Assessing the Surface Structure of Printing Papers under Pressure

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Abstract:
Although a number of paper properties are nowadays determined using measurement technology, printers are still not always in a position to reliably predict the quality of a print. This is due on the one hand to the interaction of paper, printing ink and printing-related parameters and, on the other hand, to the fact that paper properties cannot be measured under practice-oriented conditions in the laboratory. An important fundamental paper property that greatly influences print results is the surface structure of the paper. This quality is also termed smoothness (roughness). Nowadays, smoothness is usually determined in the paper industry using indirect measuring methods. In addition to smoothness, the measurement of printing smoothness is very important, i.e. the determination of the surface structure of the paper under converting conditions. Appropriate measuring instruments have been developed (Chapman tester, FOGRA contact area tester, Pira printing smoothness tester). A substantial drawback of these devices is that they only provide an integral measured value. An existing FOGRA contact area tester was therefore equipped with a high-precision distance measurement system and connected to a digital image processing system. The development of the surface structure as a function of paper deformation under load is available as the result of measurement. This technology was used to measure eight natural gravure papers (SC papers) that had been gravure printed in a large print shop. The results were evaluated by both visualisation and image analysis. The results of smoothness measurement were correlated with the print evaluations. It was established that there is a strong relationship between surface structure, the deformation behaviour of the paper under load and the quality of the printed image. The best correlations were obtained for a newly defined parameter Grad(CA)$_p$.

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The quality of modern print products is influenced by the properties of the printing paper and printing ink on the one hand and by the printing characteristics during the printing process on the other. When producing printing paper for gravure printing, for example, it is not only the choice of raw materials and the papermaking process that have high priority, the surface treatment of the paper (calendering) is also of paramount importance. During the printing process, the paper passes through several moistening and drying cycles and is thus subjected to high cyclic loads. It is the interaction of high-quality paper, optimum printing ink formulation and the high-precision settings of the printing press that ensures good runnability and printability. Paper-induced impairments in the productivity of the printing process and print quality are normally associated with high costs to both the printer and the papermaker. There has long been a demand to reliably predict runnability and printability prior to the printing process on the basis of in-depth paper characterisation in order to eliminate or at least reduce such costs.

Although it is currently possible to determine a number of paper properties using measurement technology, it is not yet possible to reliably predict the two complex properties due, on the one hand, to the above mentioned complexity of the printing process itself and, on the other hand, due to the fact that paper properties cannot be measured under practice-oriented conditions in the laboratory. An alternative means of evaluating printing quality is currently to make test prints or small-scale print runs and then evaluate the resulting prints either by visualisation and/or image analysis. This approach also entails technical outlay, however, and therefore tends to be expensive. Moreover, it does not always produce optimum results so that in-depth paper characterisation still rates highly. (**Fig. 1**).

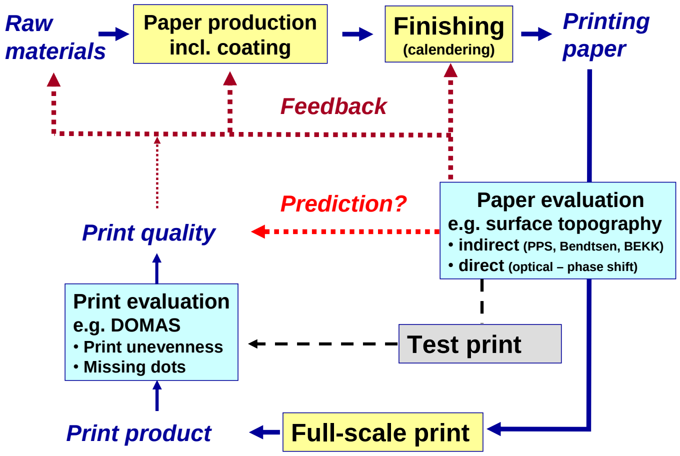


Fig. 1: Problem definition

One important fundamental property of paper that greatly influences the print results is the surface structure of the paper. This quality is also termed smoothness (roughness). Smoothness constitutes a mechanical property and should not be equated with surface gloss (which is an optical property), although certain relationships between both parameters are evident, especially in the case of natural papers (Böck, Schäfer, Zerler, 2004).

