Journal of Imaging Science and Technology® 55(2): 020501-1–020501-10, 2011.
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Effect of Different Coating Amounts on the Surface Roughness and Print Gloss of Screen Coated Offset Prints

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Abstract. *The surface topography and the corresponding microstructure of the print surface have a significant influence on the type and amount of the reflected light, whose distribution influences in turn the final appearance of the printed sample. Surface roughness of glossy coated paper with different amounts of UV coatings was tested by atomic force microscopy and scanning electron microscopy to correlate with the measured corresponding print gloss. To assess the surface topography, surface roughness characterization and fractal analysis were performed. For the overprint coating, three different screen stencils were used to regulate the coating amount applied onto the printed surface. The measurement showed that the amount of the applied coating influenced significantly the surface roughness parameters as well the measured instrumental print gloss. © 2011 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.2011.55.2.020501]

INTRODUCTION

Coatings used in the graphic arts industry have evolved from a simple protective layer to a value added design element which enhances the visual and tactile properties of the printed products. In sheet-fed offset, there is a growing tendency for presses to be fitted with coating units since the value of the print can be significantly increased by applying a coating. The coating on the offset print can be applied through a special online coating unit or via an offline coating unit which may be equipped with a roller system similar to offset printing units, or with a screen printing type stencil system. In order to achieve a more attractive visual appearance, it is necessary to enhance the surface quality with a coating material because a much greater degree of gloss can be achieved with coating than with the printing inks alone.[1] Gloss is the attribute of surfaces that causes them to have a shiny or lustrous appearance, defined by Hunter and Harold.[2] On the other hand, gloss may also be defined as the mode of appearance by which reflected highlights of objects are perceived as superimposed on the surface due to the directionally selective properties of that surface.[3] Some authors[4,5] defined gloss not just as a material property but as a group of visual effects produced by properties of the underlying material. Gloss appearance as a multidimensional phenomenon was and is an intriguing topic to investigate. Researches in the past and recent years have been directed to finding adequate methods to correlate visual and instrumental methods to quantify the complex topic of gloss quality of surfaces.[6,7] The visual gloss evaluation is often based on assessment by a panel of trained judges which perceptually evaluates the samples. CIE[8] and other authors[9] proposed several visual forms of visual gloss forms which are mainly based on the previous work of Hunter.[10] The method for the visual evaluation of gloss between surfaces of similar appearance is standardized by ASTM D4449-08.[11] Nevertheless, there is a constant problem with the observers to always correctly interpret the several proposed visual gloss types. Some authors[12,13] found failures in material constancy under different illuminations for visual gloss evaluation, and this research area is open for new solutions and results. There is much research conducted for number of materials especially in terms of visual gloss and lightness for different surfaces to define these ambiguities.[14,15]

One difficulty in studying the perception of materials is that light interacts with surfaces in a complex way. As a consequence, it may be difficult for the visual system to estimate surface-material properties independently of one another and of illumination and viewing geometry.[16] In the past several years, there has been evidently an effort to characterize gloss by instrumental methods,[17–19] as well as its influence on the other reflection properties.[20–22] There are several kinds of instrumental gloss measurements: one and probably the most commonly used is to measure the specular gloss, that is, the specular reflectance of a specimen relative to that of a reference standard (ASTM D523-89).[23] However, in essence, what the gloss numbers quantify is how well a material scatters the light incident upon it into the specular direction. The result is often interpreted as a gloss quality indication; usually the higher the gloss value is, the better the product or other customer perception is,[24] although a moderate gloss level is preferable for a large number of products. For these printed products this type of gloss meter gives no information about the gloss quality other than whether or not the desired mean gloss level is met.[7]

Depending on the level of surface topography and/or inhomogeneities in the bulk of the material, a fraction of the incident light will be scattered into directions other than the specular. Such mechanisms will contribute to the reduction of the gloss numbers of such materials.[25] The other kind of measuring techniques include the reflection haze and the distinctness-of-image gloss, in addition to specular gloss

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accepted for publication Nov. 22, 2010; published online Feb. 25, 2011.
1062-3701/2011/55(2)/020501/10/$20.00.

(ASTM E430-91). Nevertheless, the limits of this measurement have been recognized a long time ago by Harrison,[26] and the present tendency is to exploit the bidirectional reflectance distribution function (BRDF). The BRDF, however, is a function of five variables, and its measurement remains a difficult and time-consuming task;[6] hence, specular gloss meters remain most accessible to objective measurements in the industry. The ASTM D523-89 standard was improved and subsequently standardized as ISO 2813:1994.

Surface properties that affect our impression of gloss are influenced by the substrate material, surface structure, smoothness, roughness, texture, and degree of transparency. Some recent studies showed that the printed surface topography in offset printing is formed through the process of uneven surfaces due to ink transfer, which is leveled out over time, thus yielding a printed surface topography consistent with the original paper surface topography.[27–29] Another conclusion derived from these studies shows that paper properties, surface roughness, and absorption are also important for the gloss development, and, as the amount of ink used in printing is increased, the printing conditions start to influence the gloss dynamics considerably, especially on glossy papers.

An equally interesting issue that is related to the graphic arts and coating industry is the investigation of the surface phenomena because other factors that can influence the appearance of the gloss of the printed surface are the type of the coating used and complex rheological and surface tension effects of the coatings.[30] The leveling of the coatings on different substrate surfaces includes the influence of the viscosity, surface tension, yield value, coating thickness or volume, and the degree of wet coating irregularity. Several studies have been devoted to the dependence of the coating formulation, refractive indices, and surface roughness on the specular reflection and gloss.[31–35] These studies showed that the increase in roughness (amplitude) increased the spreading of reflected light, thus increasing diffuse scattering and reducing gloss. The problems of correlating gloss to surface roughness have been encountered in relation to the accuracy of characterization of surface roughness (e.g., measurement techniques with insufficient resolution), as well as to the lack of advanced analysis of the roughness.

