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The Effect of Applying UV LED-Cured Varnish to Metalized Printing Elements during Cold Foil Lamination

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Abstract: The coating process involves applying a thin material layer to a surface to engender it with specific desirable properties or enhance its performance. In the production of print media (labels, packaging, printed textiles, and promotional materials), the standard functions of the coating process include visual decoration, which involves the addition of appealing colors, textures, and patterns. A pertinent issue in the printing industry is that at present, the predominant coating process uses printing and coating technologies (gravure, flexo, letterset, letterpress, screen printing, inkjet, and electrophotography) and lamination (i.e., attaching decorative layers of materials, such as films or fabrics). In this paper, we present a new method for testing the efficiency with which different-sized metalized printing elements (using gold foil) may be applied to paper substrates; to do so, we gradually vary the amount UV-cured inkjet varnish (or adhesive) that is applied. To test the effectiveness of this method in producing metallic visual effects, we utilize seven different thicknesses of UV-cured varnish with the aid of modular piezo inkjet heads (KM1024 iLHE-30) and three different printing speeds. Our research shows that to achieve optimal production of cold metalized foil, a 21 µm layer should be deposited, and the substrate should move at a speed of 0.30 m/s.

Keywords: UV-cured inkjet; metalized foil; varnish thickness; methods of testing metalized effects

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1. Introduction

The industrial coating process involves applying a thin layer of material onto a surface to imbue it with specific desirable properties or enhance its performance. Coatings can serve various purposes, depending on the method of application and the type of coating used. Some standard functions of the industrial coating process include protection, decoration, abrasion resistance, adhesion, lubrication, electrical conductivity or insulation, acting as a thermal barrier, chemical resistance, and adding hydrophobic, hydrophilic, antimicrobial, optical, and barrier properties [1].

For industrial decorative purposes, coating materials are often chosen for their ability to provide a pleasing and eye-catching finish. Painting, powder coating, anodizing, electroplating, printing and/or coating technologies, special effects coatings, ceramic and glass decoration, automotive customization, architectural coatings, and laminating and veneering are just some of the forms that the coating process can take [2].

Foil printing methods, in terms of efficiency and efficacy, are currently dominated by UV flexographic and UV lithographic offset printing technologies, the main reason being that they cause prints to dry quickly. Polymer printing involving the controlled production of small printing elements has a great influence on the size and forming limits of printed items in later micro-stamping procedures [3,4].

2. Theoretical Basis

2.1. Lamination

Laminating processes are commonly used in printing industries including furniture manufacturing, interior design, architecture, and automotive customization. These processes generally involve bonding multiple layers of materials together to create a new composite structure. The layers may be made of different materials, each serving a specific purpose.

In the printing industry, laminating is a process used to apply thin layers of material—such as polymer or metal films, fabrics, or other decorative materials—to printed paper and cardboard in order to enhance both their appearance and durability. To complement the lamination process, the entire pre-printed surface (e.g., cardboard packaging and book and magazine covers) is coated to prevent mechanical rubbing during practical use. A typical procedure includes the preparation of the printed substrate (for a reduction in surface tension or the elimination of static electricity), application of an adequate adhesive (UV-cured varnish using a coating unit), adhesion through the application of temperature and pressure (via heated rollers or a flat thermal press), and final finishing (removal of imperfect edges on the web roll or cutting to the final desired dimensions) [5,6].

2.2. Printing of Decorative Metalized Foil

To achieve appealing effects in their marketing and sales work, graphic designers frequently use partial application of metalized foil as a special effect. The most challenging aspect of this is achieved by hot or cold application, wherein multi-layer printing foils are used instead of metallic printing inks. The composition of said metalized foil is complex and usually contains four layers: a polyester carrier layer, an intermediate releasing layer, a metalizing layer, and an adhesive layer (Figure 1).

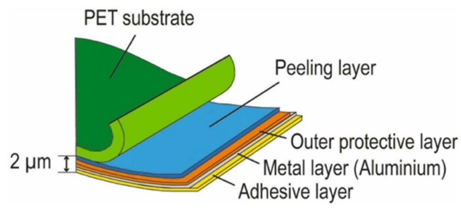

Figure 1. Typical composition of metalized foils for cold foil application [7].

To perform hot foil application, it is necessary to create a magnesium printing form (cliché) for letterpress printing (in which printing elements are situated higher than unprinted surfaces); said form is then selectively melted by heating from 80 °C to 200 °C, and with significant pressure (10 MPa), the adhesive and printing substrate are combined. The success of the separation and acceptance of the metal layer thus depends on factors such as the structure of the substrate, the thermal coefficient of the printing substrate, the printing speed, the cliché temperature, and the thickness of the printing foil. Typical hot embossing processes (carried out via a flat die press and a hot silicone rubber roller) are shown in Figure 2a,b [8,9].

