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Printability Analysis of PLA Films Using Flexographic Solvent-Based Ink According to ISO Specifications

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Abstract: This study analyzes the influence of photopolymer plate hardness and mounting tape on print quality in flexography, with a focus on evaluating the optical and colorimetric parameters of prints on white PLA film. The experiment was carried out in six variations of printing: two hardness of polymer plates in combination with three hardness of mounting tapes. A test image was printed using solvent cyan ink and all key print quality parameters were analyzed, including ink density, tonal values, and CIELAB values in accordance to ISO 12647-6:2012 standard. The results showed that combinations using the softer plate with harder tapes provided the optimal balance between halftone precision, solid density, and colorimetric accuracy. Combinations using the harder plate resulted in lower ink transfer but also less dot gain. Microscopic analysis revealed that combinations of harder plates with softer tapes led to lower ink film uniformity. The study provides useful guidelines for optimizing flexographic printing on PLA substrates.

Keywords: flexography; mounting tape; polymer plate; PLA films; print quality

1 INTRODUCTION

Flexography (often abbreviated to flexo) occupies a leading position in the packaging industry due to its ability to print on a wide range of substrates, including plastics, paper, cardboard, metallized films and non-absorbent substrates [1]. Technological developments in the last decade have enabled a significant improvement in the quality of reproduction in flexographic printing, bringing this technique significantly closer to the quality of gravure and offset printing, especially in segments such as flexible packaging printing, roll-to-roll labels and shrink sleeves [2]. One of the key challenges in flexographic printing is achieving consistent print quality, which includes control of optical density, tonal values, dot formation and color fidelity [3-5]. Parameters that significantly affect these aspects of print quality are the characteristics of the elements that directly participate in the printing process and create pressure on the substrate – primarily clichés and mounting tapes. Polymer clichés, made of flexible photopolymer materials, are available in different hardnesses, which allows adaptation depending on the type of print, printing substrate and print quality requirements [6]. The hardness of the cliché affects the volume of ink transfer, the contact pressure between the printing plate and the printing substrate, and the level of deformation of the cliché in the printing zone [7].

An equally important role is played by the mounting tape, which attaches the cliché to the plate cylinder. Depending on its hardness and compressibility, the tape can soften or intensify the deformations that occur under the pressure of the nip contact, which affects the reproduction of fine details, the stability of the halftone dot and the appearance of unwanted artifacts such as mottle, pinholing and halo effect [8]. Soft tapes enable better contact on rougher surfaces and a larger volume of ink transfer, while hard tapes ensure greater sharpness and control of halftone reproduction, but at the same time increase the risk of excessive pressure and cliché deformation [9].

The relationship between the hardness of the mounting tape and the cliché can be viewed as a dynamic system in which complex mechanical interactions occur during printing. In this system, it is particularly important to understand how these interactions affect measurable print quality parameters. Among them, the solid color density provides information about the amount of ink transferred, while the halftone values show how accurately the printing system has transferred the ink to the substrate. Colorimetric reproduction accuracy, expressed in terms of CIELAB coordinates, additionally describes how visually faithful the color in the print is to the reference.

For the purposes of quality control and mutual comparison of prints, the international standard ISO 12647-6 is used in flexo printing, which defines reference values and tolerances for key reproduction parameters [10]. The use of ISO standards allows for objective assessment of results and comparison with industry norms.

One of the most commonly used materials in the production of flexible packaging is low-density polyethylene (LDPE). However, an environmentally friendly alternative, polylactic acid (PLA), is one of the most promising biopolymers in the field of sustainable packaging [11]. Its application in flexible packaging is becoming increasingly important given the increasingly stringent environmental regulations and growing public concern about plastic pollution [12]. PLA can be formed using standard plastic processing technologies such as extrusion, film blowing and lamination. As a material for flexible packaging, PLA films are most often produced in thicknesses of 40 – 50 microns and are used for the production of food packaging, bags and laminated multilayer materials.

Milky white PLA film are increasingly used in flexible packaging due to its visual neutrality, compatibility with printing inks, and the ability to replace white-colored PE/PP films [13]. In addition, white PLA film provides a light barrier, which is important for the protection of photosensitive products (e.g., food and cosmetics). In the context of printing, PLA represents a challenging substrate due to its low surface energy, which makes it difficult for inks to adhere and requires additional surface preparation before printing, such as corona treatment (surface tension, $\sigma \geq 38$ dyn/cm) [14, 15]. For this reason, the quality of printing on PLA film largely depends on the optimization of all printing parameters – including the choice of clichés, mounting tapes, ink types, and printing conditions. In flexographic printing, PLA is most often used in combination with solvent inks that provide better adhesion and abrasion resistance.