The aim of this preliminary study was to examine the effects of the coating amount and surface roughness leveling on the print gloss. The print samples on glossy coated and matte coated papers involved two types of coating at three coating weights. The objective was to provide important economic information regarding the usage of appropriate amounts of coating in production, as well as the necessary data for the material modeling and proofing processes.

EXPERIMENTAL

A commercial glossy coated paper of 250 $\mathrm{g/m^2}$ was printed with conventional printing inks in offset printing technology on a four-color offset press. The samples after oxidative drying were coated with commercial UNICO UV glossy and matte coatings commonly used in screen printing technology. The coating amount variation was achieved using three different weaving density screen stencils (120, 150, and 180 threads/cm). To ensure a more precise application of the coating, which varies with the printing and drying processes, we calculated the applied coating weight ($\mathrm{g/m^2}$), which is a standard metric in the graphic arts industry to describe the applied coating volume. The coating amounts presented are average values for five samples of $10\times 10\ \mathrm{cm^2}$ areas of the selected coated printed sheets. Surface roughness and morphology of the uncoated and coated samples were evaluated on a Veeco di CP II atomic force microscope (AFM). All images were taken in contact mode with a symmetric etched silicon probe. Scanning electron microscopy (SEM), performed on a JEOL 646 OLV instrument, was employed to investigate the coating leveling morphology. The print gloss of the coated samples was measured at the 60° angle using the QIP Glossmaster on cyan, magenta, yellow, black solid patches according to ISO 2813:1994 standard. The surface roughness and topographic data were obtained over an area of $80\times 80\ \mu\mathrm{m}^2$ at the standard scanning rate of 0.5 Hz. The images of all samples were corrected for the mean plane of height distribution by subtraction. The need to describe the surface characteristics by more than one parameter is the most important task in texture surface standard implementation. Recent years have seen an extensive application of fractal analysis for surface characterization, and several methods have been used to analyze the coated surfaces. Among ISO surface roughness parameters, the root-mean-square deviation of the surface heights, S_q, from the mean surface plane was chosen; many authors have used it to find the correlation between the surface roughness and gloss, which can be expressed by the following equation:[34–36]

$$S_q = \sqrt{\frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}[z(x_k,y_l)]^2}, \qquad (1)$$

where M is the number of points per profile, N is the number of profiles within the sampling area, and z is the normal deviation from the mean surface plane at point x,y on the surface. Surface roughness parameters were measured on six patches on each printed sheet, and the values of surface roughness parameters presented are the arithmetic means of these measurements.

RESULTS AND DISCUSSION

Figure 1 shows the images of the surfaces of the samples taken on the atomic force microscope.

For the glossy coating, the roughest surface corresponded to the plain glossy paper with ink applied, with S_q of 284.304 nm, while the surface without ink and without coating was smoother (S_q=270.794 nm). The average S_q value across the coated printed sheet varnished with the 180 thread/cm stencil was smoother than the ink only surface, yielding an S_q value of 48.538 nm. The higher volume stencils of 150 and 120 threads/cm gave even smoother surfaces, with S_q's of 27.477 and 13.563 nm, respectively. For the matte UV coating, the lower volume stencils of 180 and 150