The cold foil printing process requires specialized multi-color offset printing machines that contain at least two printing units (Figure 3). The first printing unit applies the adhesive (a varnish or pasty ink). At the same time, the second unit brings the metalized foil into contact with the printing substrate (in the gap between the printing and offset cylinders). The full foil printing procedure is carried out on six-color UV offset printing machines, which combine a classic CMYK color printing unit with a unit for the partial or full printing of metallic foil; using this method, metallic effects can be produced with CMYK inks. Due to offset machines' printing speed, the complexity of the printing process is challenging. This is the reason for the limited number of commercially available metalized foils for this printing process. Kurz is the current industry leader in developing and producing metalized foils for the cold transfer process. Kurz now has nine metalized foils that are applied using lithographic offset techniques (the LIGHT LINE series) and flexo printing (the LUXOR ALUFIN series).

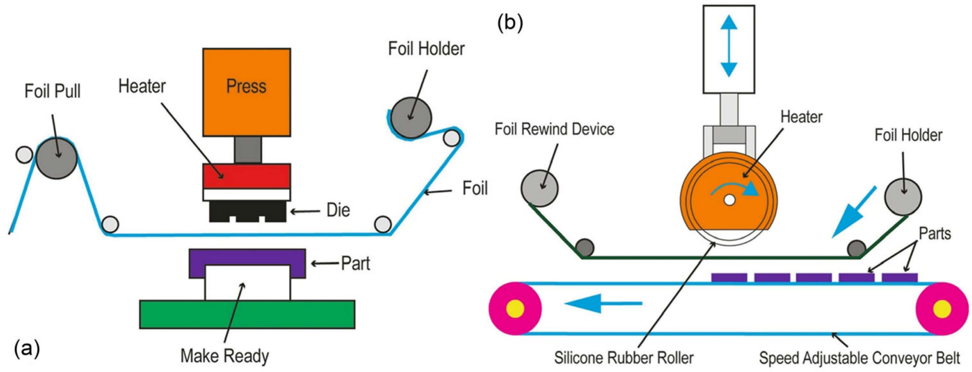

Figure 2. Principles of and tools for hot foil printing: (**a**) vertical hot foil printing machine; (**b**) roll-on hot foil printing machine [10].

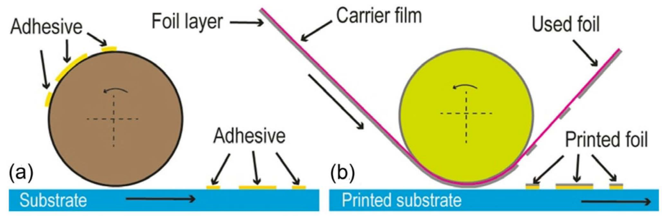

Figure 3. Principles of hot foil printing: (**a**) vertical hot foil printing machine; (**b**) roll-on hot foil printing machine [8].

The LIGHT LINE series foils create metalized aluminum, holographic, and transparent effects (type KP is intended for narrow webs, type KPO only for UV inks, and type KS for sheet-fed printing machines). The series created for flexo printing, LUXOR ALUFIN, consists of aluminum metalized and transparent foils (type KPW and KPW-OP-KB for narrow webs and aluminum metalized KPW-OP for UV inks only). The aluminum metalized foils KPS, KPS-OF, and KPS-OS are used for flexo sheet-fed printing machines [10–12].

UV-cured varnish (adhesive layer) is placed directly on the printing surface, after which heat and pressure are applied to the metalized foil. The basis of such systems is the piezoelectric inkjet head, which contains a large number of nozzles arranged in rows and columns (Figure 4a). Drops of adhesive (UV-cured varnish) are formed by the activation of the upper electrode, resulting in mechanical distortion of the micro-piezoelectric element. Such action reduces the volume of the inkjet chamber in which the adhesive varnish is stored. This culminates in the release of plenty of droplets of a minimal volume. Depending on the nozzle number, the distance between the printing lines, the speed of head movement, and the number of head passes, it is possible to apply different amounts of UV-cured varnish and thus augment the quality of the coating. The precision of the application and the details executed directly depend on the volume of the generated droplets, which can vary from 2 to 90 pl [13–16].

