Using laser speckle to measure the roughness of paper

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ABSTRACT: Paper surface roughness is an important consideration in paper and board destined for printing. The amount of coating and method of application depend on the roughness of the base paper. We present a method to measure the roughness of the paper based on analysis of speckle pattern on the surface. Images are captured by means of a simple configuration using a laser and a charge-coupled device (CCD) camera. Then, we apply digital image processing using a co-occurrence matrix, providing for a noncontact surface profiling method that can be used online.

Application: This method is an easy way to measure the roughness of paper, even online.

Surface roughness measurement is a central concern in the paper industry. Surface roughness affects paper printing resolution [1,2], and the quest to find new uses for printed paper products and to minimize production expenses requires more accurate paper surface characterization. Because paper product quality control is performed in the laboratory, delays result in controling the final quality of the product. Paper webs run at 30 m/s, and a lag in process control results in a major loss, because the quality between distinct runs varies remarkably.

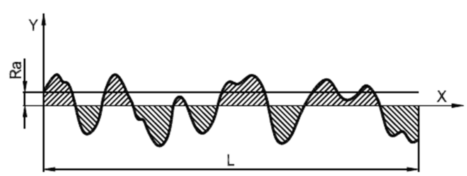
In addition to roughness, printing quality is determined by formation, printing method, porosity, and other factors. Air leak measurement methods have been standardized and are used in the paper industry to rate surface roughness. The air leak rate between a measured paper surface and a specified flat surface is recorded by using specialized pneumatic devices under laboratory conditions. Such a measurement closely corresponds to the roughness of a surface; the greater the air leak, the rougher the surface. The measured roughness is given in micrometers, milliliters per seconds, or seconds, according to Parker print-surf (PPS), Bendtsen, and Bekk methods, respectively. Air leak methods are relatively easy to apply to paper and give stable results, although they measure roughness indirectly, need laboratory conditions, and thus, are unsuitable for on-line use. To measure the actual paper surface topography, it is scanned with mechanical or optical profilometer. These methods provide accurate information on surface topography, but also demand laboratory conditions. Bonham et al. [3] have related imaging topography with air-leak roughness instruments

In our work, the image formed by speckle in the paper surface is considered as a texture, and therefore texture analysis methods are suitable for the characterization of paper surface. The results are contrasted to air leak methods.

PAPER SURFACE ROUGHNESS

Paper surface topography is rated by smoothness or roughness. These two notations are complementary; smoothness meaning the degree to which surface is free from irregularities and inequalities, and roughness meaning degree of unevenness or irregularity over the surface. The relation between paper surface roughness and the internal pore structure of paper cannot be defined in theory. Paper surface consists of a fiber grid, where the uppermost layers are not properly connected to lower layers. Roughness is an important factor in the final printing quality in printing papers, graphic boards, and many packaging boards [4]. Gloss, ink absorption, and the amount of coating required to obtain a desired characteristic are largely determined by surface roughness. A rough base paper needs more coating to cover surface variations.

The average roughness area (Ra) is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length, where L is the length of profile and z(x) is the height absolute value from the reference profile in point x (**Fig. 1**) [5,6].



$$Ra = \frac{1}{L}\int_0^L z(x)dx$$

1. Average profile roughness.

Roughness definition

Paper surface can be characterized as one of three classes of roughness [6]:
- sub-micro roughness at length scales <1 µm
- micro roughness at 1-100 µm
- macro roughness at 0.1-1 mm

Sub-micro roughness is connected to the surface properties of individual pigment particles and pulp fibers. Micro roughness consists of the shapes and positions of fibers in the paper surface. Macro roughness derives from paper formation. All three roughness classes affect paper gloss, and micro and macro roughness also affect paper uniformity. Macro roughness is a dominant attribute in the printing and coating properties of paper [6]. A direct measurement of surface roughness is difficult. Roughness usually is defined as a deviation from an ideal, flat reference plane, where all the surface elements are in the same level [7]. The instruments for surface roughness characterization typically measure the deviation from a flat surface or compare the inspected surface to a reference surface.

