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Investigation of the Effects of Process Parameters on the Performance of Gravure Printed Films on Flexible Substrates

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Abstract

The performance of printed films placed on flexible substrates is examined in this study in relation to important gravure printing process parameters. Parameters such as printing speed, gravure cell geometry, ink composition, solvent concentration, and impression pressure were systematically analyzed using a Design of Experiments (DoE) approach. The printed films were evaluated in terms of thickness, surface roughness, transparency, and electrical conductivity. Results indicate that ink solid content and cell geometry significantly affect film thickness and uniformity, while printing speed influences ink transfer efficiency and surface morphology. The findings provide valuable insights for optimizing gravure printing conditions to produce high-quality functional films for packaging and printed electronics applications.

Keywords; Gravure Printing, Flexible Substrates, Film Thickness, Print Quality.

INTRODUCTION

Due to its promise for producing lightweight, flexible, and affordable devices for uses including "flexible displays, sensors, solar cells, RFID tags, and smart packaging, printed electronics and functional printing technologies" have attracted a lot of attention in recent years. Among various printing technologies, gravure printing has emerged as a promising technique because of its "high printing speed, excellent image quality, precise ink transfer, and compatibility with roll-to-roll manufacturing processes" (Kipphan, 2001).

Gravure printing is an intaglio printing procedure that involves the transfer of ink from "engraved cells on a printing cylinder to a substrate" via controlled pressure. The process enables the deposition of uniform thin films over large areas and is widely used in packaging, decorative printing, and printed electronics applications (Kipphan & Nussbaum, 2006). The quality and functionality of gravure-printed films depend on several process parameters, including printing speed, gravure cell geometry, impression pressure, ink viscosity, surface tension, solvent content, and substrate characteristics. Variations in these parameters can significantly affect ink transfer efficiency, film thickness, surface morphology, optical properties, and electrical performance (Magdassi, 2010).

Flexible substrates such as "polyethylene terephthalate (PET), polyethylene (PE), and biaxially oriented polypropylene (BOPP)" are increasingly used in gravure printing due to their flexibility, low weight, and compatibility with continuous manufacturing processes. However, achieving uniform film formation on these substrates remains challenging because substrate "surface energy, roughness, and ink–substrate interactions strongly influence wetting, adhesion, and drying behaviour" (Perelaer et al., 2010). Therefore, understanding the relationship between process parameters and printed film characteristics is essential for improving product quality and manufacturing efficiency.

Previous studies have demonstrated that gravure cell geometry plays a crucial role in determining the amount of ink transferred to the substrate and consequently influences film thickness and uniformity (Hrehorova et al., 2011). Similarly, printing speed and ink rheological properties have been reported to affect coating quality, surface roughness, and functional performance of printed films (Vak et al., 2010). For functional applications such as conductive and transparent films, even minor variations in process conditions can result in significant changes in electrical conductivity and optical transparency (Sirringhaus, 2005).

A thorough grasp of the combined impact of "process parameters on film performance" is still lacking despite extensive study on gravure printing. Most studies focus on individual parameters, whereas industrial printing processes involve complex interactions among multiple variables. Therefore, systematic investigation and optimization of these parameters are required to achieve high-quality and defect-free printed films.

The purpose of the current study is to examine how important "gravure printing process parameters" affect the performance of printed films that are deposited on flexible substrates. Particular emphasis is placed on evaluating the effects of printing speed, gravure cell geometry, ink composition, and solvent concentration on film thickness, surface roughness, transparency, and electrical conductivity. The findings are expected to provide valuable insights for optimizing gravure printing processes in packaging and printed electronics applications.

BACKGROUND HISTORY

Printing technology has evolved from a medium for graphic communication to an advanced manufacturing tool capable of producing functional devices and intelligent packaging systems. Among the various printing technologies, gravure printing has established itself as one of the most efficient and reliable methods for high-volume production due to its ability to deliver consistent print quality, precise ink transfer, and high-speed operation (Kipphan, 2001).

The gravure printing process originated in the late nineteenth century and is based on the intaglio principle, where the image area is engraved below the surface of a “printing cylinder”. The engraved cells are filled with ink, which is then pressure-transferred to a substrate. The process gained widespread industrial acceptance in packaging and publication printing because of its ability to reproduce fine details and maintain quality over long production runs (Kipphan & Nussbaum, 2006).