A number of smoothness measuring methods have gained market acceptance in the course of time and are generally subdivided into direct and indirect methods. The direct methods attempt to describe the surface geometry directly, whereas the indirect methods provide an equivalent parameter for smoothness that correlates with the surface, but which in turn is influenced by other parameters to a greater or lesser extent.

Nowadays, smoothness is usually determined in the paper industry using indirect measuring methods. It can safely be assumed that in future this process will be superseded by direct smoothness measuring methods. Besides smoothness, the measurement of printing smoothness is also very important, i.e. the determination of the surface structure of the paper under converting conditions. Appropriate measuring instruments (Chapman tester, FOGRA contact area tester, Pira printing smoothness tester) have been developed that make use of the structure-induced difference in reflection behaviour of a paper pressed against a glass prism. A substantial drawback of these devices is that they only provide an integral measured value.

The following table provides an overview of the smoothness measurement methods that exist in the paper industry.

Tab. 1: Principles of roughness determination (Volk, 1970)

Indirect methods	Direct Methods
without measuring pressure	
- Air leak instruments (Parker Print Surf, BEKK, Bendtsen) - Friction tester	- Laser profilometry - Digital strip projection
with measuring pressure	
- Gloss meter - Capacitive instruments	- Mech. sensing profilers - Contact area measurement

Within the scope of this research project, eight natural gravure papers (2 SCA papers, 2 SCB papers, 4 improved newsprint papers) that had been gravure printed in a large print shop were measured. The results were evaluated by both visualisation and image analysis. **Tab. 2** compiles some basic properties as well as the results of the print evaluations.

The full-scale prints were evaluated visually by comparing pairs of prints with respect to the following complex parameters: overall impression (Total), print quality in areas of low coverage (missing dots – MD) and print unevenness in solid areas (PU). The resulting paired comparison index is higher, the better the print quality of the sample is. Furthermore, the samples were measured using the DOMAS image analysis system which consists of a variety of modules for print product evaluation. This makes it possible to analyse halftone dots. The printing parameter characterised as "DOMAS-MD" provides the number of missing dots / cm^2 in the examined sample. In addition, the print unevenness in solid areas was examined by power spectrum analysis (PSA) based on structures contained in the printed image (DOMAS-PU). The result is lower, the more uniform the printed image of the sample is. The latter applies as well to the formation index (FI) which DOMAS also analysed.

Tab. 2: Paper grades, properties and printability

No.	G	m_A	ρ	FC	FI	Print quality				
		g/m^2	g/cm^3	%	(PSA)	Visual – Pair comparison index			DOMAS	
						Total	MD	PU	MD	PU
A	INP	51.5	1.01	35.0	415	60	20	44	5.06	31.6
B	INP	51.8	1.08	35.1	367	116	120	184	2.31	16.6
C	SCB	51.8	1.04	32.1	358	80	168	88	1.69	27.4
D	INP	52.0	1.06	34.9	400	60	16	8	6.44	35.8
E	INP	52.1	1.11	35.9	360	72	140	80	1.38	29.6
F	SCB	52.2	1.13	37.8	221	156	120	180	1.25	20.9
P1	SCA	55.9	1.19	38.6	229					
P2	SCA	55.3	1.18	37.3	268					

G	Grade	Total	Overall evaluation
FC	Filler content	MD	Areas of low coverage
FI	Formation index	PU	Print unevenness

A large group of smoothness measurement methods that are well established in the paper industry include air leak instruments. These instruments measure by indirect means, operating according to the principle that a certain airflow will pass between a flat surface of specified shape and a sheet of paper under defined proof conditions. The rate of the resulting volumetric flow is directly dependent on the flow resistance and thus on the roughness of the paper surface. An extensively used representative of this measurement principle is the smoothness sensor according to Parker Print Surf (PPS) which reports roughness in the micrometer range.

All air leak instruments have a common drawback, i.e. that a more or less large amount of air can penetrate vertically into and pass through the paper sample, thus falsifying the results of measurement. The error is dependent on the thickness, porosity, compressibility and the smooth of the sample itself. In addition, this measuring technique does not allow the number and magnitude of surface deviations to be differentiated, although these parameters are also important for printability.