Given the ubiquity of PLA films in modern packaging solutions, the study of parameters that affect the print quality on this material is of high practical importance. The results of this research can contribute to the optimization of the printing process, especially in production conditions where it is important to reconcile the requirements for high print quality with the economy and repeatability of the process.

2 METODOLOGY

As part of this research, an experimental method (Fig. 1) was designed to test the influence of the hardness of the mounting tape and the hardness of the polymer cliché on the quality of solid tone and halftone reproduction in the flexographic printing process.

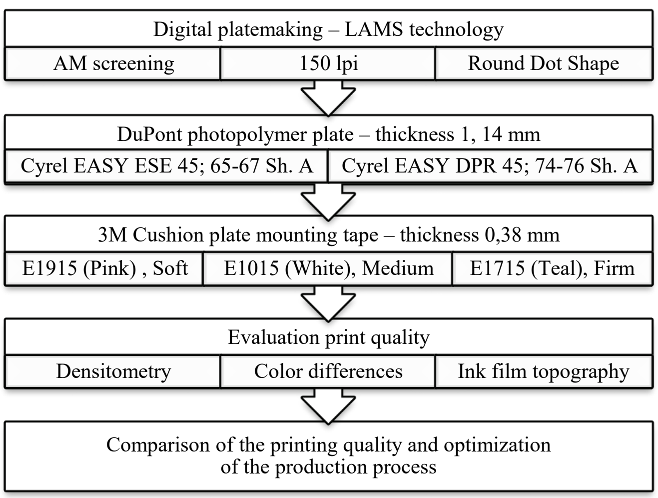

Figure 1 Research framework

For the purposes of the research, an industrial flexo machine for printing flexible packaging was used, and a milky white PLA film, 40 μm thick, was selected as the printing substrate. This material was chosen because of its competitiveness with classic white PE and PP films, with the additional advantage of compostability and environmental friendliness [16]. Its optical properties as well as physical characteristics, especially non-absorbentness and flexibility, make color reproduction challenging. It is most often used in the packaging industry for food products and hygiene products.

2.1 Digital Platemaking Process

The experimental part of this study began with the creation of a test image containing color control patches. These measuring patches allow for the evaluation of print quality using recognized and validated scientific methods and techniques. An amplitude modulated halftone screen, 150 lpi line screen with a round dot shape was used in the screening process. Two types of polymer plates of different hardness, manufactured by DuPont, were used to make the printing plate. The first is a softer plate (Cyrel EASY ESE), hardness 65 – 67 Shore A, intended for rougher printing substrates and lower printing pressures. The second is a harder plate (Cyrel EASY DPR), with a hardness of 74 – 76 Shore A, which is intended for smooth printing substrates and more demanding halftone reproduction. Both clichés were made using the digital CTP process (Computer-to-Plate) on the ESKO CDI Spark 4260 device, using the principle of laser removal of the LAMS layer of the polymer plate (Laser Ablation Mask System), which ensured high precision in the production of printing elements. The cliché thickness was standard – 1.14 mm, which meets the requirements for packaging flexographic printing.

2.2 Printing Process

Printing was performed on an eight-color UTECO Diamond HP 808 central drum flexographic press with a web width of 1250 mm. The process followed the "from roll-to-roll" principle at a printing speed of 200 m/min, using cyan solvent-based inks. The plates were mounted on the plate cylinder using 3M Cushion-Mount E-series mounting tapes, all 0,38 mm thick, which differed in hardness (compressibility). Three types of tapes were used:

- E1915 Plate Mounting Tape (Pink): soft tape, characterized by high compressibility, suitable for a more even print and better adaptation to uneven surfaces (abbreviated term in the article: Soft Tape)
- E1015 Plate Mounting Tape (White): medium-hardness, standard variant suitable for balanced reproduction (abbreviated term in the article: Medium Tape)
- E1715 Plate Mounting Tape (Blue-Green): hard tape, low compression, which ensures better edge formation on the print, but can increase mechanical pressure on the dots (abbreviated term in the article: Firm Tape).