The advancement of materials science and printed electronics has expanded the application of gravure printing beyond traditional graphics. Researchers have increasingly explored gravure printing for depositing functional materials such as conductive inks, semiconductors, sensors, and transparent conductive coatings on flexible substrates (Krebs, 2009). Because they are lightweight, flexible, and compatible with roll-to-roll production processes, flexible substrates such as "polyethylene terephthalate (PET), polyethylene (PE), and biaxially orientated polypropylene (BOPP)" have become indispensable materials (Perelaer et al., 2010).

The performance of gravure-printed films depends on several interconnected parameters, including printing speed, impression pressure, gravure cell geometry, ink rheology, solvent concentration, and substrate characteristics. These factors influence ink transfer, wetting behavior, film thickness, surface morphology, and functional performance of the final product (Magdassi, 2010). As demand for flexible electronics, smart packaging, and sustainable manufacturing continues to grow, optimizing gravure printing parameters has become a critical research area.

Recent developments in nanomaterials and conductive inks have further enhanced the potential of gravure printing for manufacturing functional films with tailored optical, electrical, and mechanical properties. However, achieving uniform and defect-free films remains challenging because small variations in process parameters can significantly affect performance. Consequently, systematic investigations of printing parameters are necessary to improve process efficiency and product quality (Sirringhaus, 2005).

RESEARCH OBJECTIVES

To examine how important "gravure printing process parameters" affect printed films' performance on flexible substrates.

Specific Objectives:

a. To analyze the influence of printing speed on film thickness, uniformity, and surface morphology.
b. To study the impact of gravure cell geometry (cell size, depth, and shape) on ink transfer efficiency and coating quality.
c. To evaluate the role of ink parameters (viscosity, surface tension, and solid content) on printability and final film properties.

d. To examine the relationship between process parameters and film characteristics, including thickness, surface roughness, optical transparency, and electrical conductivity.
e. To identify optimal parameter combinations for achieving high-quality, functional printed films suitable for packaging and printed electronics applications.

MATERIAL & METHOD

1. Materials

- **Flexible Substrates:** Commonly used flexible materials such as "polyethylene terephthalate (PET), biaxially oriented polypropylene (BOPP), and polyethylene (PE)" films with controlled thickness and surface treatment.

- **Gravure Inks:** Solvent-based or water-based inks with varying:
    - Viscosity (measured in cP)
    - Surface tension (mN/m)
    - Solid content (%) Functional inks (e.g., conductive silver or carbon-based inks) may also be used for conductivity evaluation.

- **Solvents and Additives:** Suitable diluents, dispersing agents, and binders to adjust ink rheology and stability.

Instruments and Equipment

- **Gravure Printing Machine:** Laboratory or pilot-scale gravure printing setup with adjustable process parameters such as printing speed, impression pressure, and doctor blade angle.
- **Gravure Cylinders:** Cylinders with varying **cell geometries** (cell depth, volume, and line screen) to study their influence on ink transfer.
- **Viscometer/Rheometer:** For measuring ink viscosity and flow behavior.
- **Surface Tensiometer:** To measure ink surface tension.
- **Film Thickness Gauge / Profilometer:** For measuring the thickness and surface profile of printed films.
- **Atomic Force Microscope (AFM) / Surface Roughness Tester:** To analyze surface roughness and morphology.
- **UV-Vis Spectrophotometer:** For measuring optical transparency of printed films.
- **Four-Point Probe System:** To measure electrical conductivity of printed functional films.
- **Drying Unit / Oven:** Controlled drying of printed samples to ensure consistency.

Experimental Design

- A **systematic parametric study** will be conducted by varying:
    - Printing speed (e.g., low, medium, high)
    - Gravure cell geometry (different cell volumes and depths)
    - Ink properties (viscosity and surface tension ranges)

- A **Design of Experiments (DoE)** approach (e.g., factorial design) will be adopted to study the interaction effects between parameters.

Methods / Procedure

1. **Substrate Preparation:** Flexible substrates will be cleaned and conditioned under controlled temperature and humidity to ensure uniform surface properties.
2. **Ink Preparation:** Ink formulations will be prepared by adjusting viscosity and surface tension using solvents and additives. All formulations will be characterized prior to printing.

