow, indicating the generation of a greater contact area. This pictorial information can be presented in various forms depending on the nature of the image processing. The simplest numerical information is a measure of the contact area. Figure 23 shows how this changes with pressure and demonstrates for this paper a high degree of two-sidedness. Even analysis of this data is complex as questions such as:

- What is the pressure in the printing process?
- What contact area is required for quality images? need to be answered

Figure 22 **The effect of restraint on the contact area**

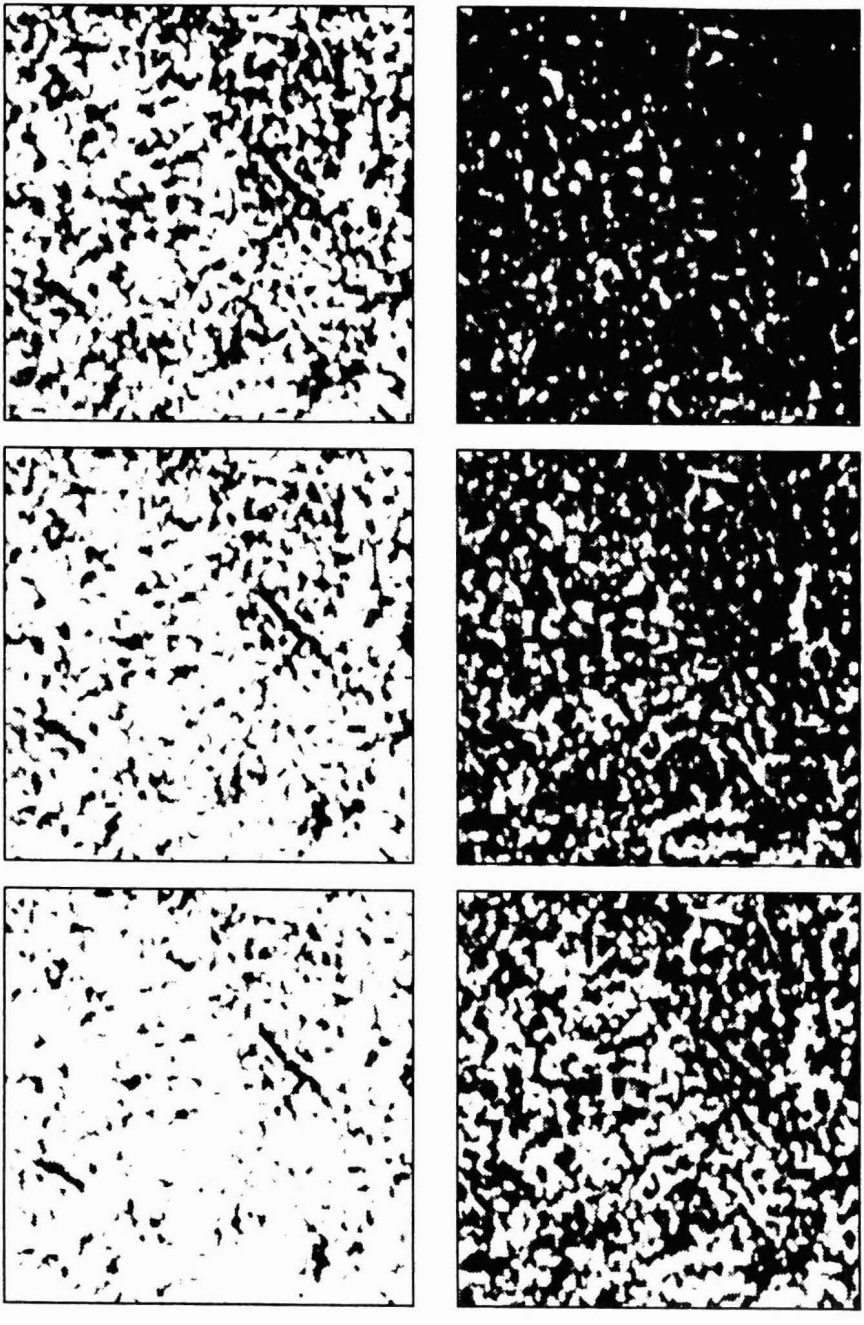
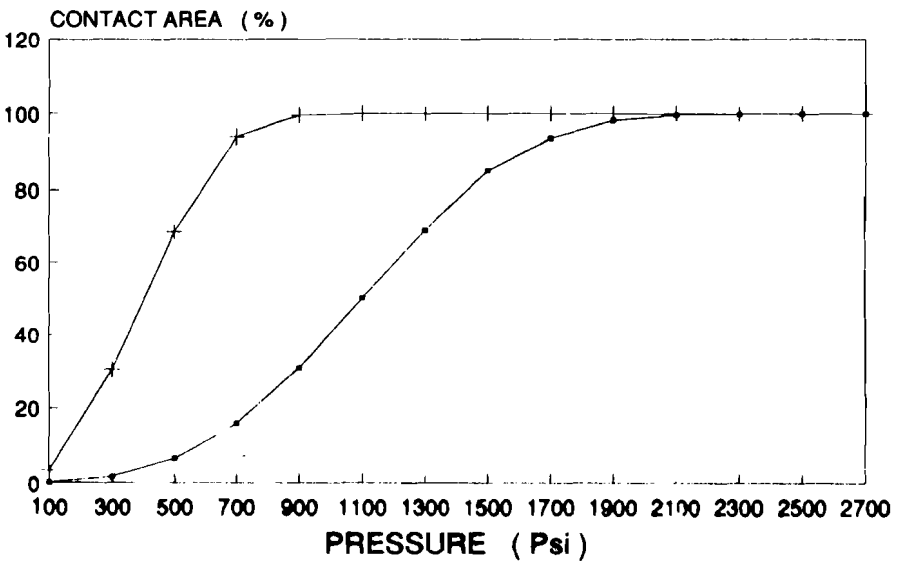