The printing experiment (Tab. 1) was performed in six stages, and in each stage different hardness of the polymer cliché (Softer and Harder) and different hardness of the mounting tape (Soft, Medium and Firm) were used. Each of the two polymer clichés was mounted on the plate cylinder using three different mounting tapes, resulting in six combinations. The test image contained elements for quantitative and qualitative analysis of the print. Solid tone patches were included in the test image to measure optical density and CIELAB values, as well as halftone patches of 25%, 50% and 75% tonal values, which enabled the evaluation of actual tonal values on the print.

Table 1 Technical specifications of the printing process

Printing Specifications	
Flexo printing press	UTECO Diamond HP 808 Mod 120 Flexo CI Printing Press, 8 colors
Printing speed	200 m/min
Web / print width	1250 / 1200 mm
Print repeat min-max	360 – 800 mm
Flexo ink	Sun Chemical SunSpectro Process Cyan solvent based ink
Substrate	PLA Milky White Film; thickness 40 µm
Plate mounting tape, thickness 0,38 mm (0,015 inch)	
Tape 1	3M Cushion-Mount Plate Mounting Tape E1915, Polyethylene Foam, Pink, Soft
Tape 2	3M Cushion-Mount Plate Mounting Tape E1015, Polyethylene Foam, White, Medium
Tape 3	3M Cushion-Mount Plate Mounting Tape E1715, Polyethylene Foam, Teal, Firm
Photopolymer plate, thickness 1,14 mm (0,045 inch)	
Polymer 1	DuPont Cyrel EASY ESE 45, Hardness 65-67 Shore A – Softer plate
Polymer 2	DuPont Cyrel EASY DPR 45, Hardness 74-76 Shore A – Harder plate

Plate-to-substrate printing pressure is a factor that has a major impact on ink transfer and is defined by nip engagement (Fig. 2). The nip engagement between the plate and the substrate was kept constant throughout the experiments at 75 µm, as any variation in this parameter would affect the deformation of the plate against the substrate. Nip is a line of contact between two rolls, plate and impression cylinder. Nip engagement is the positive displacement of the printing plate to the substrate, specified in µm, which increases the printing pressure [17].

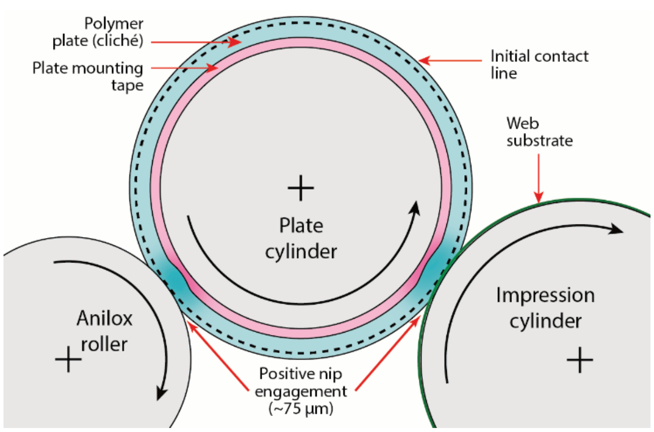

Figure 2 Positive nip engagement between the polymer plate and the substrate

Lower pressure (nip engagement < 50 µm), makes it difficult to transfer ink evenly, primarily when printing on rough printing surfaces. Conversely, if the pressure is too high (nip engagement exceeds 150 µm), the dots will be compressed further, leading to potential deformities [18].

A test form was printed in single color – cyan, using solvent ink. Using one color allowed for isolation of the analyzed parameters and avoidance of interference between colors. The ink was previously prepared and brought to optimal viscosity in accordance with the manufacturer's recommendations and maintained uniformly throughout the printing process.

2.3 Evaluation

To ensure objectivity and comparability of the results, all measurements were performed in accordance with the international standard ISO 12647-6:2012 [10]. According to this standard (for standard flexographic printing), reference CIELAB values for solid tone process inks are defined and are valid for printing on white printing substrates (films and papers) that do not contain optical brighteners. Reference CIELCH values (rounded to the nearest integer) are also defined based on the CIELAB values. The values refer to standard measurement conditions under D50 illumination and a viewing angle of 2°. Tolerances for L^*, a^*, b^* (±3) and tolerances for C^*, $h°$ (±4) are used for precise control of individual components of process inks under industrial printing conditions, to ensure that printers can reproduce colors correctly despite small variations. In this way, tolerances allow the reproduction of perceptually similar colors, but even within this range, differences in perception may occur. The different tolerance for the CIELAB and CIELCH systems is related to the way colors are defined in 3D color space (coordinate or cylindrical system) and how the difference between colors is perceived.