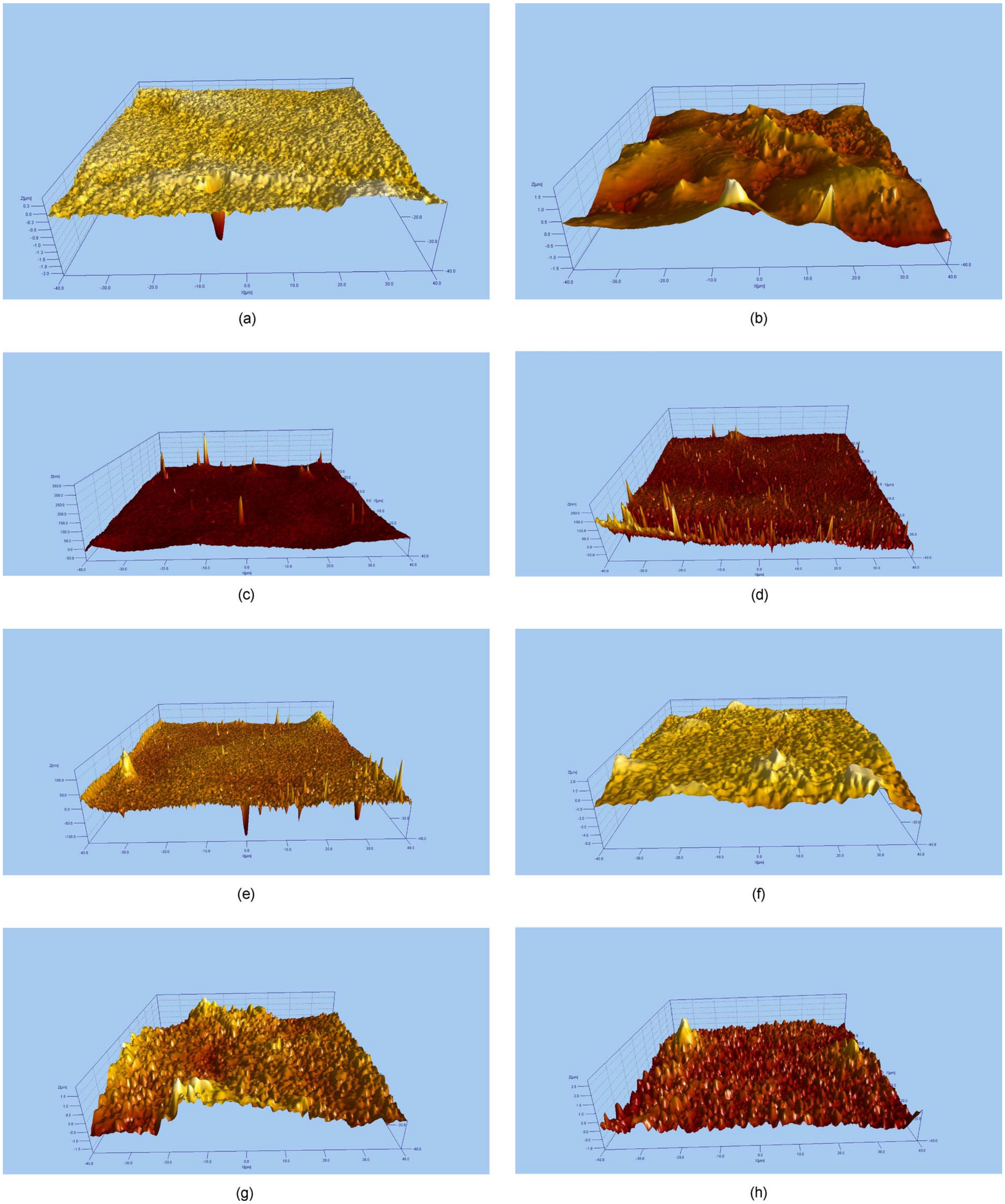


Figure 1. AFM images of the plain glossy paper and with different amounts of glossy UV coating: (a) glossy paper, no ink no coating; (b) printing ink, no coating; (c) glossy coating, 180 threads/cm; (d) glossy coating, 150 threads/cm; (e) glossy coating, 120 threads/cm; (f) matte coating, 180 threads/cm; (g) matte coating, 150 threads/cm; and (h) matte coating 120 threads/cm.

Table I. Results for the surface roughness, print gloss, and amount of applied glossy coating.

Sample type	Quantity of coating (g/m^2)	AMF S_q value (nm)	Print gloss value of 60°
Glossy paper (Type 1 ISO 12647-2)	0	270.794	33.36
Offset printing ink on glossy paper	0	284.304	44.62
UV glossy coating screen stencil 180 threads/cm	4.824	48.538	60.05
UV glossy coating screen stencil 150 threads/cm	5.248	27.477	62.6
UV glossy coating screen stencil 120 threads/cm	9.448	13.563	75.1
UV matte coating screen stencil 180 threads/cm	9.484	349.414	15.83
UV matte coating screen stencil 150 threads/cm	12.548	324.621	21.95
UV matte coating screen stencil 120 threads/cm	14.948	269.965	25.85

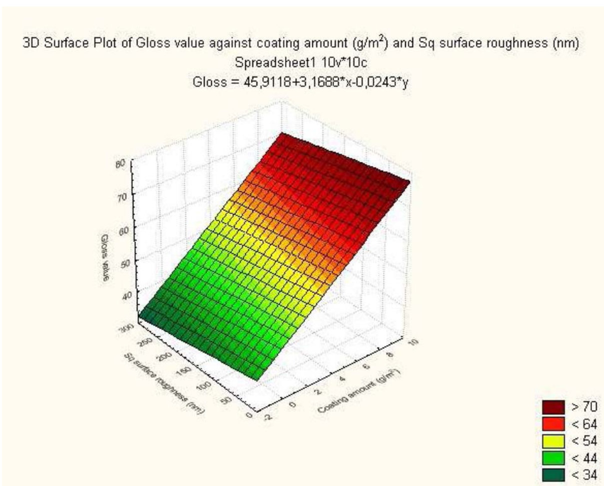


Figure 2. Correlation between the gloss and quantity of coating and the gloss and surface roughness of the printed sheets without coating and with three glossy coating amounts.

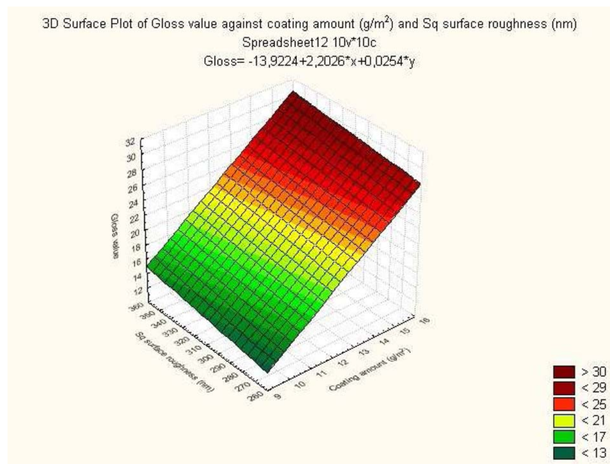


Figure 3. Correlation between the gloss and quantity of coating and the gloss and surface roughness of the printed sheets with three matte coating amounts.

threads/cm gave rougher surfaces than the plain paper, surface with ink, and all glossy coated samples. The highest volume stencil of 120 threads/cm resulted in a lower S_q value of 269.965 nm, which is lower than the other matte coated samples and close to the value of printed uncoated surfaces. The results for the S_q factor, the print gloss value, and the amount of coating applied are presented in Table I

A comparison of the results obtained shows a decrease in the roughness from the initial very rough surface of the plain unprinted and printed uncoated papers and a rise in the measured print gloss. The increase in the coating amount and stencil opening was accompanied by the increase in the print gloss value. This quantity showed a sharp rise after the coatings compared to the printed paper with ink, but a further increase in the coating amount resulted in a very small increase in the print gloss even if the surface roughness decreased to a large extent. This effect was somewhat different for the matte coatings, where the initial smaller amount gave rougher surface than the printed samples and smaller print gloss value, which increased with the additional matte coating amounts, accompanied by a decrease in the S_q value.