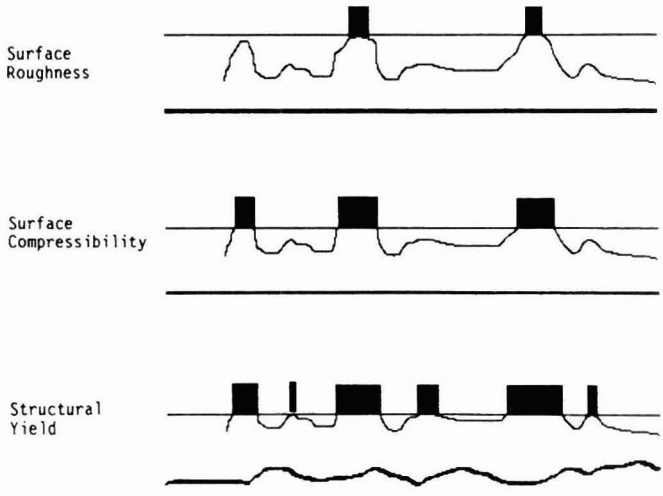
Figure 23 **Contact area versus pressure**



It is perhaps relevant to ask these questions anyway.

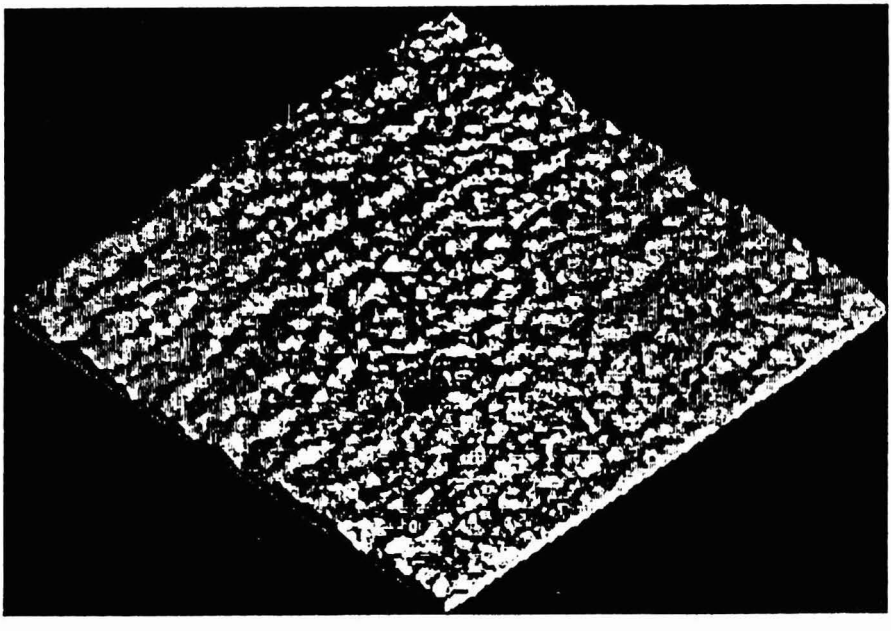
Results obtained from various papers and from papers processed in different ways (eg calendering) we are developing an understanding of paper deformation in a printing nip. We currently believe that 'printing smoothness' is a mixture of surface roughness, surface compressibility, and structural yielding (Figure 24). The structural yielding element can be investigated through measurements of the development of contact area with and without a deformable backing material.