However, as a key condition for determining an acceptable perceptual difference between colors in the flexographic printing industry, the parameter $\Delta h_{ab} < 6°$ is used, and it refers to the change in color hue. Δh_{ab} is a wider tolerance that allows greater perceptual freedom in color, taking into account even a small change in chromaticity and lightness. The reason lies in the fact that people do not perceive colors equally in all directions: even a small change in chromaticity (C^*) or lightness (L^*) can mean that two colors can have different perceptions despite a minor difference in hue (h°). As specified by ISO 12647-6:2012, the recommended CIE LAB values of the print substrate are as follows: L^* should be greater than 88, a^* should range from –3 to +3, and b* should range from –5 to +5. The tested PLA printing substrate meets the stated criteria ($L^* = 91{,}59\%$, $a^* = –0{,}23$, $b^* = 1{,}56$) and has a slight yellowish tone, characteristic of white biodegradable films, as shown by the positive value of the b^* coordinate.

Each of the six variations characterized by the overall compressibility of the printing plate to the substrate was applied in the printing process with the same parameters – printing speed, pressure force and ink viscosity – to eliminate the influence of external variables.

Colorimetric and densitometric measurements of the prints were taken using an X-Rite Exact handheld spectrometer with a 45°/0° geometry, lighting conditions D50/2°, and a 2 mm aperture size. The average value of three measurements is calculated for each observed print quality parameter. The increase in tone value, considered the primary indicator of reproduction quality, is defined as the difference between the measured and nominal dot area coverage of the corresponding color patches. Tonal value increase (*TVI*) is not necessary fully compensated, as this would result in color reproduction that is too light. A controlled TVI within the limits specified by the ISO standard is entirely acceptable phenomenon.

Tab. 2 presents subjective color difference metrics that align with human perception, utilizing the CIEDE2000 equation, which more accurately reflects how human observers perceive color differences [20].

Table 2 Subjective color difference metrics based on the CIEDE2000 equation [20]

k	$\Delta E_{min}(k)$	$\Delta E_{max}(k)$	Perception of color differences
1	0,0	0,5	Hardly
2	0,5	1,5	Slight
3	1,5	3,0	Noticeable
4	3,0	6,0	Appreciable
5	6,0	12,0	Much
6	12,0	24,0	Very much
7	24,0	∞	Strongly

For analyzing the uniformity of the ink film on the print, solid cyan patches were captured throughout all six stages of the printing experiment. For this analysis, a Dino-Lite AM4000 digital microscope was employed, featuring a 1,3 MP resolution and an integrated LED light for enhanced color sample visualization. Samples were captured at 200× magnification and a resolution of 1280×1024 pixels. The Interactive 3D Surface Plot feature, integrated into the ImageJ 1.47 software, was utilized for processing and analyzing the microscopic images.

This methodological approach enabled a clear identification of the impact of individual components of the printing system on solid tone and halftone reproduction, as well as making recommendations for optimizing printing in flexographic packaging production.

3 RESULTS AND DISCUSSION

3.1 Colorimetric Values of Solid Cyan

Using the measured CIELAB and corresponding CIELCH values for solid cyan (Tab. 3) across the six stages of the printing experiment, along with the reference values specified by the ISO 12647-6:2012 standard, color difference value, difference in lightness and hue difference of the samples were calculated (Tab. 4).

Table 3 Colorimetric CIELAB and CIELCH values for solid cyan

Solid Cyan		L (%)	a^*	b^*	C_{ab} (%)	h_{ab} (°)
Reference ISO 12647-6		54 ± 3	−37 ± 3	−50 ± 3	63,0 ± 4	233° ± 4°
Softer Plate	Soft Tape	52,02	−33,61	−55,24	64,66	238,68
	Medium Tape	51,56	−34,75	−51,75	62,33	236,12
	Firm Tape	51,65	−35,92	−52,61	63,70	235,68
Harder Plate	Soft Tape	56,78	−34,38	−57,84	67.29	239,27
	Medium Tape	55,95	−35,85	−57.88	68,08	238,22
	Firm Tape	56,18	−35,18	−56,89	66,89	238,27

The graph in Fig. 3 shows the values of tolerances ΔE_{00}, Δh_{ab} and ΔL for the solid tone of cyan for six stages of the printing experiment compared to the permitted deviations defined in accordance with the ISO 12647-6:2012 standard, which are shown in the figure with dashed lines.