The development and application of inkjet technologies have been undertaken by numerous world-famous electronics companies (HP, Palo Alto, CA, USA; Kodak, Rochester, NY, USA; Konica Minolta, Chiyoda City, Japan; Kyocera, Kyoto, Japan; Fuji, Tokyo Midtown, Japan; Ricoh, Tokyo, Japan; Epson, Nagano, Japan; Spectra, Denver, CO, USA), who have produced numerous inkjet machines [13,17]. Some novel piezo inkjet heads currently on the market are the Konica Minolta KM1024i series heads [18]. The built-in heater in these heads enables stable temperature control of highly viscous solvent inks, UV-cured inks, and oil-based inks. These heads have 1024 nozzles (in a high-density structure featuring four lines of 256 nozzles), corresponding to a printing width of 72 mm (Figure 4b). As they can be operated at a frequency from 27 to 56 kHz, they are ideal inkjet printing heads for high-speed single-pass inkjet printers. Ultimately, their native addressability is 360 npi (90 npi $\times$ 4 lines), which corresponds to a drop size of 30 pl, 13 pl, and 6 pl (with eight greyscale levels) [19].

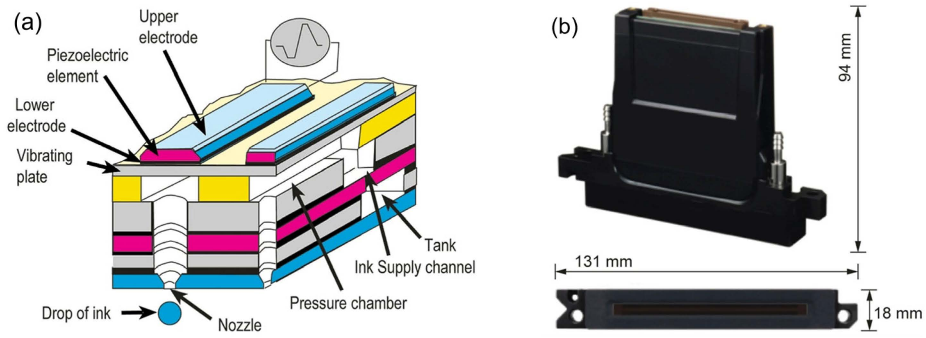

Figure 4. Construction of an inkjet piezo nozzle for applying UV-cured ink (adhesive): (**a**) schematic view; (**b**) KM series head KM1024i [18].

The curing of colorless UV varnish involves a photopolymerization reaction between monomers/oligomers, photoinitiators, and additives. Reactive monomers/oligomers (most often acrylates and less often unsaturated polyester resins) are the basis of UV inkjet varnish formulations and enable the additional polymerization of free radicals. By increasing the functionality of monomers/oligomers, the number of cross-linkers (and thus the density of the polymer film) can be increased. A greater number of cross-linkers in the polymer film results in the formulation of a firmer, less elastic film that is more resistant to solvents, wear, and scratches; however, these films also exhibit reduced adhesion due to shrinking as a result of UV radiation (fixing) [20].

Depending on their intended application, the operability of inkjet heads and machines needs to be tested. Various scientific papers, international standards (ISO, IEC), and national standards (DIN, ASTM, JIS) have examined printing elements and inks [21–29].

Therefore, this paper aims to examine the success of detecting the quality of the metallic surface without using methods based on line width and line darkness measurements. The inkjet printing process requires the fulfillment of two criteria: quality in both the direction of printing (MD = machine direction) and the alignment of the nozzles (CD = cross direction). A module of five inkjet heads of type KM1024iLHE-30 has a factory-declared addressability of 360 dpi (CD), while the addressability in the machine direction (MD) is not declared because it depends on the selected speed of the printing substrate. In addition, the paper featured optimum settings for the application of UV-cured adhesive using the Konica Minolta inkjet head KM1024iLHE-30 and for the successful transfer of the laminated film to the substrate, a fine art board [30].

3. Materials and Methods

A modified contrast–resolution test chart was used for this experiment. Print images had an addressability of 1200 spots per inch, utilizing a screen with 133 lines per inch. The circular patterns of samples were as follows: 0.63 cy/mm (2 circles), 0.81 cy/mm (3 circles), 1.04 cy/mm (4 circles), 1.35 cy/mm (5 circles), 1.74 cy/mm (6 circles), 2.91 cy/mm (7 circles), 3.76 cy/mm (8 circles), 4.85 cy/mm (9 circles), and 6.25 cy/mm (10 circles). The original contrast row of column A to column J was removed, causing the sample to form an achromatic bitmap [19].

The bitmapped form was saved in PDF format using Adobe Illustrator, making it suitable for the raster image process (Hakiri KM IC602). An identical Hakiri KM IC602 controller was used to make the reference print (a high-quality black-and-white image with a resolution of 1200 $\times$ 3600 dpi) alongside an EP machine from the Japanese manufacturer Konica Minolta Accurio Print C3080 with an associated black Simitri powder toner [30].

UPM semigloss double-coated cardboard was used for fine art prints (with SRA3+ format dimensions and a 300 g/m^2 grammage during the printing process) [31].