Fig. 2 compiles both printed image evaluation parameters obtained by image analysis. It reveals the smoothness values according to Parker Print Surf. It is clear that there is no direct correlation between the PPS values and the printed image evaluations.

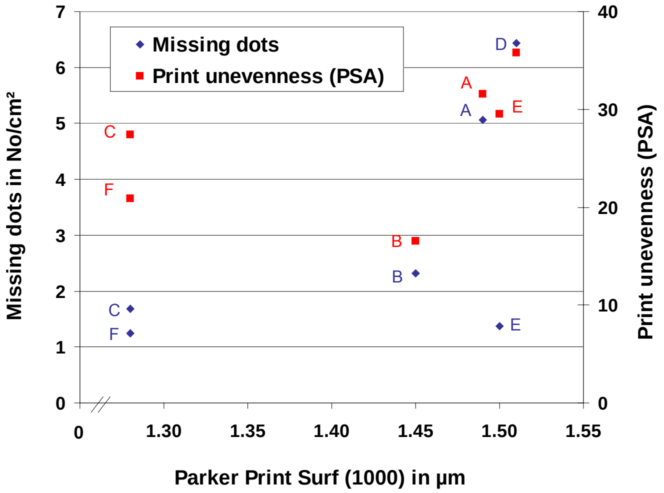


Fig. 2: Printability - Parker Print Surf Assessment

The above mentioned practice-oriented determination of smoothness is responsible for the divergence between the results of smoothness measurement and the results of printability.

The FOGRA optical contact tester has existed for several decades and is suitable for evaluating the surface structure of papers under load. An existing FOGRA optical contact tester was equipped with a high-precision distance measurement system and connected to a digital image processing system. This made it possible to obtain additional information about the reaction of paper volume and paper surface above and beyond the integral quality parameters of the contact area that have long been traditional in the paper industry.

The simultaneous digital measurement of the contact area, the pressure applied, the deformation of the paper and the synchronised detection of contact area images (greyscale images) make the development of the surface structure in the form of the contact area as a function of the paper deformation under load available as a data-image matrix. This database allows paper compressibility to be calculated based on the thickness reduction as a result of load on the one hand (**Fig. 7**). On the other hand, the database provides information relating to the speed and uniformity of the reaction of the paper surface during the printing load based on the spatial coordinate-dependent contact area values. **Fig. 3** shows a basic schematic drawing of the modified FOGRA optical contact tester.

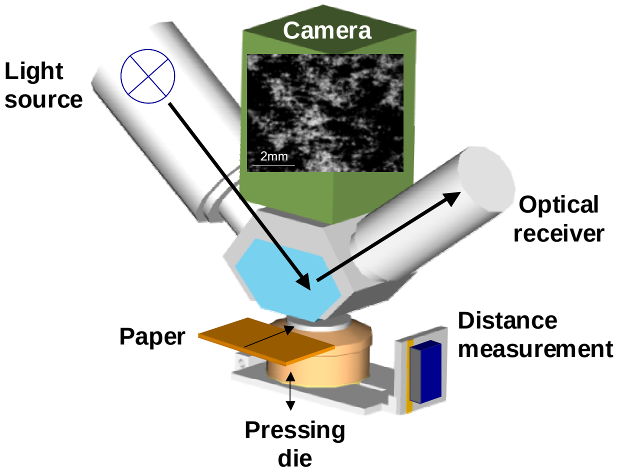


Fig. 3: Measurement System

During the measurement process, a pressing die presses the paper sample vertically against a glass prism. The total number of points of contact is then counted. The number of points of contact will be higher, the softer and smoother the paper sample is. One speaks of optical contact when the gap between the glass prism and the paper sample is equal to or less than half the wavelength of the light. In physical terms, this means a disruption of total reflection and thus a drop in the signal being measured. This is determined by a photoelectric receiver as the amount of light measured at the angle of total reflection. The contact area, expressed in per cent, includes all those areas in the sample that are in optical contact with the glass prism based on the total surface area measured. The measuring set-up makes it possible to look at the measured surface in a vertical direction from above. When viewed in this way, the observer sees the contact areas as bright regions and the non-contact areas as dark regions (Brune, Haller, 1968). The integrated optical distance measurement system functions in a contact-free manner and makes it possible to determine paper deformation with a resolution of equal or greater than 20 nm.