The ΔE_{00} values, which represent the total visual difference between the printed color samples and the given reference, in all combinations except for the combinations of the softer cliché with the Medium and Firm tape slightly exceed the upper tolerance limit ($\Delta E_{00} = 3$). For the two highlighted samples, the values are within the recommended tolerance ($\Delta E_{00} \approx 2.5$), and according to Tab. 2, the difference in color is "Noticeable", while for the other four samples it is already "Appreciable".

Table 4 Difference in lightness and hue, color differences for solid cyan

Solid Cyan		ΔL	ΔE_{00}	Δh_{ab}
Reference ISO 12647-6		$\Delta L \le 3$	$\Delta E_{00} \le 3$	$\Delta h_{ab} < 6°$
Softer Plate	Soft Tape	−1,98	3,03	5,68
	Medium Tape	−2,44	2,65	3,12
	Firm Tape	−2,35	2,51	2,68
Harder Plate	Soft Tape	+2,78	3,81	6,27
	Medium Tape	+1,95	3,09	5,22
	Firm Tape	+2,18	3,13	5,27

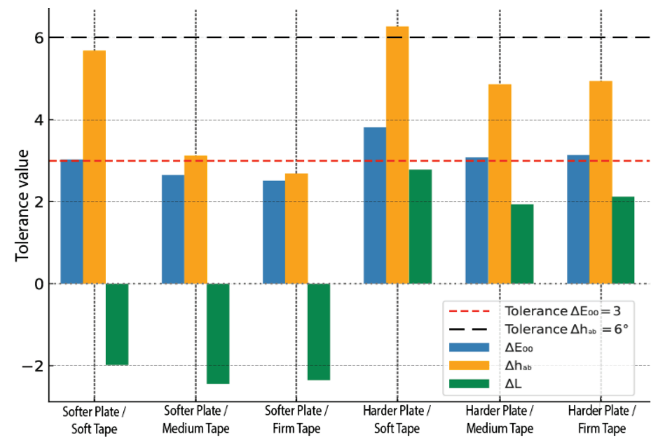

Figure 3 Tolerance values for solid cyan in relation to the permitted values according to the ISO 12647-6:2012

However, ΔE_{00} does not say anything about the colorimetric color change of the samples, but only determines whether the deviation is acceptable or not. A similar pattern to the ΔE_{00} deviation can be seen in the Δh_{ab} values, which represent the change in color hue expressed in degrees – the smallest changes were also noted for combinations of the softer cliché with Medium and Firm tape. The biggest deviations in the color hue were observed in combinations with Soft tapes, where the values of Δh_{ab} are at the upper limit of the deviation of 6°. This indicates the mechanism that Soft tapes, due to its greater compressibility, enable increased cliché contact with the substrate, which leads to increased ink transfer (Fig. 4, image A).

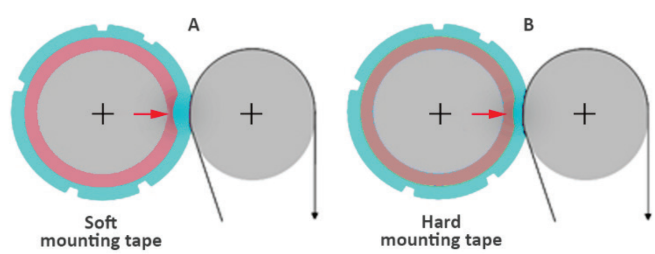

Figure 4 Compressibility effect of the hardness of the mounting plate on the total impression pressure

The ΔL value indicates the difference in lightness of the sample compared to the reference. Negative values mean that the print is darker than the reference, while positive values indicate a lighter result. All combinations with a softer cliché showed negative ΔL values ($\Delta L \approx -2$), which indicates a slightly darker print, but still within tolerance. On the other hand, the use of a harder cliché resulted in lighter prints, with the largest deviation in the combination with Soft tape ($\Delta L = +2,78$), and with increasing tape hardness these deviations decrease. These results confirm the assumption that harder clichés transfer less ink due to its lower compressibility and reduced contact with the printing substrate (Fig. 4, image B), which at the same time gives a significant tone deviation $\Delta h_{ab} > 5°$.