The experimental samples were printed on an identical printing substrate and a JET Varnish 3DS film varnishing and printing machine, which has 5 inkjet print heads (KM 1024 LHE-30 positioned in the distribution of 3 + 2 heads) and a UV light source module consisting of 2 LED lamps. The first LED UV lamp contains 4 modules with a power of 5 W, while the second LED UV lamp has only 1 module with a power of 12 W. For UV treatment, LED UV lamps emit a wavelength of 395 nm [32].

Six different coatings (from 21 μm to 58 μm) were printed using MGI UV inkjet fast-drying varnish. The JETVARNISH 3DS machine features HubManager 2.8.5 software, using which it is possible to directly adjust the varnish applied. Data on the application of LED UV varnish were not obtained directly through measurement but were obtained indirectly (from the data of the manufacturer). The fast-drying glossy varnish JV3DS contains acrylic monomers and polymers, photoinitiators, and various additives. The main ingredient is the polymer diphenyl (2,4,6-trimethyl benzoyl) and phosphine oxide $(CH_3)_3C_6H_2COP(O)(C_6H_5)_2)$ [33].

Alongside the varnish application unit and the LED drying lamp, there is a metalized foil application unit (foils). Murata Gold-type foil was used. The length of the metalized foil was 500 m, meaning a maximum transfer of 32 cm × 45 cm foil could be achieved. The temperature was controlled in 6 independent zones, with the possibility of regulating the foil temperature from 90 °C to 190 °C (a constant heater temperature of 105 °C was used for the experiment). RIP MGI Juti 3.2 was used to control the application of transparent varnish. In contrast, an AIS scanner with 180 defined check positions was used to manage the position of the varnish channel. The varnish channel was created using the alpha channel generated in Adobe Photoshop CS6 25.7 [34].

For research purposes, nine samples were printed (divided into three experimental wholes). In the first experiment, the quality of varnish acceptance was tested with an Elcometer 480 gloss meter, which was used to assess 12 points on the surface with only printed lacquer, on the printed gold foil, and on the unprinted substrate [35]. The second part of the research consisted of 6 samples in which the thickness of the varnish varied before contact with the foil (21 μm, 29 μm, 36 μm, 43 μm, 51 μm, and 58 μm). In the third part of the research, the printing substrate's movement speed varied (0.300 m/s, 0.240 m/s, and 0.159 m/s), and varnish was consistently applied in a 21 μm thick layer. After forming the samples for image analysis, the samples were scanned in a CanoScan LiDE 700F scanner (RGB image, 600 dpi, TIFF format) (Canon, Fukushima, Japan). Before image analysis (corresponding to the contrast–resolution test chart), all images were cut in Adobe Photoshop to the same TIFF grayscale format (size 9 × 6 cm with an original resolution of 600 dpi). We used the open-source program ImageJ 1.5.3 with the following macro program to calculate surface coverage.

```
run("HSB Stack");
run("Stack to Images");
selectWindow("Saturation");
close();
selectWindow("Hue");
close();
selectWindow("Brightness");
run("Options...", "iterations = 1 count = 1");
setOption("BlackBackground", false);
```

Based on the detected black pixels, the area of the contrast–resolution test was determined, the average results of which were processed and analyzed using OriginPro 8.5. Figure 5 shows a flow chart of the experiment.