Figure 2 shows the correlation between the gloss and coating amount on the one hand and the gloss and surface roughness on the other for the glossy UV coating. As can be seen, there is an overall linear increase in the gloss with the coating amount and the gloss loss with increase in the surface roughness value.

The regression analysis of the correlation of the print gloss with the other two parameters (the surface roughness S_q value and coating amount) gave a multiple r value of -0.92 for the correlation of coating amount and surface roughness and for the correlation between the S_q surface roughness parameter and the print gloss. The correlation between the amount applied of glossy coating and measured specular gloss was 0.96.

Figure 3 shows the correlation between the gloss and coating amount on the one hand and the gloss and surface roughness on the other for the matte UV coating. As can be seen, there is a drop in the gloss after the applied matte coating and an overall linear increase in the gloss with the coating amount; the gloss increases with a decrease in the surface roughness value.

The regression analysis of the correlation of the print gloss with the other two parameters (the surface roughness

S_q value and coating amount) gave a very low correlation ($r<0.8$) where the results for the printed uncoated samples and the matte coated samples are concerned. If only the coatings are observed, the r value for the correlation between the coating amount and gloss is 0.99, between the coating amount and surface roughness −0.96, and between the surface roughness and print gloss $r=-0.94$.

To further examine the influence of the coating on the surface roughness, which influences the total reflection, we studied the height distribution and skewness (S_{sk}), surface kurtosis (S_{ku}), maximum valley depth (S_v), and maximum peak height (S_p). The skewness (S_{sk}) of the topographical height distribution S_{sk} is a measure of the asymmetry of surface deviations from the mean plane, and it can be expressed as

$$S_{sk}=\frac{1}{MNS_q^3}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}[z(x_k,y_l)]^3. \tag{2}$$

This parameter can be used effectively to describe the shape of the topography height distribution. For a Gaussian surface which has a symmetrical shape for the surface height distribution, the skewness is zero. For an asymmetric distribution of surface heights, the skewness may be negative if the distribution has a longer tail at the lower side of the mean plane or positive if the distribution has a longer tail at the upper side of the mean plane.

The S_{ku} describes the shape of topographical height distribution, i.e., the "peakedness" of the surface topography, and it is defined by the following expression:

$$S_{ku}=\frac{1}{MNS_q^4}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}[z(x_k,y_l)]^4. \tag{3}$$

This parameter characterizes the spread of the height distribution. A Gaussian surface has a kurtosis value of 3. On the other hand, a centrally distributed surface has a kurtosis value larger than 3, whereas the kurtosis of a widely spread distribution is smaller than 3. By a combination of the skewness and the kurtosis, it is possible to identify surfaces which have a relatively flat tops and deep valleys.

Figure 4 shows the height distribution for the different coated samples, printed and plain paper, whereas Table II gives the results for the corresponding S_{sk}, S_{ku}, S_v, and S_p values. The analysis of these quantities was performed using the Image Metrology SPIP software.

As can be seen from Fig. 4 and Table II, the height distribution is narrowing with the application of ink and coatings, which reflects a smoothing of the surface. The S_{sk} factor indicates a Gaussian-like distribution of the heights. The plain paper has a small S_{sk} value of 0.355, which indicates a wide distribution of the heights on the surface, while higher S_{sk} values (for the coated samples, 0.450, 0.674, and 0.382) indicate a larger offset caused by the leveling of the surface, with a few larger offsets from the coated surface, where a single peak can cause a larger offset from the leveled surface. The S_{ku} factor describes the peakedness of the surface topography, and its smaller values indicate a broader height distribution; the plain paper ($S_{ku}=3.63$) has a broader height distribution close to the Gaussian surface, while the heavily coated (120 thread/cm stencil) sample with value of $S_{ku}=7.48$ has a smaller S_{ku} value than the samples coated with 180 threads/cm and similar values as the samples coated with the 150 threads/cm stencil.

The UV matte coatings showed an increase in skewness from the initial amount of coating (0.256) to the larger volumes of coating (120 threads/cm stencil), whose S_{sk} value was 0.380. All S_{sk} values were smaller for the matte coated samples than for the glossy coated ones. A decrease in the S_{ku} values for the matte coated samples was also observed. Here also, the overall values were smaller than those for the glossy coated samples.