3.2 Halftone Reproduction

In contemporary graphic technology, print quality is largely determined by the fidelity of halftone dot reproduction. The densitometric measured method enables evaluation of all significant print quality parameters. A key factor that affect print quality and the accuracy of dot reproduction is the variation in dot size, which can lead to shift in tone and brightness of color. Therefore, defining TVI is a crucial parameter for characterizing print processes. Table 5 shows the values of the optical density and TVI of cyan measured at three characteristic measurement patches (25%, 50% and 75% TV) for the six phases of the printing experiment. The table also contains the TVI reference values in accordance with ISO specifications for comparison.

Table 5 Optical density and tone value increase for cyan sample

Combinations Plate / Tape	Optical Density *OD*	Tone Value Increase *TVI* (%)		
		25 %	50 %	75 %
Softer Plate / Soft Tape	1,44	22,61	29,93	21
Softer Plate / Medium Tape	1,55	23,18	32,02	21,57
Softer Plate / Firm Tape	1,60	24,23	33,82	21,95
Harder Plate / Soft Tape	1,08	15,49	20,24	14,06
Harder Plate / Medium Tape	1.,19	19,19	23,94	17,77
Harder Plate / Firm Tape	1,25	20,52	25,27	18,15
ISO 12647-6:2012	-	14,00	18,70	13,20

Based on the results of measurements at three key measuring patches, the TVI curves are presented graphically (Fig. 5). Although the curves do not precisely show the reproduction of all tones, they give sufficient insight into how much each stage of the printing experiment deviates from the recommendations of the ISO standard.

TVI in midtones is considered a key criterion for controlling halftone reproduction, as it directly reflects the degree of dot deformation and can result in loss of detail. According to ISO 12647 6:2012, the reference value for *TVI* at 50% is 18,7%. The results of *TVI* with six different combinations showed a clear demarcation of performance precisely in the midtones.

The minimum *TVI* (~ 20%) was achieved with the Harder Plate / Soft Tape combination. This result confirms the theoretical assumption of mechanical interaction in printing: the harder polymer plate provides resistance to deformation, while the soft tape alleviates the contact pressure and prevents the spread of the halftone dots. As a result, the dots remain well formed, but with minimal ink transfer, which is reflected in lower solid densities ($D = 1,08$). Such a print provides exceptional dot sharpness, but may result in slightly lighter and less saturated tones.

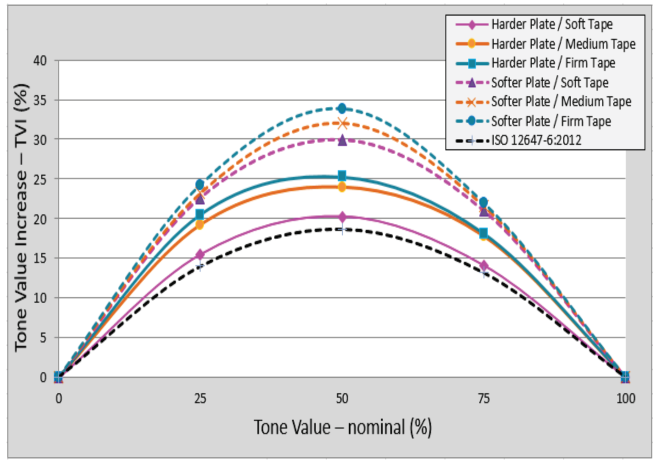

Figure 5 *TVI* curves of six stages of printing experiment

The highest *TVI* (~ 32%) was achieved with the combination of the softer plate with the harder tapes. During the interaction in printing, the opposite mechanism occurs compared to the previously mentioned: the soft cliché, under the pressure of the hard tape, significantly deforms and expands the halftone dots and transfers much more ink. This effect results from the high degree of compressibility of the soft polymer plate, which, together with the hard tape, significantly presses the ink onto the substrate, enabling maximum ink transfer ($D > 1,55$). The result is highly saturated tones, but also blurred and filled halftone dots. Furthermore, the combination of Softer Plate / Medium Tape shows optimal values because the halftone dots remain sharp enough without excessive deformation, and the solid tone are saturated enough to meet commercial requirements.