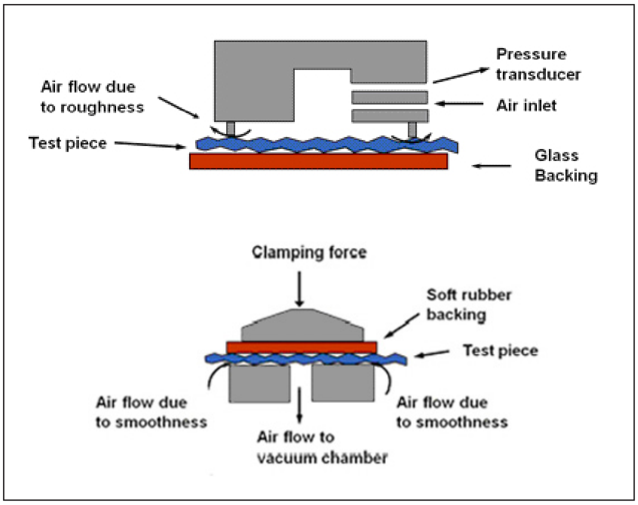
Measuring paper surface roughness

Air leak, optical, and profilometry methods are used to describe surface roughness. Each of these methods provides numerical roughness values from the measured surfaces, but the values may characterize different types or scales of roughness. In the air leak methods, the air that escapes from between a flat surface and the paper surface is measured. A smoother surface adjusts better to a probe; therefore, air leak is slower between the inspected surface and the probe edges. Currently, the paper industry uses air leak methods because they are easy to use and provide results that correlate well with each other.

In optical methods, the surface roughness measurement is based on the interaction between light and the paper surface. One optical method uses the projection of fringes over the surface and calculates the surface roughness from the deformation of the fringes. Another optical approach is to measure light scattering; a rougher surface scatters more light than a smoother one. Finally, laser speckle measurement (the method used in this work) uses the properties of speckle to measure surface roughness.

Air leak methods

Air leak methods currently are the standard test for measuring surface roughness. The air leak rate between the paper surface being measured and a specified flat surface is recorded using specialized pneumatic devices, as specified in ISO (8791-1:1986) "Paper and board: Determination of roughness/smoothness (air leak methods); Part 1: General method." Testing is usually performed using the Bendtsen or Bekk method (**Fig. 2**), as specified in ISO (8791-2:1990) "Paper and board: Determination of roughness/smoothness (air leak methods) Part 2: Bendtsen method" and ISO (5627:1995) "Paper and board: Determination of smoothness (Bekk method)."



2. Setups of the air leak methods Bendtsen (top) and Bekk (bottom).

The standard air leak method dates back to the 1970s and only small adjustments have been made to it since then. Methods differ in the pressure on which the measuring surface is pressed to paper, measured quantity (time, volume), softness of the flat surface, or measured area. Bendtsen roughness is achieved by clamping the test piece between a flat glass plate and a circular metal surface and measuring the rate of airflow between the paper and metal surface, the air being supplied at a nominal pressure of 1.47 kPa. Bendtsen air permeance is measured as the mean airflow through a 10 cm^2 area of the test piece clamped between the flat surface and a circular gasket. Bekk smoothness is again measured by the air leak method but, unlike the previous instruments described, air is drawn across the surface of the test piece under partial vacuum. Smoothness obtained by this method is defined as the time required for 10 cm^3 of air, under a vacuum of 50.66 kPa (0.5 bars), to pass between the surface of the paper and a polished 10 cm^2 glass disc, the paper and disc being held under a pressure of 1 kg/cm^2. The surface width is 13.5 mm, giving a contact area of 1018 mm^2.

Profilometers

Profilometers measure the actual topography of a surface. They have significantly better spatial resolution than do air-leak devices. Profilometers can produce a three-dimensional (3-D) image from the measured surface, in contrast with the air-leak devices, which provide a single value. Unfortunately, profilometers are too slow for online use. Profilometers have a mechanical or optical stylus, which travels on a surface. A mechanical stylus senses the surface by moving across the surface with a very sensitive probe. The spatial resolution is restricted to the stylus size, which is no smaller than 5 µm.