The Pearson correlation for the surface roughness parameters and instrumental measured print gloss was calculated, where the value +1 is in the case of a perfect positive (increasing) linear relationship, −1 is the case of a perfect decreasing (negative) linear relationship, and some value between −1 and 1 in all other cases, indicating the degree of linear dependence between the variables. The correlation between S_{ku} and S_{sk} and the measured print gloss for the glossy UV coating was very weak ($r<0.5$), while the correlation between the maximum valley depth and peak height was characterized by larger r values of −0.88 for the valley gloss and $r=-0.92$ for the peak to measured gloss correlation. With the increase of the coating amount, the difference between the maximum valley depth and maximum peak height decreases, and the measured instrumental specular gloss increases. For the matte coating including the printed paper, the correlation is only relevant to the valley and peak relationship ($r=0.91$), while the other correlations are very weak. If the printed paper is excluded and only the coated samples are observed, there is a high correlation for all the measured parameters. The r value for the correlation between S_{ku} and measured gloss is −0.96, between S_{sk} and gloss −0.95, between the valley and gloss −0.79, and between the peak and measured gloss $r=-0.92$. These correlations could be useful for the characterization of the matte coated samples, whereas for the glossy coated samples only the maximum valley and peak values yielded high correlations with the measured specular gloss.

In the practice of printing and coating, however, one encounters surface objects that exhibit random properties due to the physical and chemical interactions between the surfaces. It is often assumed that these objects exhibit the self-affine properties in a certain range of scales. Self-affinity is a generalization of self-similarity, which is a basic property of the most of the deterministic fractals. To make a part of a self-affine object to look like the whole object it is necessary to perform anisotropic scaling. Many randomly rough surfaces are assumed to belong to the random objects that exhibit the self-affine properties, and they are treated as self-affine statistical fractals. The power spectral density (PSD) belongs to the frequency domain analysis and can be used to visualize the data obtained by the AFM. At a randomly

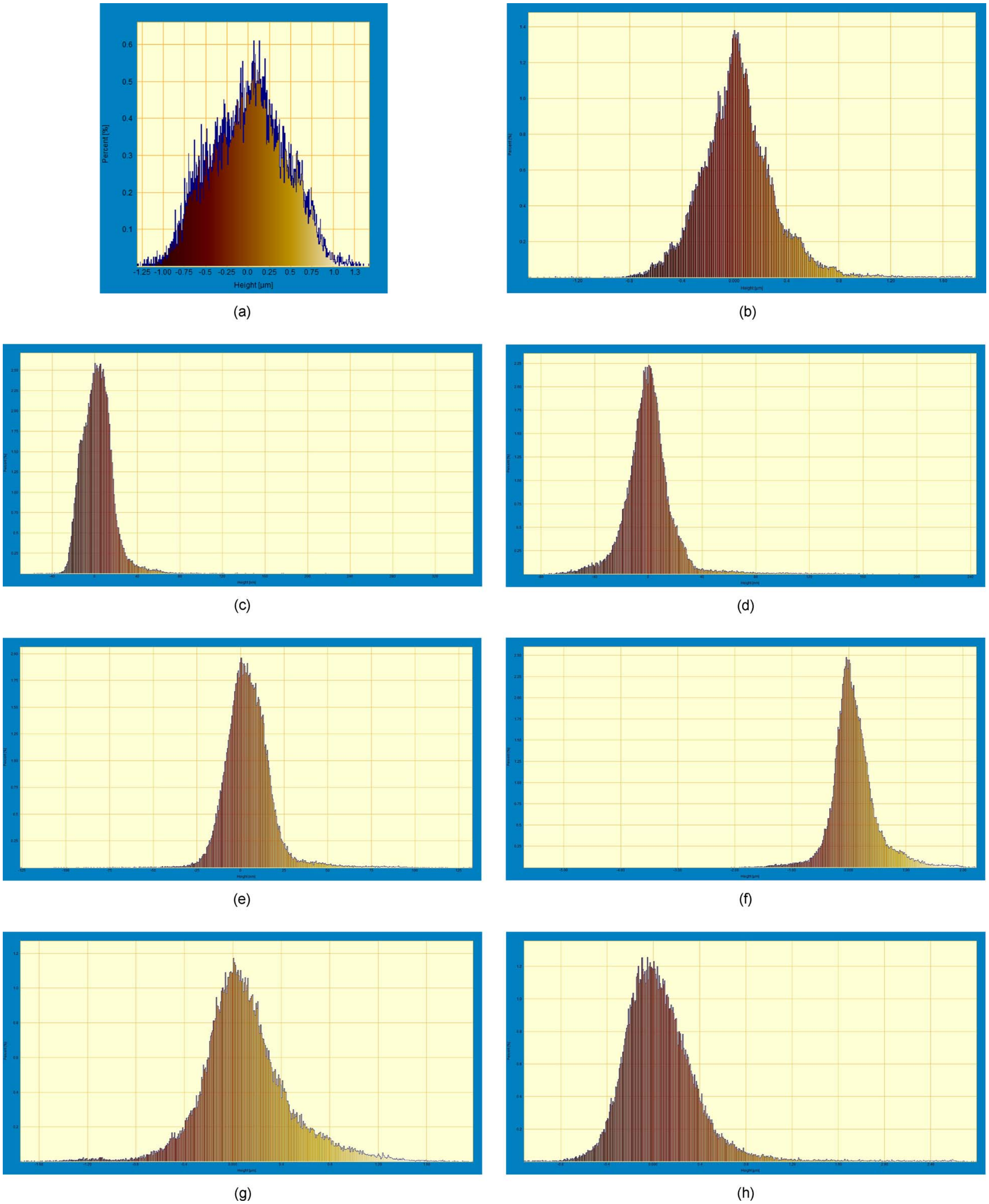


Figure 4. Histograms of the height distribution for the different samples: (a) plain paper, (b) ink on paper, (c) ink on paper coated using the 180 threads/cm stencil and glossy coating, (d) ink on paper coated with the 150 threads/cm stencil and glossy coating, (e) ink on paper coated with the 120 threads/cm stencil and glossy coating, (f) ink on paper coated using the 180 threads/cm stencil and matte coating, (g) ink on paper coated using the 150 threads/cm stencil and matte coating, and (h) ink on paper coated using the 120 threads/cm stencil and matte coating.