3.3 Ink Film Topography

In addition to the colorimetric and densitometric values, the print quality of cyan throughout the six experimental stages was also assessed by examining the uniformity of the ink film on the print and the presence of pinholing effect, which is carried out using image analysis [21].

Microscopic images of the solid cyan for evaluation are examined with the ImageJ software (using the Interactive 3D Surface Plot feature), which translates optical density into corresponding height values to illustrate the thickness of the ink film [22]. During the transformation, the *Invert* option was enabled to ensure that the darkest areas—indicating the thickest ink film—would appear at higher elevations in the visualization (Fig. 6).

The optical density projection clearly shows greater uniformity or smoothness of the surface when using softer polymer plates (Stages I – III). Furthermore, improved surface uniformity of both polymer plates occurs when using mounting tapes of higher hardness (Fig. 6, right images). The rightmost samples have a notably smoother surface texture and show fewer visible pinholes compared to the samples on the left side (Fig. 6). The appearance of pinholing can be caused by various factors, and one of the most significant is the thickness of the ink film, which correlates directly with the hardness of the polymer plate.

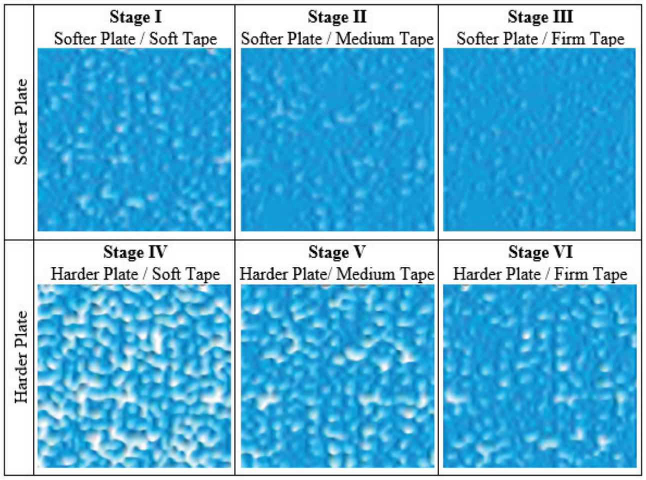

Figure 6 Topographic visualization of solid cyan across various printing stages

4 CONCLUSION

The analysis reveals that the hardness of the mounting tape and polymer cliché is a critical factor in print quality. However, no combination of these parameters achieves perfect performance across all measured criteria. Optimal reproduction of a solid tone depends not only on the amount of transferred ink (as indicated by ΔL), but also on the chromatic characteristics of the color. The combination of a softer cliché with a Medium and Hard tape shows the best results for a solid tone: $\Delta E_{00} \approx 2,5$; $\Delta h_{ab} \approx 3$ with a slightly darker print ($\Delta L = –2,4$). However, the combination of harder plate with Medium tape proved to be the best for halftone reproduction (TVI_{50} = 20,2%), with optimal tolerance values for solid tone. This combination allows for a balanced interaction and creates a good compromise between dot sharpness and solid tone coverage.

The soft polymer itself adapts more to the printing substrate. If combined with a tape that is too soft, the overall compressibility is very high, which leads to excessive ink transfer and therefore an unstable solid tone print ($\Delta h_{ab} \approx 6$). This also leads to excessive *TVI* in the print, which results in reduced contrast and closure of fine details. On the other hand, in combination with harder tapes (Medium and Firm), better control is obtained, while still allowing sufficient ink transfer due to the elasticity of the polymer.

These patterns consistently confirm the theoretical framework, according to which the hardness of the printing plate determines the resistance of the halftone dots to deformation, while the hardness of the tape modulates the contact pressure between the polymer plate and the substrate. The combination of a harder plate and a soft tape optimally preserves details, while a softer plate with a harder tape maximizes ink transfer. If dot sharpness and fine details are a priority (small text and thin lines), the Harder cliché / Soft tape combination is recommended, as it guarantees the most faithful reproduction. Conversely, when the main goal is color intensity and a strong visual impression (background tones on packaging), the Softer plate / Hard tape combination is optimal. Combinations with Medium tape provide a stable, intermediate option that balances well between halftone dot sharpness and color saturation.

In future research, it is recommended to extend the analysis to other colors, substrate types and process parameters to ensure broader applicability of the conclusions obtained.

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