Figure 24 **Paper deformation**



To visualise the effect of the changing surface under compression the image analyser can construct a pseudo surface.

Figure 25 **3d surface compressability map**



3.3 Microabsorbency

In an attempt to study local changes in absorption phenomenon an ink jet printer has been programmed to produce a test pattern of separate dots for latter analysis. The analysis (using an image analyser) is a simplified print quality type test, where the dots are assessed for size and circularity (see section 3.4).

The power of these techniques is being able to correlate information on different facets of the paper. For example the measurement of local changes in absorption may be due to local changes in mass in the sheet (though not directly). The image analyser can correlate the information in a formation map (Figure 26) with the size of the dots (Figure 27). The presence of the cross allows the two images to be superimposed at pixel accuracy using spatial and rotational correlation techniques, (Figure 28).

Figure 26 **Formation map**

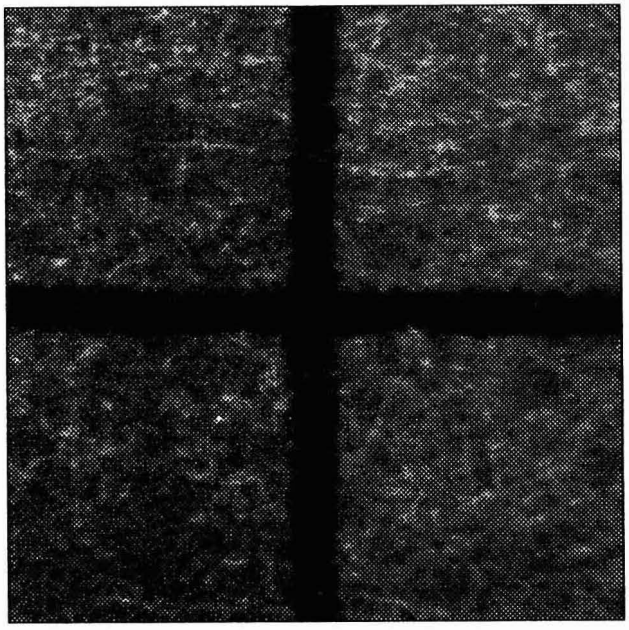


Figure 27 **Dot size**

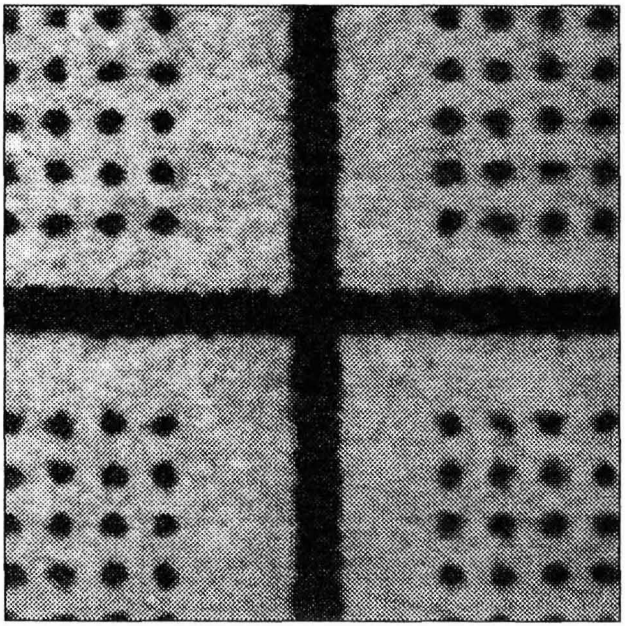
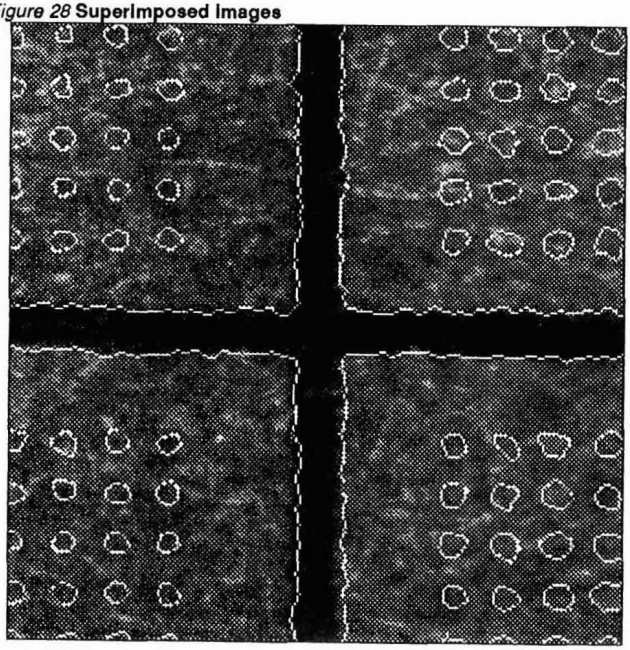