Table II. S_{sk}, S_{ku}, S_v, and S_p values for the samples.

Sample	Skewness, S_{sk}	Surface kurtosis, S_{ku}	Maximum valley depth S_v (nm)	Maximum peak height S_p (nm)
Glossy paper, no ink no coating	0.335	3.63	922.12	1126.93
Ink on glossy paper	0.442	5.08	1262.43	1616.275
Glossy coating with 180 threads/cm stencil	0.450	10.53	249.276	384.748
Glossy coating with 150 threads/cm stencil	0.674	7.38	122.158	258.563
Glossy coating with 120 threads/cm stencil	0.382	7.486	125.308	122.489
Matte coating with 180 threads/cm stencil	0.256	4.764	1469.388	1671.435
Matte coating with 150 threads/cm stencil	0.368	4.189	1472.575	1565.123
Matte coating with 120 threads/cm stencil	0.380	3.23	883.134	1240.787

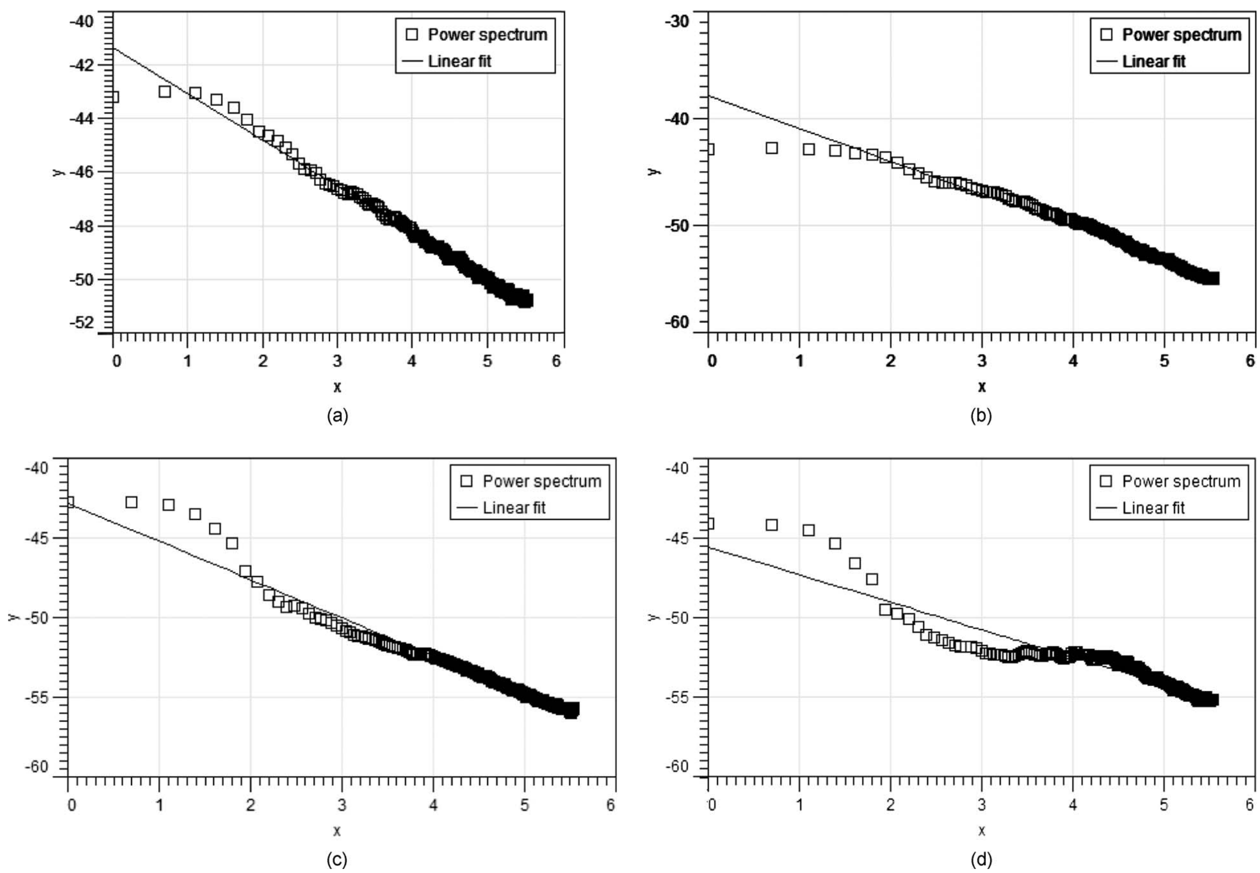
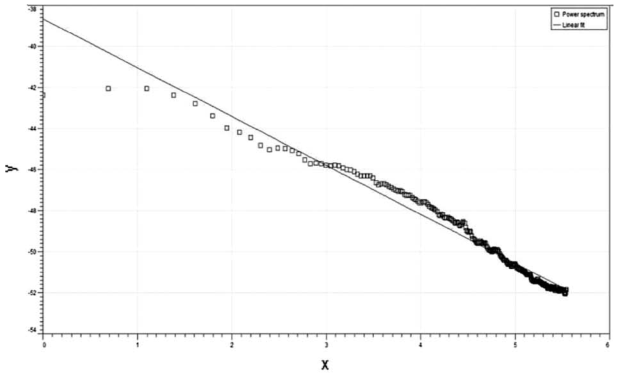