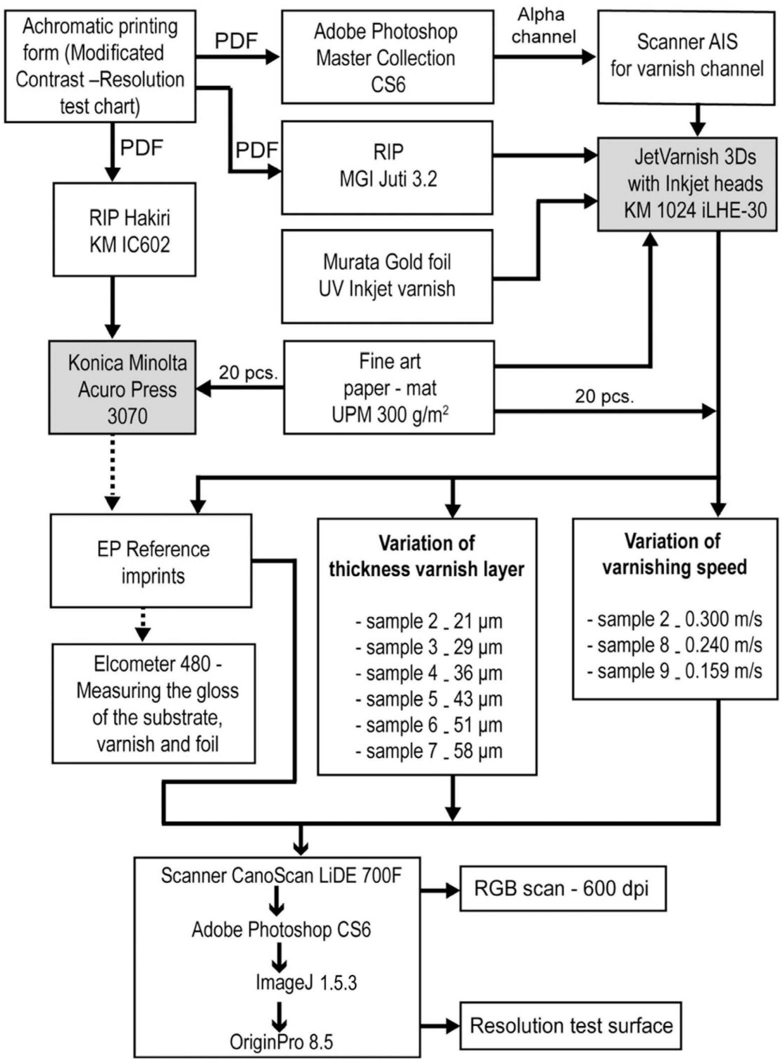

Figure 5. Chronological flow of the experiment.

4. Results and Discussion

To determine the successful acceptance of the metalized foil, it is necessary to perform a preliminary analysis of the substrate and an analysis of the varnish's adhesion. For this purpose, optical reflectance (gloss measurement) was used to create profiles at 12 characteristic positions on the cardboard substrate, the cardboard substrate with varnish, and the cardboard substrate with both varnish and adhered foil. For this purpose, a three-channel gloss meter—which is intended for measuring matt, semi-matt, and glossy surfaces—was used according to the ISO 2813:2014 standard [35]. After measurement with ten replicates (samples), the mean value of each of the 12 positions was calculated. These values are presented in the profile graph in Figure 6.

Observing the profiles, it can be seen that the lowest gloss value was determined for matte-coated cardboard, with an average value of G_{avg} = 47.8 GU. On the surface of the cardboard, the measured gloss values varied between the minimum amount of gloss, G_{min} = 40.1 GU (position 5), and the maximum amount of gloss, G_{max} = 53.6 GU (position 3). This alone resulted in a change of ΔG = 13.5 GU in the gloss value of the paper, which means that the surface is very uneven and has highly varied glossiness (indicating roughness).

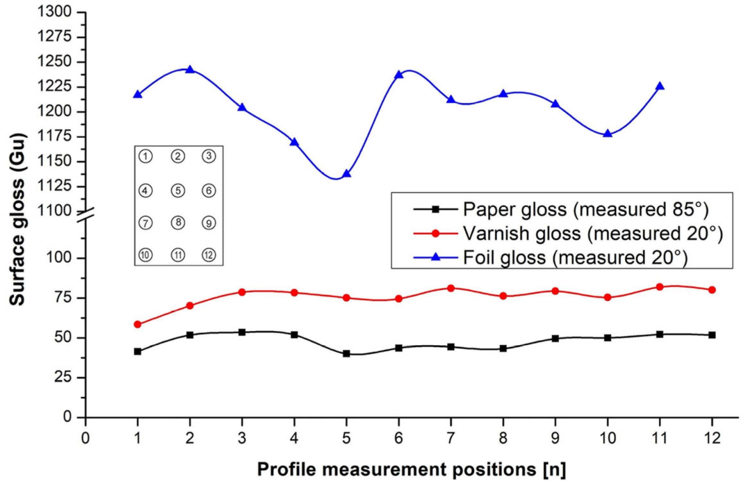

Figure 6. Gloss profiles of the surfaces used in the experiment (cardboard, cardboard + varnish, cardboard + varnish + foil).

The thickness of the varnish directly affects the acceptance of the metallic foil. Greater varnish thickness engenders better foil adhesion. Additionally, the uniformity of the varnish is crucial for the homogeneity of the film's adherence. Further analysis shows that the varnish applied in a 21 μm layer had a higher gloss value than the cardboard substrates. The mean gloss value of the varnished surface was G_{avg} = 75.8 GU, and the values varied between the minimum amount of gloss, G_{min} = 58.4 GU (position 1), and the maximum amount of gloss, G_{max} = 82.0 GU (position 11). Therefore, the change in the gloss value of the varnish amounted to ΔG = 23.6 GU. The varnishing process did not result in a uniform surface, and the inkjet technique using the KM 1024 and LHE-30 heads produced uneven deposits in the overlapping zones of the print heads.

The metalized surface achieved very high gloss values of over 1000 gloss units. However, we observed fluctuations in the degree of metallic luster. The used metallic foil Murata Gold exhibited the highest shine, with an average value of G_{avg} = 1198.0 GU. The extremes ranged from a minimum brightness value of G_{min} = 1137.6 GU (position 4) to a maximum brightness value of G_{max} = 1236.7 GU (position 5). We observed a great change of ΔG = 99.1 GU in the glossiness of the film. Although such a deviation in gloss values is significant, it was not visually perceptible; that said, it still suggests that the adherence of the film was imperfect.