Optical profilometers use a laser as a stylus. In autofocusing instruments, a detector measures reflected laser light focused on the examined surface, and the light reflected from the surface is analyzed by a detector, which measures deviations from the ideal focus position. The advantages of the optical profilometer is that it provides a noncontact measurement and better resolution, but speed improvements are needed.

Speckle

Surface roughness measurement also can be accomplished by a speckle-based instrument. A surface speckle pattern, which is a grainy structure in the space produced by scattered light from a rough surface when illuminated by coherent light, contains rich information about the surface fine geometrical properties, such as the surface roughness [8]. The speckle pattern images taken by an image sensor present texture form. The surface roughness information immersed in the speckle pattern images may be extracted by texture analysis.

Since the invention of lasers, researchers have discussed the relationships between surface roughness and speckle pattern statistical properties as a new method for off-line and online surface measurements. A variety of speckle methods for surface roughness measurements have been developed using different properties of speckle fields and the different setups of optical systems. For instance, surface roughness measurements can be obtained by speckle pattern illumination [8-11], speckle contrast, and speckle correlation [8-11]. Surface roughness measurement by means of speckle pattern illumination is convenient to determine root mean square roughness in the submicrometer range, but the method requires a complicated optical illumination system consisting of a diffuser and a lens. Speckle contrast methods, [12-15], which are based on the first-order statistics of surface speckle patterns, can usually evaluate surface roughness values of Ra <0.3 μm.

Speckle correlation methods [16-19], which are based on second-order statistics, may work on surface roughness Ra of 1-30 μm. However, they often need two speckle pattern images, which may be obtained by changing the incident light angle from the surface, rotating the surface to be measured, or using two laser light beams. Such correlation methods are difficult to use for in-process surface roughness measurement of moving objects, except for using two-laser light illumination.

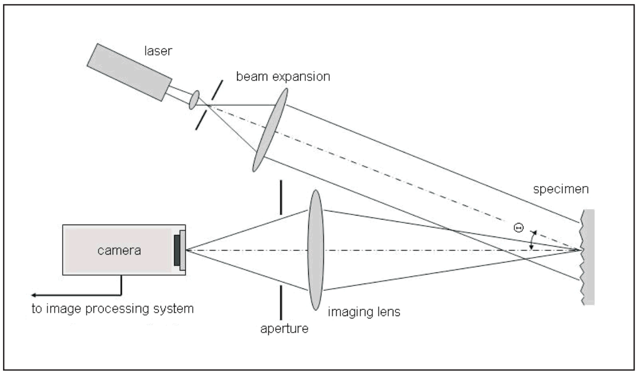
Various researchers have explored surface roughness extraction by means of texture analysis [20-24]. Gadelmawla [23], for example, investigated the surface roughness characterization method using a gray level co-occurrence matrix (GLCM) of surface texture images, which were captured by a visual system. Chang and Ravathur [20,21] characterized surface roughness from the texture images of much roughened surfaces using multiresolution wavelet decomposition. The surface roughness Ra range in their experimental investigation covers 20–60 μm. However, very little literature about surface roughness characterization, directly from speckle pattern texture images using texture analysis, can be found.

For this study, we investigated the statistical properties of speckle pattern texture on the surface of paper from the point of view of computer texture analysis. We present a simple method for characterizing paper surface roughness from a single laser speckle pattern image, which is taken by a simple configuration consisting of a laser and a charge-coupled device (CCD) camera. The surface roughness is extracted by using the GLCM of the speckle pattern texture image and quantized by the features of the GLCM.