Fig. 4 shows the results of conventional contact area measurement that were obtained for the eight gravure papers. The results are shown separately for the top and bottom sides under a maximum pressure of 5 MPa. The measured data make it possible to classify the papers in three different paper qualities.

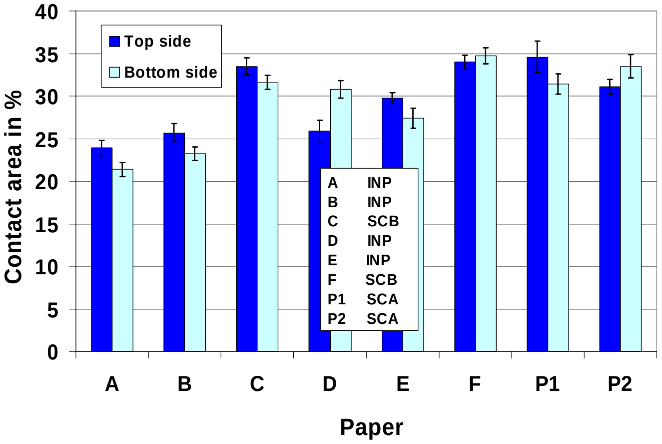


Fig. 4: Contact area of gravure papers

Proceeding from an unloaded (unstressed) paper sample whose surface topography is being determined by a non-contact optical measuring system, the application of pressure can be envisaged as follows (**Fig. 5**).

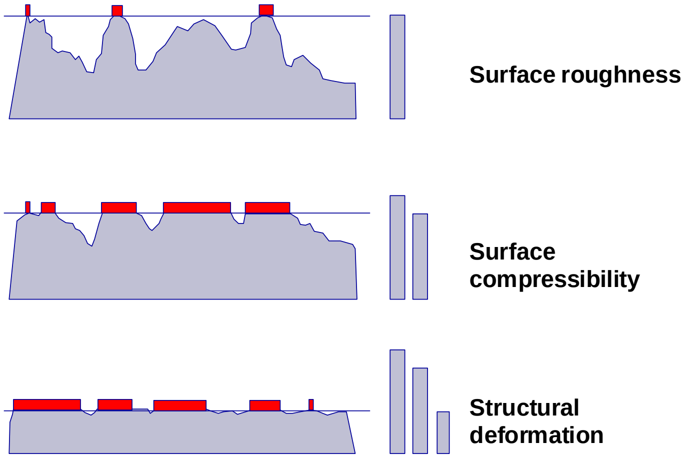


Fig. 5: Types of deformation

First of all, particularly high peaks on the paper surface are flattened, as evidenced by the appearance of individual points of contact (bright pixels) in the contact area images. As pressure continues to build up, islands of confluent contact areas form. This in turn causes material to be displaced from the peak areas into the surrounding valleys. Depending on how well the surface can be deformed, the contact area will be observed to increase either rapidly or somewhat more slowly (surface compressibility). Surface compression proceeds together with the structural deformation of the paper sample as a whole (structural deformation). Once maximum pressure has been attained, it is maintained at a constant level. This causes the plastic paper deformation to continue, thus resulting in a measurable reduction in thickness and an increase in contact area.

Fig. 6 shows by way of example the time-dependent progress of paper deformation for three of the sampled papers. The vertical line at time t = 3.6 s in **Fig. 6** indicates when the maximum pressure of 5 MPa is attained. Subsequent plastic deformation can be demonstrated by increasing the contact area (visually by lightening up the contact area image) for the paper surface as well as by continuously compressing the entire paper sample.