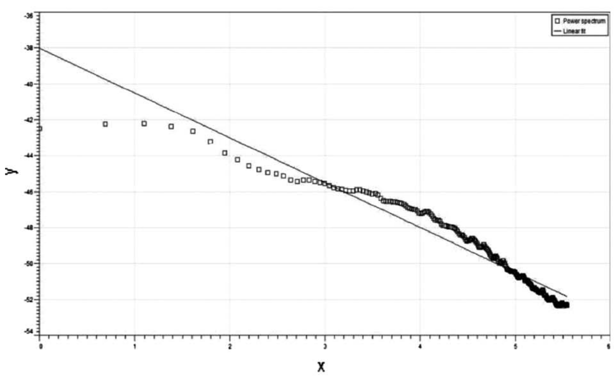
Figure 5. PSD graphs of the analyzed surfaces coated with different amounts of UV glossy coating by using different screen stencils, with the calculated D_f values: (a) plain paper, $D_f=2.64$; (b) ink on paper, $D_f=1.97$; (c) printed paper coated with the 180 threads/cm stencil, $D_f=2.30$; (d) printed paper coated with the 150 threads/cm stencil, $D_f=2.64$; and (e) printed paper coated with the 120 threads/cm stencil, $D_f=2.75$.

rough surface (such as our thin film coatings), many different spatial frequencies are present. This is quantitatively expressed by the PSD, giving the relative strength of each roughness component of a surface microstructure as a function of spatial frequency. Some authors used the PSD to evaluate surface in the frequency domain.[37,38] For the PSD fractal analysis of different coating amounts we used the GWYDION software package. The power spectrum method is based on the dependence of the power spectrum on the fractional Brownian motion.[39–41] In this method, every line height profile that forms the image is Fourier transformed, the power spectrum was evaluated, and then all these power spectra are averaged. Fractal dimension is evaluated from the slope β of a least-squares regression line fit to the data points in the log-log plot of power spectrum as $D_f=7/2-\beta/2$.

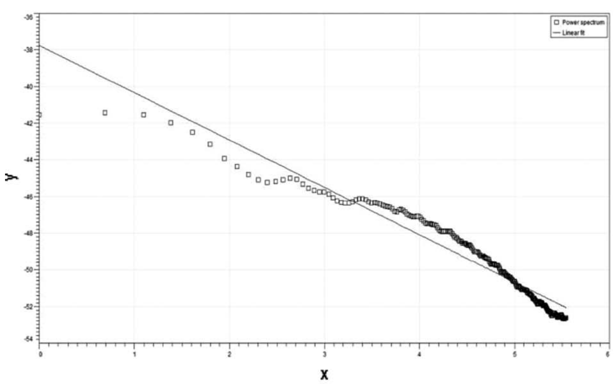
Figure 5 presents the PSD graphs of the analyzed sur-



(a)



(b)



(c)

Figure 6. PSD graphs of the analyzed surfaces coated with different amounts of UV matte coating by using different screen stencils, with the calculated D_f values: (a) printed paper coated with the 180 threads/cm stencil, $D_f=2.24$; (b) printed paper with the 150 threads/cm stencil, $D_f=2.3$; and (c) printed paper coated with the 120 threads/cm stencil, $D_f=2.3$.

faces coated with different amounts of glossy UV coating by using different stencils, along with the calculated D_f values.

As can be seen, the best linear fit is shown the plain paper, with the D_f value of 2.64, the largest D_f value being observed for the print with the largest coating amount. Analogously, the printed paper with no coating has the smallest D_f value (1.97). Therefore, similar to the gloss value, the D_f value increases with the increase in the amount of applied coating material. Thus, the smaller the D_f value, the rougher the surface.

Figure 6 shows the PSD graphs of the analyzed surfaces coated with different amounts of matte UV coating using different stencils, along with the calculated D_f values.

In order to evaluate the quality of different coatings we have also analyzed the surfaces by SEM to better visualize the effect of the amount of coating. The samples were coated with gold to ensure better evaluation, and the micrographs are presented in Figure 7.

From Fig. 7 we can visually observe the porous coating on the surface, which has a similar finish pattern. Figure 7(b) shows the changes in the surface topography after the application of printing ink, whereby a large number of the cavities are filled with the printing ink. The application of the coating levels the paper side, almost the same as the ink side, with some leftover particles on the very plain surface. The coated areas show a very uniform pattern, with the exception of some regions where local irregularities, such as isolated coating and other particles, are present on the surface. Besides the isolated particles, some smaller regions with rougher surfaces can be observed, where the roughness and the offset of the leveled plain seem to come underneath the coating itself. This effect is often observed near the borderline of the coating and is most probably a result of ink deposition. When a matte surface is examined, a clear microroughness is visible on the microscopic images of all the samples. Visually, they cannot be established any obvious regularities. The microroughness of the surface structure of the coating film is to a large extent due to the matting agents in the form of larger particles and aggregates. These particles vary in size and shape and are mainly in or below the upper sublayer of the coating. The SEM analysis of the three different coating volumes showed a similar pattern of leveling and larger, almost uniform surfaces, where it is hard to visually define the borderline between the printed and unprinted areas beneath the three coating amounts.