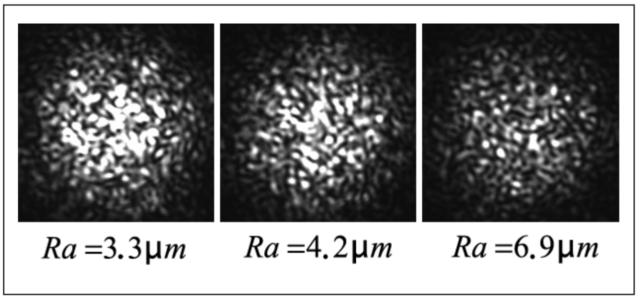
THEORY AND SYSTEM SETUP CONFIGURATION

Figure 3 shows the basic configuration of the setup for surface roughness measurements by means of speckle pattern images. The setup is built with a CCD camera with 756 × 576 effective pixels, with 8 bits per pixel, a 5 mW helium-neon laser with a wavelength of 632.8 nm, and a beam expander, the power of which can be adjusted to avoid the digital camera signal saturation. The field of view is 10 × 10 mm. The camera is located in the sample normal direction. The format of the images was 200 × 200 pixels, with 256 gray levels and a 10 mm diameter speckle pattern. The angle between the incident laser light beam and the normal direction was fixed to be as small as practical to reduce the effect of the direction of surface microstructure in the surface roughness evaluation. In the setup, the angle is 15°. By means of the simple setup, different speckle pattern images from paper surface roughness samples were obtained.

Figure 4 shows three images of the speckle pattern variations for different rugosities. This implies that the speckle pattern texture properties change with the surface roughness, and it is possible to extract the surface roughness from the speckle pattern texture images using texture analysis.



3. The basic configuration of the setup for surface roughness measurements.



4. Speckle pattern variations against the paper surface roughness.

Computation of speckle pattern texture

Information extraction from texture images can be obtained by different texture analysis methods, which are classified into four categories: statistical, geometrical, model-based, and signal processing methods. We investigated the surface roughness evaluation method using the gray level co-occurrence matrix, a statistical method [25]. The GLCM is based on second-order statistics, which deal with the spatial relationships of pairs of gray values of pixels in texture images [26].

The texture image GLCM indicates how often pairs of gray levels of pixels, which are separated by a certain distance "d" and lie along a certain direction "θ", occur in a texture image. In other words, the GLCM method establishes the joint probability density to show the distribution characteristics between pixels with same gray value. The probability measure can be defined as:

$$P(i,j,d,\theta)=\{C_{i,j}|(d,\theta)\}$$

where $C_{i,j}$, the co-occurrence probability between grey is levels i and j, is defined as:

$$C_{i,j}=\frac{P_{i,j}}{\sum_{i,j=0}^{N-1} P_{i,j}}$$

where $P_{i,j}$ represents the number of occurrences of grey levels i and j within the given window, given a certain (d, θ) pair; and N is the quanticized number of grey levels. The sum in the denominator thus represents the total number of grey level pairs (i, j,) within the window, and is normalized [22-27].

For a given direction and offset, we determined the number of times the gray level is repeated. This normalized value is the value of the cell of the co-occurrence matrix. **Figure 5** shows a test image with five gray tones, and **Table I** shows the calculation of the P_{ij} matrix for this test image.

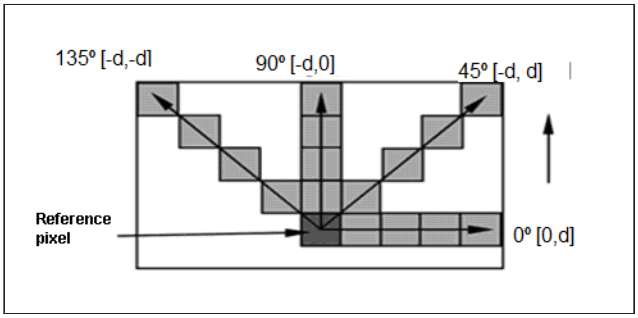
Let an offset d be the distance that separates two pixels whose gray values are i and j, respectively; d = 1 means the pixel pairs are neighboring pixels, d = 2 means pixel pairs are separated by one pixel, and so forth. If giving four angles (directions) of 0°, 45°, 90°, and 135° (**Fig. 6**), along which the pairs of pixels lie, for a fixed offset distance d, we obtain the four matrices P_0, P_{45}, P_{90}, and P_{135}, and can calculate the number of times the gray level is repeated. Table I shows the gray level matrix P_0 with d = 1, as a computational example, where the image size is 5 × 5 mm, with five gray levels [27].