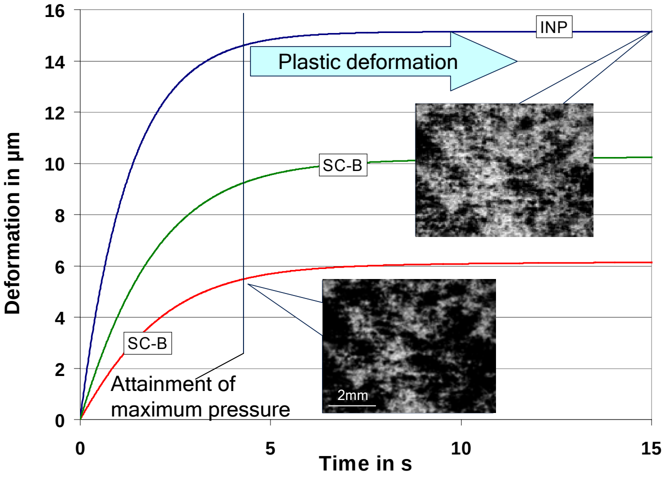


Fig. 6: Deformation as a function of pressure and time

Standardising the value of thickness reduction at time t = 30 s to the starting thickness of the paper sample produces paper compression in the form shown in **Fig.** 7. The paper compression values arrange themselves neither according to the paper grade (SC-A, SC-B, improved newsprint) nor according to their thickness or pore volume. Hence, the individual production conditions must be investigated taking the raw material composition of the individual papers into consideration.

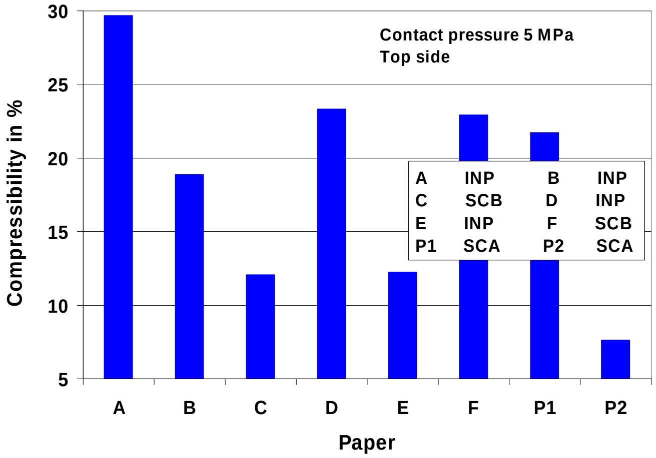


Fig. 7: Compressibility of gravure papers

Fig. 8 shows contact area development as a function of paper deformation.

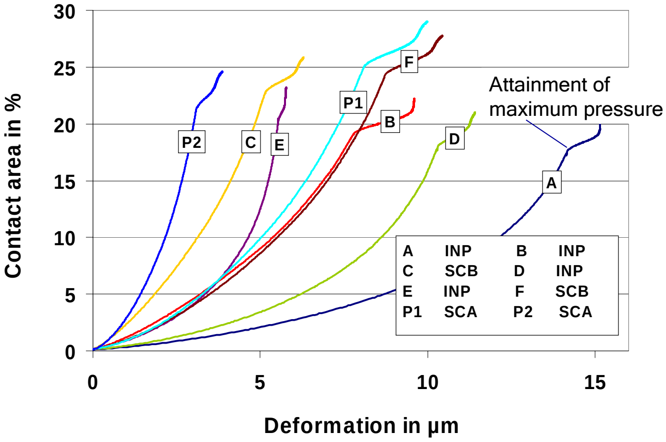


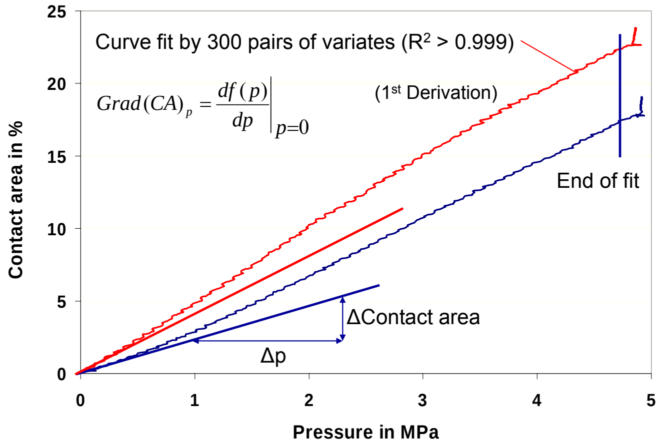
Fig. 8: Contact area as a function of deformation

After a rapid increase in contact area and deformation until maximum pressure is attained, the curves then pass into an area in which the contact area develops in almost linear fashion as deformation increases. The final portion of the curve is characterised by a faster increase in contact area.