Printing Process:

- Gravure printing will be performed under controlled environmental conditions.
- Process parameters such as printing speed and impression pressure will be varied systematically.
- Different gravure cylinders will be used to study the effect of cell geometry.

3. **Drying and Curing:** Printed samples will be dried under standardized conditions using a hot air oven or drying unit to ensure complete solvent evaporation.

Characterization of Printed Films:

- **Thickness Measurement:** Using a profilometer or thickness gauge.

- **Surface Roughness:** Measured using AFM or surface roughness tester.

- **Optical Properties:** Transparency analyzed using a UV-Vis spectrophotometer.
- **Electrical Conductivity:** Measured using a four-point probe method.

Data Analysis:

- Statistical analysis will be conducted to determine the significance of each parameter.
- Correlations between process parameters and film properties will be established.
- Graphical and regression analysis will be used to interpret trends and optimize conditions.

4. Date Collection & Result Analysis

According to the screening experiments, "GRAVURE-PRINTED FILMS and solvent content" had a major impact on the printed film's properties, particularly the pinhole area. An attempt was made to lessen the occurrence of pinholes by altering the "GRAVURE-PRINTED FILMS and solvent composition" in the inks, as pinholes are often undesired for functional films. As a result, the solvent was maintained at roughly the same levels but the GRAVURE-PRINTED FILMS content was considerably decreased. Given that a central composite design was selected, "five levels of each factor" were selected. Additional factor levels were selected between the two extremes, and the speed and pressure factor levels were maintained in about the same range. The factor levels selected for this experiment are listed in Table 5.1. Since this experiment employed the same plate as the screening experiment, it should be mentioned that "the cell geometry" variables were only adjusted at two levels.

Table 5: Factor level settings for printing experiment

	Cube Points for Central Composite Design				
Factor	**-2**	**-1**	**0**	**1**	**2**
Roller Pressure (lb/inch)	30	35	40	45	50
Solvent Weight %	10%	15%	20%	25%	30%
Speed (m/min.)	5	10	15	20	25
GRAVURE- PRINTED FILMS Weight%	25%	30%	35%	40%	45%
Stylus Angle	N/A	150	N/A	110	N/A
Tone	N/A	90%	N/A	100%	N/A
Line Screen (cells/in.)	N/A	300	N/A	360	N/A

Initially, it was expected that "the screening experiment" would reveal irrelevant elements that could be removed. On the other hand, the primary experiment excluded only "the ink vehicle type". The Sunester vehicle produced a smaller pinhole area, but "the ink vehicle" had no effect on void area. As a result, the Sunester was selected as the primary experiment's ink vehicle. Since "the same gravure plate" was utilised and could not be altered, the cell shape variables stayed same. There were seven experimental variables in all, all of which were included in "the main experiment" after being determined to be significant in the screening experiment. A mixed central composite design was generated using MINITAB statistical software, with four of the variables classified at five levels and "the cell geometry variables" classified at two levels. Following the experiment, MINITAB was also utilised for data analysis. The run sequence was once more randomised and the experiment was conducted utilising the same printing press operating conditions.

A 1000 µm scan length was used to measure the thickness. To begin the scan, "the profilometer stylus" was placed slightly away from the film on the substrate. About 70% of the scanned profile was made up of "70% film thickness and 30% substrate; that is, on a 1000 µm scan, 200 µm would be used to scan the substrate", after which the stylus would reach the edge of the film, and then 700 µm of film thickness. From the film's edge to the conclusion of the scan on the inside of the film region, it was considered that the thickness remained roughly constant. Additionally, it was believed that the substrate's waviness would not be substantial during the scan. Figure 5.1 displays an example scan.