4	4	3	0	0
0	0	0	0	0
1	0	0	2	2
1	0	0	2	2
1	1	3	2	2

5. Test image with five gray levels.

		Neighbor Pixel				
		0	1	2	3	4
Reference Pixel	0	Number (0,0) =7	Number (0,1)=0	Number (0,2)=2	Number (0,3)=0	Number (0,4)=0
	1	Number (1,0)=2	Number (1,1)=1	Number (1,2)=0	Number (1,3)=1	Number (1,4)=0
	2	Number (2,0)=0	Number (2,1)=0	Number (2,2)=3	Number (2,3)=0	Number (2,4)=0
	3	Number (3,0)=1	Number (3,1)=0	Number (3,2)=1	Number (3,3)=0	Number (3,4)=0
	4	Number (4,0)=0	Number (4,1)=0	Number (4,2)=0	Number (4,3)=1	Number (4,4)=1

I. P_{ij} matrix for d = 1 and θ = 0.



6. Offset and direction definition to calculate co-occurrence matrix.

Surface roughness extraction from texture

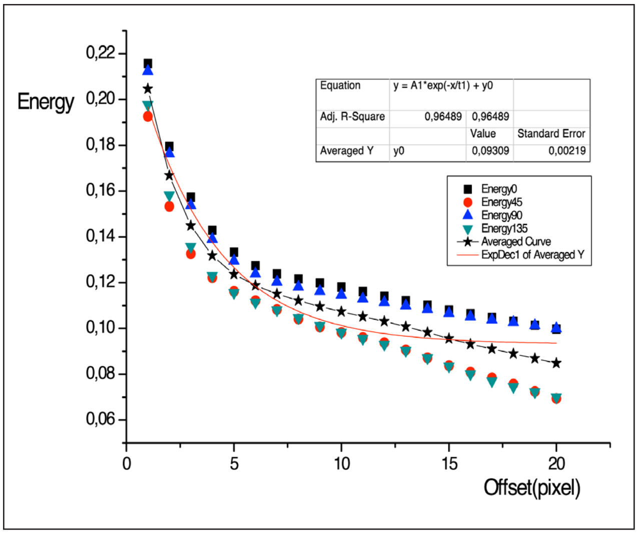
A co-occurrence matrix is capable of texture analysis by using texture features extracted from it. Haralick et al. [25,26] suggested 14 textural features that can be used. Here, we chose three features: contrast, energy, and homogeneity. The contrast feature measures the local variations in the gray level co-occurrence matrix; energy measures the uniformity; and homogeneity measures the closeness of the distribution of elements in the GLCM to the GLCM diagonal.

If $P_{i,j}$ is the normalized co-occurrence matrix N × N, then textural features are defined as follows:

$$\sum_{i,j=0}^{N-1} P_{i,j}(i-j)^2 \qquad \text{(Contrast)}$$

$$\sum_{i,j=0}^{N-1} P_{i,j}^2 \qquad \text{(Energy)}$$

$$\sum_{i,j=0}^{N-1} \frac{P_{i,j}}{1+(i-j)^2} \qquad \text{(Homogeneity)}$$



7. Energy in the four directions, plotted with respect to the offset x, average curve, and curve adjusted with the value $y_0 = 0.09309$.

If we consider the feature energy in the four directions, and we plot its value with respect to the offset d, we obtain the results of **Fig. 7**. If we average the results obtained for the four directions, we can approximate the results by a function given by:

$$y = A1\exp\left(\frac{-x}{t1}\right) + y_0$$

where y_0, A1, and t1 are the parameters that define the function energy of the co-occurrence matrix of the texture.

To be able to quantify the surface roughness from the texture features, our experimental results show that the exponential component parameters of the energy feature have a good relation to the surface roughness in contrast to the other two features. In particular, the parameter y_0, which represents the energy with an offset infinite, has a direct relationship with the roughness.