The central aim of the experimental work was to determine how the thickness of UV-cured varnish (adhesive) affects the reproduction accuracy of small printing elements. To obtain the most accurate results, a high-quality BW print was taken as a reference (via electrophotography with a raster output scanner imaging unit) rather than the original digitized image. Figure 7 shows the results of the surface acceptance of metalized printing elements, while Figure 8 shows bitmap images of digitized metalized samples before Image J analysis.

In analyzing the metalized surfaces of the samples (made with seven different thicknesses of varnish application at a constant printing speed machine of 0.300 m/s), we observed that the surface of the accepted metal foil increased with the increase in the thickness of the varnish applied. However, this increase in the surface area was accompanied by a closure of finer circles and a loss of finer details in the image. Compared to the EP reference sample, all metalized elements were of lower quality and showed a visible loss of circular segments. The best impression (i.e., the smallest increase in the printed area achieved) was made with sample S2 ($\Delta A_{ref\_21\mu m}$ = 152.39 mm^2). Sample S7 had the most significant increase in surface area with the thickest varnish application ($\Delta A_{ref\_58\mu m}$ = 1611.625 mm^2). At the same time, rows 5 to 10 (with 5 to 10 circles in the field) were completely closed and therefore presented as a solid color; the varnish pattern on the circular surface completely disappeared and instead formed a homogeneous solid golden tone. The most significant deviation in the surface was thus observed in the samples with the smallest and most significant application of UV-cured varnish; this difference amounts to ΔA_{S2_S7} = 1459.24 mm^2.

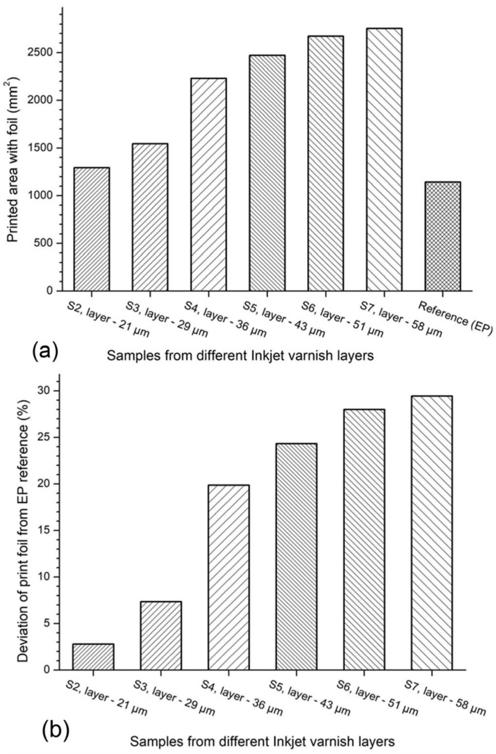

Figure 7. Results of the resolution test of samples created by varying the application varnish with a JET Varnish 3DS machine: (**a**) printed area in mm^2; (**b**) deviation between samples and EP reference.