CONCLUSIONS

The measured gloss values of screen coated samples were evaluated and correlated with the surface roughness parameters and coating amounts. The samples with larger amounts of UV coating, applied through a stencil mesh, showed higher gloss values, resulting also in a decreased surface roughness. The S_{sk} and S_{ku} values are larger for the coated than for uncoated samples and for glossy than for matte samples, where, after an initial rise in both values for the 180 and 150 threads/cm stencil, there is a decrease toward lower values for the 120 threads/cm stencil. This indicates that the application of larger amounts of coating yields a surface leveling, which tends to decrease the overall surface roughness. This leveling can also be observed with the change in the range between the maximum valley depth and maximum peak height of the samples. The D_f value of the coated samples, obtained by fractal analysis, showed that the increase in the applied coating amounts resulted in higher PSD values for the glossy coating, while on the matte substrate smaller changes were observed with the applied coating volume.

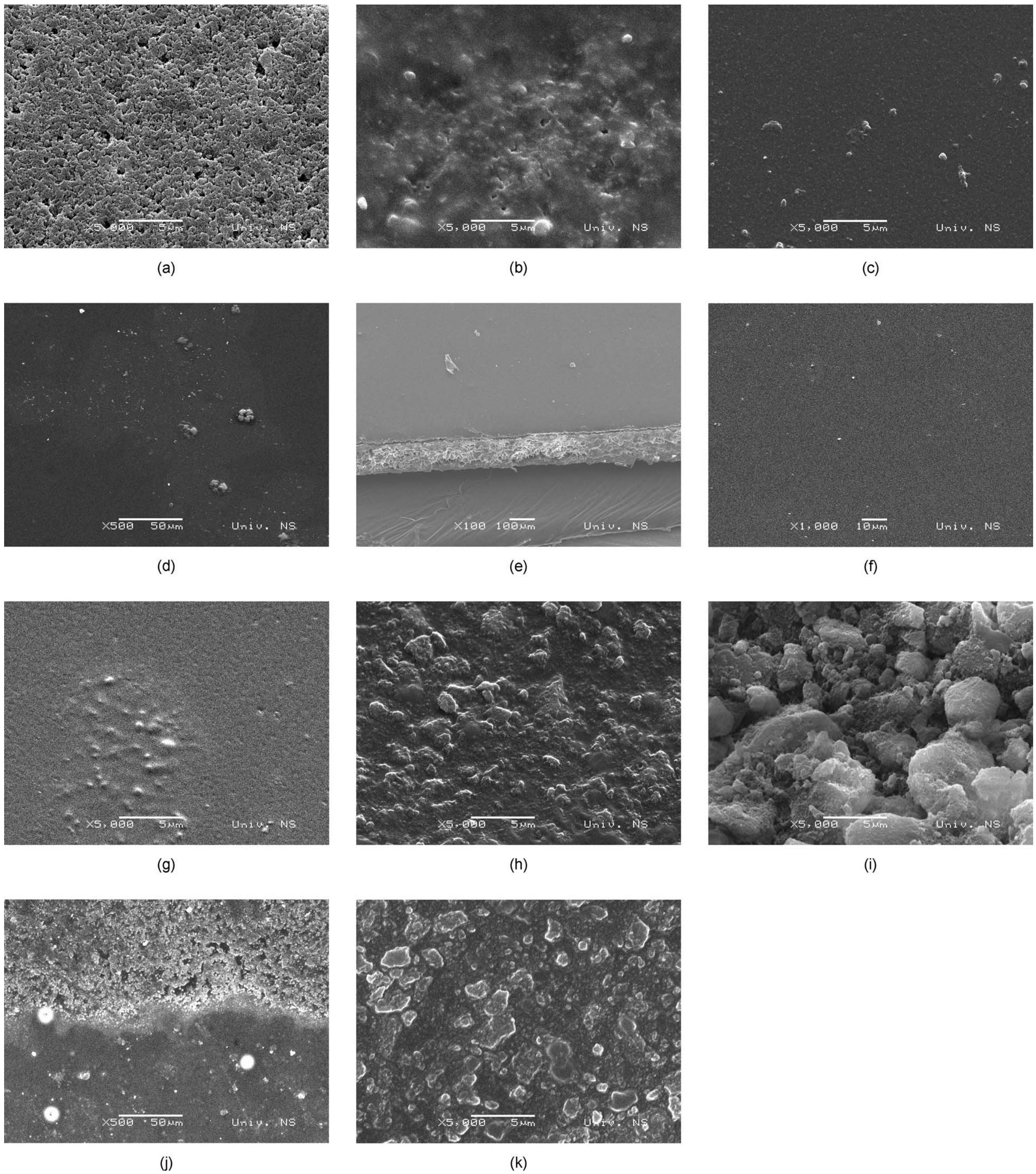


Figure 7. SEM micrographs of some of the examined samples: (a) 5000× magnification of the plain glossy paper with no ink and no coating; (b) 5000× magnification of the glossy paper printed with ink; (c) 5000× magnification of glossy coated glossy paper with no ink; (d) 5000× magnification of glossy coated printed paper with the 180 threads/cm stencil; (e) cross section of sample (d); (f) 1000× magnification of the glossy paper coated with the glossy UV coating, 150 threads/cm stencil; (g) 5000× magnification of the printed glossy paper coated with the glossy UV coating, 150 threads/cm, stencil; (h) 5000× magnification of the printed glossy coated paper coated with the matte coating, 180 threads/cm stencil; (i) 5000× magnification of the printed glossy coated paper coated with the matte coating, 150 threads/cm stencil; (j) the border between matte coated surface and uncoated paper surface; and (k) Matte coated sample, 120 threads/cm stencil.

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