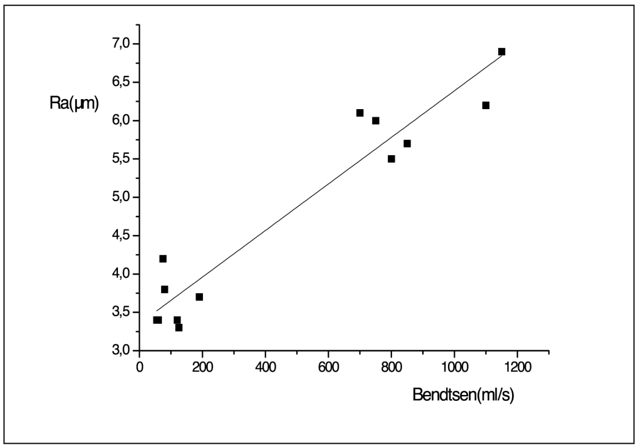
RESULTS

We characterized the roughness of 14 different types of cigarette papers with similar optical proprieties using one optical method (a confocal microscope optical 3-D profilometer operating in confocal mode) and an air leak method (Bendtsen and Bekk) and calculated the y_0 parameter using speckle patterns. The software used to capture and analyze the images of speckle patterns included Intellicam from Matrox Imaging (Dorval, QC, Canada), MATLAB (Digital Image Toolbox) from MathWorks (Natick, MA, USA), and Origin (OriginLab, Northampton, MA, USA). **Table II** shows the results obtained with 14 paper sheets, which include white base paper, yellow base paper, medium porosity filter paper, low porosity filter paper, verge paper, and velin paper.

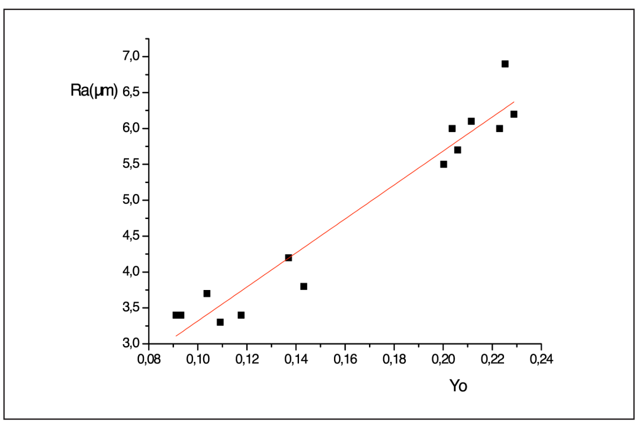
Figure 8 compares the results obtained using the confocal microscope (Ra) with the results obtained with the Bendt-

Sample No.	Ra Confocal µm	Bendtsen (mL/s)	Bekk (s)	Y_0
1	6.9	1150	4.4	0.22522
2	6.2	1100	4.4	0.22881
3	6.1	700	5.4	0.21148
4	6	750	6.2	0.20363
5	6	750	5.6	0.22299
6	5.7	850	9.8	0.20588
7	5.5	800	9.2	0.20018
8	4.2	75	95	0.13699
9	3.8	80	97	0.14317
10	3.7	190	35	0.10370
11	3.4	120	60	0.11762
12	3.4	60	106	0.09309
13	3.4	55	106	0.09112
14	3.3	125	61	0.10913

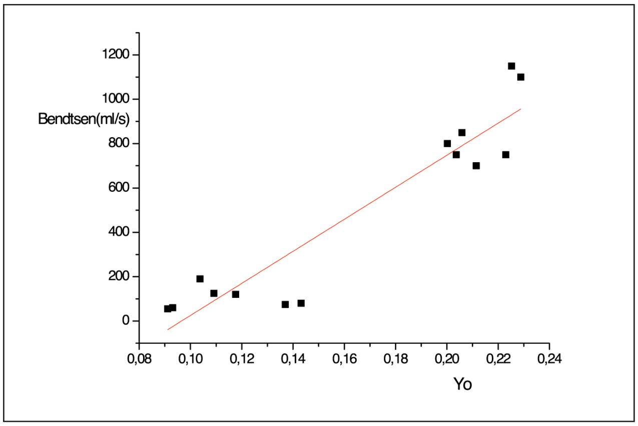
Table II. Results obtained measuring the roughness with a confocal microscope, with the methods Bendtsen and Bekk and using the parameter y_0 obtained from the matrix of co-occurrence of the image of speckle.