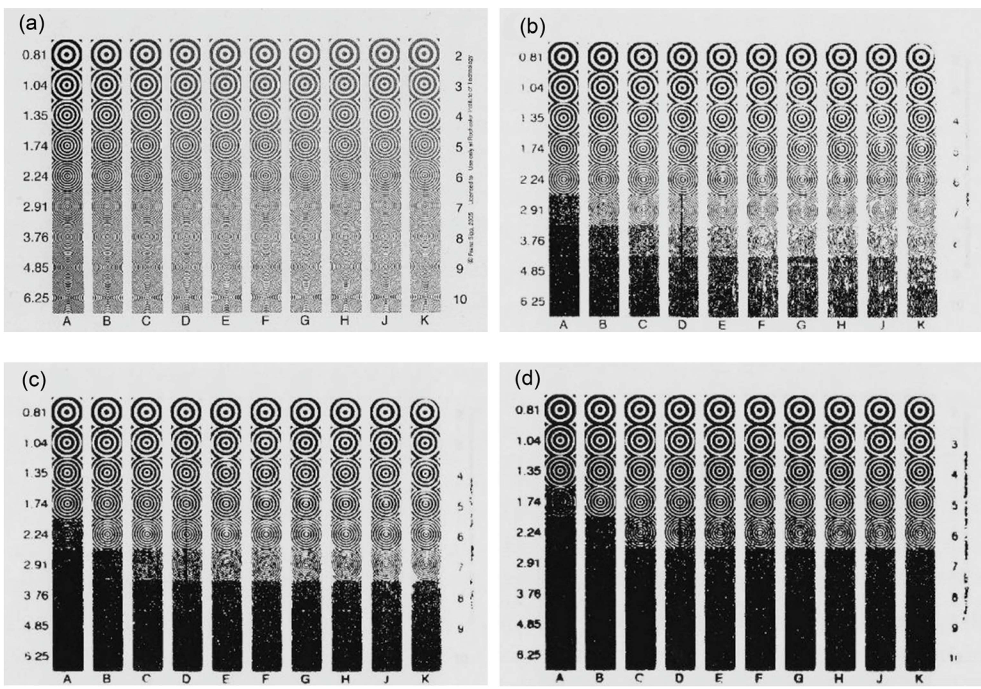

Figure 8. *Cont.*

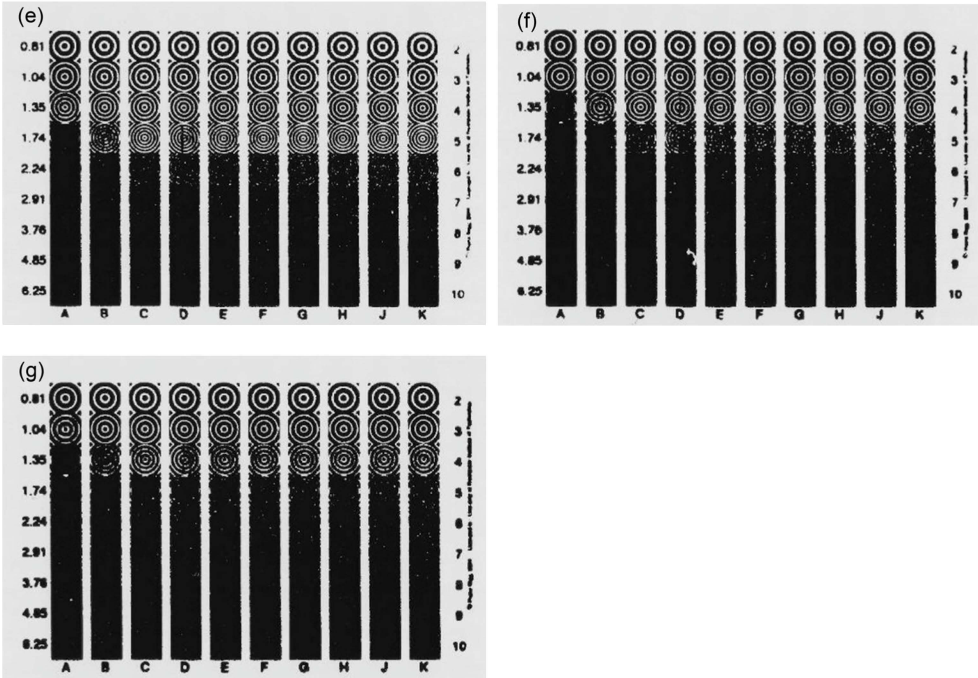

Figure 8. Bitmap images of metalized elements after cold foil transfer: (**a**) EP reference; (**b**) layer with 21 µm; (**c**) layer with 29 µm; (**d**) layer with 36 µm; (**e**) layer with 43 µm; (**f**) layer with 51 µm; (**g**) layer with 58 µm.

Besides the thickness of the varnish coating, a parameter that also affects the quality of inkjet printing is the printing speed. When analyzing the metalized surfaces of samples made with three different varnish application speeds (with a constant application thickness of 21 µm), minimal changes in the acceptance of the metal foil were observed. Figures 9 and 10 shows the results of surface acceptance of metalized printing elements, while Figure 8 shows bitmap images of digitized metalized samples before ImageJ analysis.

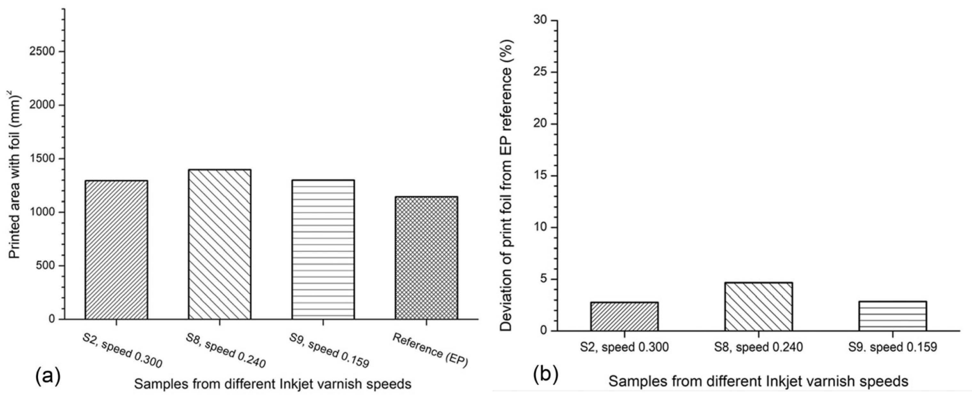

Figure 9. Sample resolution test results obtained by varying the printing speed of the JET Varnish 3DS machine: (**a**) printed area in mm^2; (**b**) deviation between samples and EP reference.