Figure 28 **Superimposed Images**



3.4 Print quality analysis

There are several techniques that can be applied to the measurement of print quality.

Conventionally the print is manually inspected by trained personnel. Though this is undoubtedly the most effective method of assessing the quality of the print from a user perspective, it does not lend it self to the generation of quantitative objective numerical information.

Recently image analysis has been used to measure facets of the print that are thought to be related to the human interpretation of print quality. Examples of these include contrast, edge raggedness and sharpness.

The actual print quality is determined by a number of factors separable into two sections; those due to the printing device itself and those due to the interaction of the paper and the printer.

In an investigation into the affect the paper has on the print quality, indices should be sought that are independent of the printing device used.

Digital printing systems produce output in the form of dots. As basis of the image, all the quality features in that image can be defined from a study the these dots in isolation.

For image data the output is created from dots on all printing processes.

A dot has several properties, measurements must be made of the magnitude of these properties and their variation across the paper surface.

Dot properties

Dimensions:

- Area
- Perimeter
- Circularity
- Raggedness

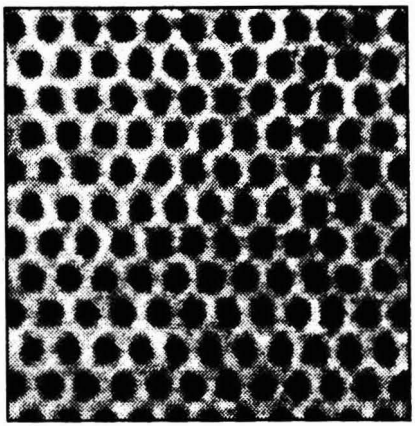
Optical Density:

- Optical Density Profile

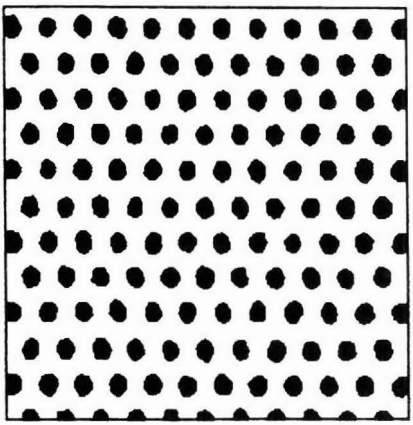
These characteristics can be measured via image analysis.

Once these properties have been quantified, then the additional information on printer resolution allows the calculation of image quality characteristics such as line edge raggedness, coverage and maximum contrast.

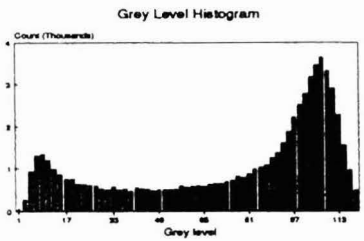
Figure 29 **A typical print quality analysis**

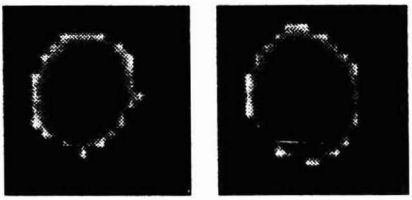


Grey-level image



Thresholded image





Enlarged views of two of the identified dots