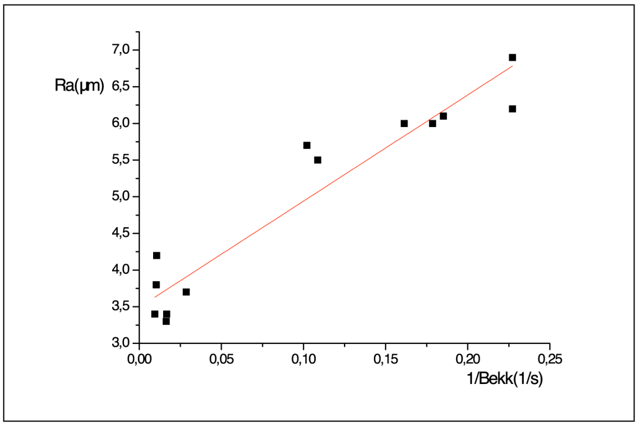
8. Ra using the confocal microscope versus the Bendtsen method (r^2 =0.91).



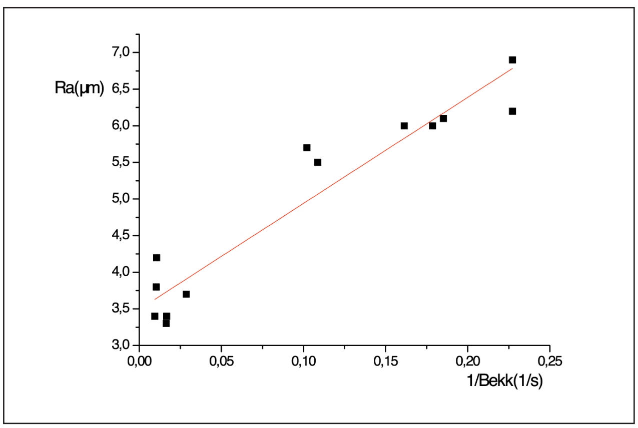
9. Ra using the confocal microscope versus the parameter y_0 (r^2 = 0.93).



10. Bendtsen method versus the parameter y_0 ($r^2 = 0.87$).



11. Ra using the confocal microscope versus the Bekk method ($r^2 = 0.91$).



12. Bekk method versus the parameter y_0 ($r^2 = 0.84$).

sen method. **Figure 9** compares the results obtained using the confocal microscope (Ra) with the parameter y_0. **Figure 10** compares the results of the Bendtsen method versus the parameter y_0. **Figure 11** show Ra using the confocal microscope versus the Bekk method. **Figure 12** shows the results of the Bekk method versus the parameter y_0.

CONCLUSIONS

We have put forward a surface roughness measurement technique through investigating the features of the texture image GLCM of the surface speckle pattern. Many texture features can be extracted from the gray level co-occurrence matrix. In our research, the most used features have been studied with respect to surface roughness. We found that the variation of the feature energy with different offsets is related with surface roughness.

We found a good relation between the measurements of the roughness using a confocal microscope, and air leak methods (Bendtsen and Bekk), and a parameter related with the feature energy of the matrix of co-occurrence for the speckle pattern in 14 surfaces of different papers. We believe that this is a first approximation to the measure of roughness of paper using laser speckle, and although the method does not accomplish the present quality control tolerances, more work must be done to increase the precision to a satisfactory level. **TJ**

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We chose this topic to research because of our interest in speckle optics, and its relation with roughness. This study complements our previous research about paper formation using wavelets.

The most difficult aspect of this research was to find a useful mathematical tool, such as the co-occurrence matrix, to relate with the speckle pattern. One of the most interesting discoveries was the potentiality of the co-occurrence matrix in image analysis.

This research might enable mills to measure surface roughness online. Our next step is to try to improve the agreement of this method with the standard methods Bendtsen and Bekk.

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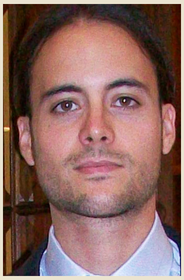

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