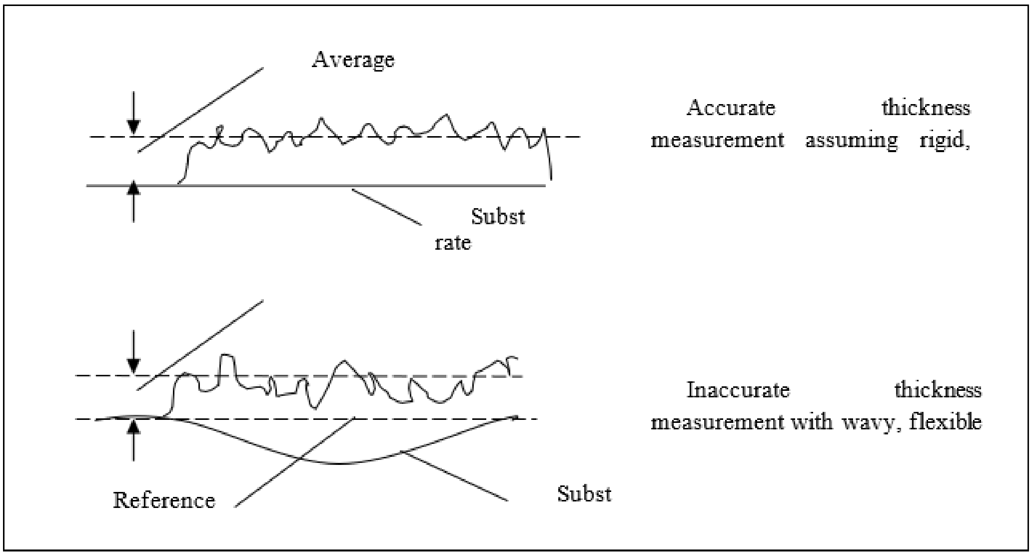

Figure 1: Illustration of waviness effect on thickness measurement

Speed

An analogue dial with settings ranging from 1 to 10 regulates "the printing pace of the K Printing Proofer" utilised in the investigations. Although the machine specifications indicate that it is capable of printing at a rate of 40 m/min, it lacks "any built-in measurement capabilities". The pace at which "the pressure roller assembly" moves across the gravure plate is referred to as the printing speed. A high-speed camera was utilised to record the roller head assembly's movement in relation to a fixed length reference in "order to calibrate the machine for testing". The speed was determined by utilising the high-speed camera software to acquire 'the time elapsed between two fixed reference points", which were spaced three inches apart, and operating the press at each dial setting. Figure 5.2 displays the calibrated speed chart.

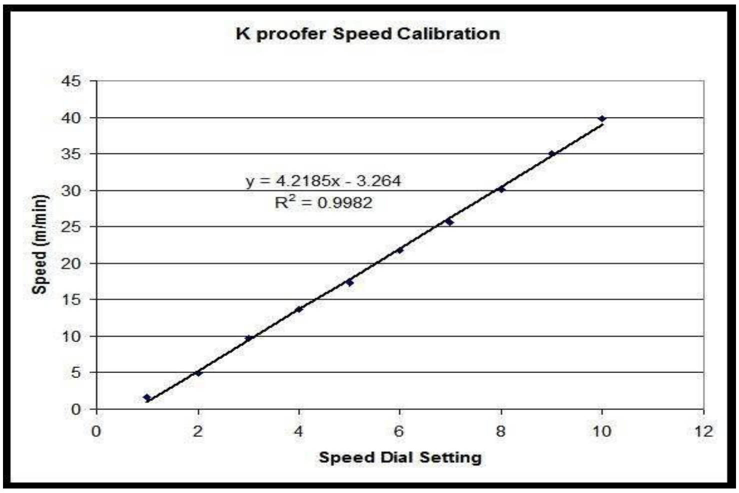

Figure 2: Speed Calibration

Chart for gravure printer

Pressure

Flexiforce thin-film pressure sensors were used to gauge the imprint roller's pressure. "The K printing proofer" does not have direct pressure control. Nonetheless, integrated micrometres can be used to regulate the roller's position in relation to the gravure plate. Consequently, by calibrating the micrometre setting to pressure, the pressure may be indirectly regulated. A complex issue that involves "the geometry of the pressure roller, the friction between the roller and the substrate, as well as between the substrate and the gravure plate", and the dynamic conditions under which it operates is the actual contact pressure between the roller and gravure plate. In addition, a viscoelastic rubber covering the roller was found to 'relax under pressure". "Rubber flattens and the contact area" expands as the roller's pressure increases. As a result, it is more practical to describe the pressure in "pounds per inch, or force per unit length of roller". The force that the micrometres apply to the roller's ends when it is being adjusted may be measured to determine this. Force measurements were conducted using "two Flexiforce piezoresistive force sensors". To provide a consistent loading over the force sensors' detecting region, two tiny steel discs were placed on "the top and bottom of the sensors". The sensors' resistance changed in response to the force change, and the machine's pressure settings were calibrated using the resistance. Figure 5.3 shows "the calibration charts for the two sensors" that were employed.