The analysis of the surfaces of the printed samples created by varying the speed of varnish application shows that the surfaces of sample S2 and sample S9 were almost equal ($\Delta A_{S9\text{-}S2}$ = 0.0768 mm^2). However, the 0.15 m/s increase in speed resulted in a partial loss (not transference) of more minor elements on the print. The largest surface area was achieved at a speed of 0.240 m/s (A_{S8} = 4.6645 mm^2), representing an increase of ΔA_{max} = 255.263 mm^2 from that of the reference print. This led us to conclude that the tested varnish application speed did not significantly affect the printing resolution.

Therefore, it can be established that the gain and loss of information upon resolution testing are affected more by the increase in varnish applied than by changes in application speed.

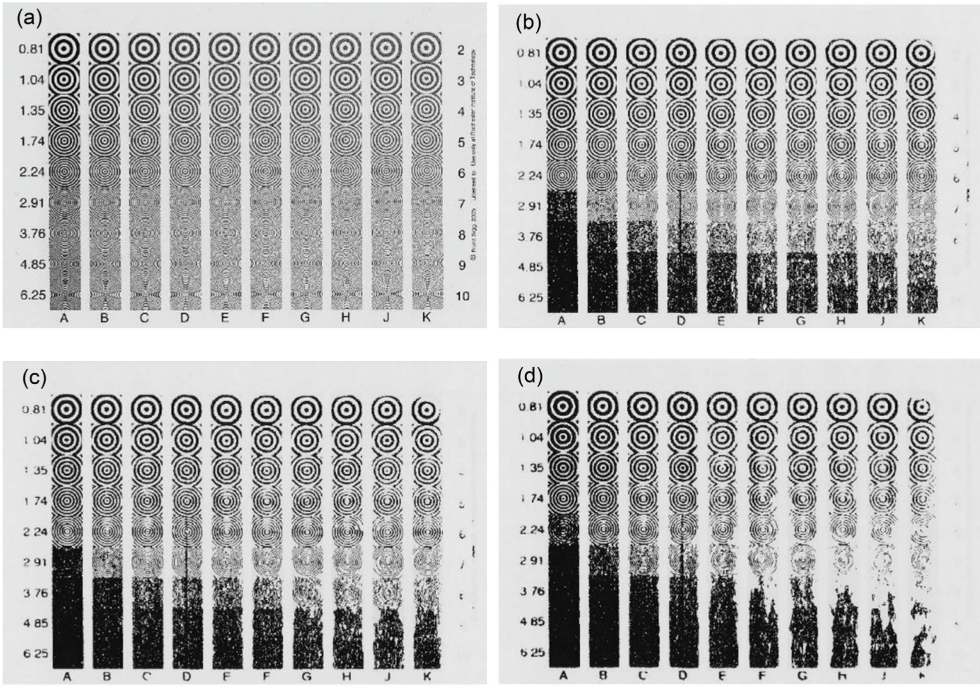

Figure 10. Bitmap images of metalized elements after cold foil transfer: (**a**) EP reference; (**b**) layer generate with speed 0.300 m/s; (**c**) layer generate with speed 0.240 m/s; (**d**) layer generate with speed 0.159 m/s.

5. Conclusions

The modified method of analyzing prints using inkjet technology presented herein achieved more realistic results than previous methods because circular image elements do not differentiate between machine direction (MD) and cross direction (CD). However, the cold foil process carried out with the Konica Minolta inkjet head KM1024iLHE-30 generated metalized samples without achieving high-quality reproduction (i.e., from 4.85 cy/mm to 6.25 cy/mm) via small printing elements.

Due to the uneven surface treatment of the factory-produced semigloss-coated cardboard, the application of the UV varnish was not uniform (upon gloss detection) and, therefore, neither was the application of metallic foil. With increased varnish application, each metalized print exhibited an increased surface area. However, with more extreme varnish applications, more and more of the finer parts of the reproduced images were lost. Regulating the speed with which UV varnish was deposited did significantly affect the transfer of the metalizing foil, and a higher speed did not produce good results.

Upon experimentally increasing the thickness of the varnish coating, the printed surface increased by 29.43%, and a minimum area of 4.66% was achieved by varying the speed. Using the JET Varnish 3DS printing system (MGI Digital Technology, Fresnes, France) with KM 1024 iLHE-30 heads and acrylic fast-curing glossy varnish (JV3DS varnish), we attained optimal results with a coating thickness of 21 μm and a printing speed of 0.300 m/s.

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