In the case of papers A, B, D, E (improved newsprint papers), the deformation that occurs in the third segment is so marginal that, almost without exception, paper flow reflects the increase in contact area. The SC papers reveal greater increases in deformation in this region. It is assumed that the surface of the SC papers has a greater deformation potential (more flexible fibres) due to the greater proportion of virgin fibres in the SC papers.

Although this semi-statistical analysis of the deformation processes on a time scale of seconds is of great interest in understanding the reaction of paper as a whole, it is insufficient to make reliable predictions about the phenomena that occur in the surface structure in the printing nip, since it must be assumed that the time of passage is less than 5 ms in this case. In order to approximate this time response, the functional relationships between contact area (CA) and pressure (p) as well as contact area and overall paper deformation were described mathematically based on measured data and then processed analytically.

The first derivation at location p = 0 MPa of the contact area development over pressure is defined as the parameter Grad(CA)$_p$. It describes the initial reaction of the paper surface during pressure build-up (**Fig. 9**).



Grad(CA)$_p$ initial reaction of the paper surface to pressure

Fig. 9: Definition of the parameter Grad(CA)$_p$

Fig. 10 expresses the parameter Grad(CA)$_p$ that was determined for the eight gravure papers. The differences in paper grades (improved newsprint vs. SC) virtually cancel each other out. More intense reactions of the surface to the pressure build-up are observed in papers C, E and F.

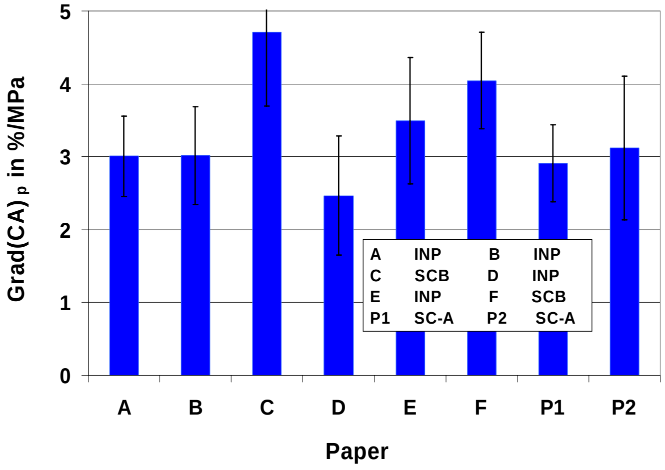


Fig. 10: Grad$(CA)_p$ of gravure papers

The production print trials provided evidence that paper surfaces with a high Grad(CA)p value (high surface reaction potential) exhibit good printability in regions with low area coverage (few missing dots) (**Fig. 11**).

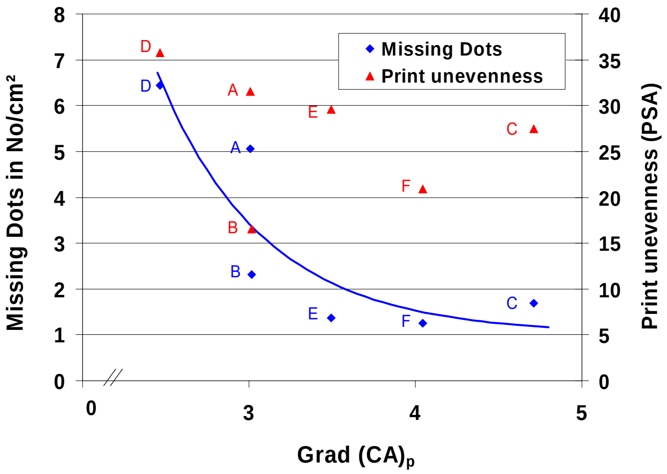


Fig. 11: Missing Dots and print unevenness as a function of Grad$(CA)_p$

Print unevenness in full tone, in addition to the number of missing dots, is another measure of print product quality. No statistically significant correlation could be found between unevenness and surface structure and paper compressibility, respectively. The results of print unevenness that are also shown in **Fig. 11** merely reveal a declining tendency with increasing surface reactivity of the papers. In view of the large number of colours that can be used to print solid areas, the effect of the surface structure on the print results is not as predominant as in the case of low area coverage. Properties such as penetration behaviour, porosity, formation and the like are of greater importance for this printability parameter. Additional in-depth studies aimed at more precisely describing the complex interactions that occur are already in the pipeline.