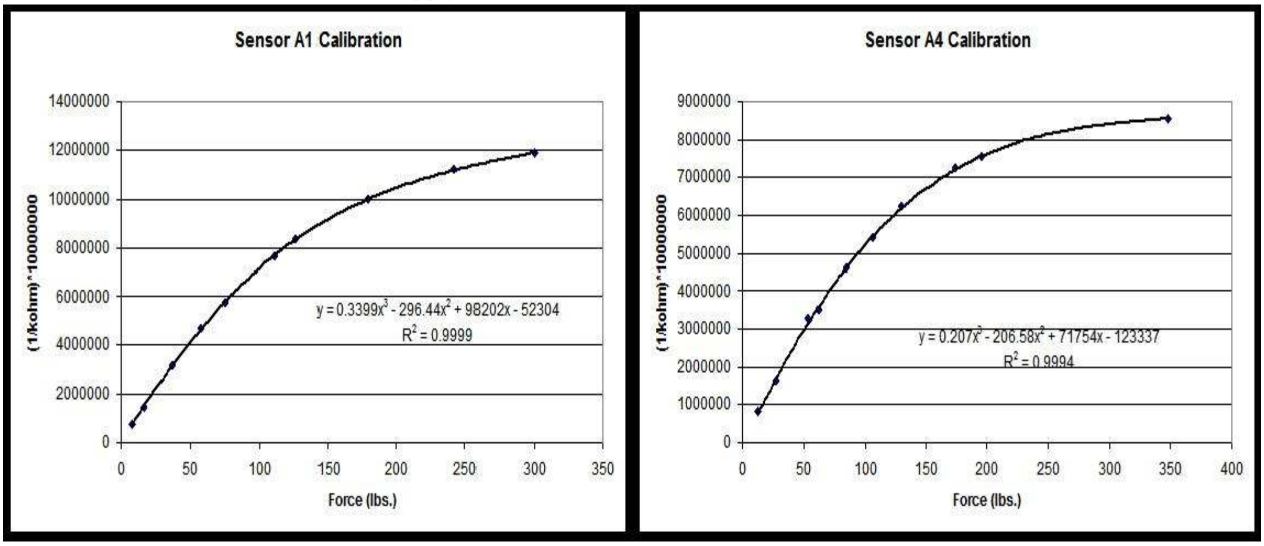

Figure 3: Flexiforce sensor calibration curves

Dwell Time

The duration of close contact between a location on the substrate and the gravure surface is known as the dwell time. This can be readily determined by "measuring the length of contact" for a specific impression roller pressure and subsequently dividing it by the roller's speed. Table 5.2 displays the rubber roller's contact length for each applied pressure setting.

Table 5.2: Pressure, Speed, and dwell time for factor level combinations

Linear Pressure (lbs/in)	Speed (m/min)	Roller Contact Length (mm)	Dwell Time (s)
35	10	15.0	0.090
45	10	17.0	0.102
35	20	15.0	0.045
45	20	17.0	0.051
30	15	13.5	0.054
50	15	17.5	0.070
40	5	16.5	0.198
40	25	16.5	0.040

Cell Geometry

Table 5.3: Cell geometry nominal values

Cell	Nominal Line Screen (cell/inch)	Nominal Stylus (° angle)	Nominal Tone (%)
1	360	110	100
2	360	110	90
3	360	150	100
4	360	150	90
5	300	110	100
6	300	110	90
7	300	150	100
8	300	150	90

CONCLUSION

The performance of printed films deposited on flexible substrates was examined in this work in relation to important gravure printing process parameters, such as "printing speed, impression pressure, gravure cell geometry, ink solid content, and solvent concentration". The findings revealed that gravure cell geometry and ink solid content are the most influential factors affecting film thickness, surface roughness, and print uniformity, while printing speed significantly impacts ink transfer efficiency and coating quality. The results also indicated that "the optical, physical, and functional properties of the printed films" are significantly influenced by the interactions among process parameters. Through statistical analysis and experimental optimization, the study identified process conditions that enhance film uniformity, reduce printing defects, and improve overall film performance. These findings provide valuable insights for optimizing gravure printing processes and support the development of high-quality printed films for applications in flexible packaging, printed electronics, and functional coatings.

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