The formation of additional gradients was able to demonstrate that the ratio of surface structure change to overall compressibility should be large, and the overall compressibility at a given pressure should be small as a prerequisite for a good printed image (few missing dots). This means that surface deformability is much more important for the print results than compressibility. The demands for a "soft and smooth" paper for gravure printing must therefore be upheld, although the demands must apply to the surface structure now more than was the case in the past.

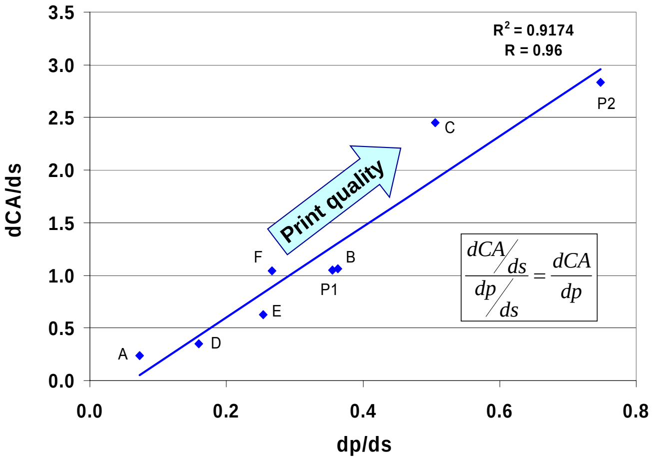


Fig. 12: Initial reaction of paper to pressure

The uniformity of the paper surface and the changes that occurred were evaluated by power spectrum analysis based on the contact area images. This involved determining an index value which was lower, the more uniform the greyscale image was. A completely black image (no contact area) and an entirely white image (100% contact area) define the limit values and have an index value of zero.

Beginning with a black image (no paper contact), the proportion of bright image areas (points of contact) increases as the pressure increases. This corresponds to an increase in unevenness and thus a higher index. As the pressure curve progresses, the index passes through a more or less pronounced maximum, reaches a maximum pressure value, after which it levels off at a plateau value. An exact interpretation of the image sequences will follow in subsequent studies.

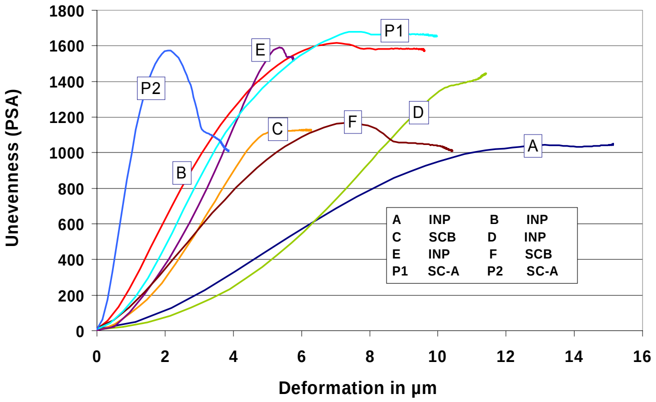


Fig. 13: Unevenness parameter as a function of deformation

Literature Cited

Böck, A., Schäfer, W., Zerler, D.
2004 „Prüfung von Papier, Karton und Pappe“ (Schriftenreihe der Papiermacherschule Gernsbach), Band 5, 3. Auflage

Brune, M., Haller, K.
1968 „Das FOGRA-Kontaktanteilmessgerät zur Glättemessung an Papieren“, Wochenblatt für Papierfabrikation 96; pp 731-736

Volk W.
1970 „Überblick über die Glättemessverfahren“ Wochenblatt für Papierfabrikation 98; pp 45-51