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The influence of pressure during intaglio printing on banknotes durability

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1. Introduction

Intaglio printing (gravure printing, steel engraving) is currently an obligatory way to protect banknotes and other types of products in majority of the world countries due to its ability to provide relief image elements with high tactile effect (portray, inscriptions, digital denomination, micro text) [1]. Intaglio printing machines are the limited accessed equipment as this technology is used only for securities manufacturing.

One of the technological peculiarities of gravure printing is high pressure within the contact area of the plate and printing cylinders. This causes the pressuring effect on the paper which is getting smoother. This influencing factor being an another proof for applying intaglio printing instead of its imitation also influences strength features of the banknote substrate to be printed [2].

2. Analysis of intaglio printing influence on banknotes substrate strength

During the printing nip high pressure causes specific prints of the banknotes substrate resulting in roughing of its fibbers thus creating calendaring effect of the intaglio printing (Fig. 1).

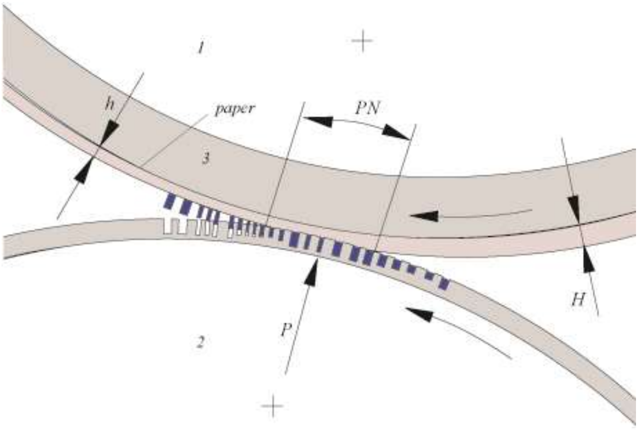

Fig. 1 Schematic image of the printing nip of plate cylinder *1* and printing cylinder *2*. Plate cylinder is covered with blanket *3*

The Fig. 1 shows that after passing through PN nip area paper thickness decreases from *H* to *h* resulting from the pressure *P* caused by the printing cylinder. During intaglio printing high linear pressure between the plate cylinder and printing cylinder (up to 1000 kN/m [3]) causes deforming (embossing) of the paper. Such influence is analogical to paper calendering during its manufacturing. The pressure of the calender rolls is significantly lower constituting 80-100 kN/m, sometimes up to 600 kN/m [4]. Intaglio printing speed is about 8000 pages per hour [3] that taking into consideration page dimensions in printing direction allows determining printing speed as 85-95 m/min while calendering speed is 500-2000 m/min [4]. Thus, paper calendering if compared to intragliopriting is characterized with lower linear loads and shorter pressure influence applied on paper. However if we consider that calenders comprise 10-16 rolls then the time of pressure influence on paper during calendering and intaglio printing may be compared. Additional wetting within 5.5-30% depending on calendering degree is obligatory during the paper calendering. The process of intaglio printing takes place under the conditions of paper moisture within 6.5-7.5% corresponding to calendering degree of writing and printing paper [4].

High pressure caused by steel engraving influences both the structure of the substrate and its surface thus resulting in decreasing of paper porosity. This in its turn leads to establishing stronger bonds between the fibers of the banknotes basis thus strengthening the substrate.

One of the features of the intaglio printing is usage of the viscous inks created on the basis of wax. On its way to plate cylinder the ink temperature in gradually rising: if the temperature is kept within 17-21°C in the ink boxes, the temperature of the chablon rollers is about 34°C, of the collector roller is 36°C and that of the plate cylinder is 80-82°C. Thus, heating system of the plate cylinder melts the ink (to be more correct wax-like compound) changing its rheological properties (decreasing viscosity and increasing flow ability), increasing adhesion and penetration into the structure of substrate. After printing the ink fixing occurs without additional drying as the ink dries again thus creating mechanically strong carcass spread throughout whole banknote surface. Besides, the ink penetrates into the paper. The ink penetration into the paper structure simultaneously seals the substrate providing better bonds between the fibbers [2].

Thus, intaglio printing influences the paper structure and its surface analogically to paper calendering during its manufacturing. Steel engraving seals the substrate structure both by pressuring and by ink penetration into the basis thus decreasing the banknote soiling during its circulation and increasing its strength [2]. All these factors lead to strengthening of the banknote substrate increasing their durability.

3. Testing procedure

To conduct research on determining changes in banknotes deterioration characteristics experimental samples of Ukrainian hryvnia of 2 UAH denominations were manufactured. The technological process of samples manufacturing included offset printing with further intaglio printing. The samples groups differed by intaglio printing parameters (Table 1): single sided intaglio printing with low pressure of printing nip; normal pressure of printing nip; high pressure of printing nip as well as double sided intaglio printing. The process of intaglio printing was performed on "Super - Orlof - Intaglio" printing machine with speed 85 m/min. The pressure of the printing nip during intaglio printing was regulated by increasing and decreasing distance between printing and plate cylinders in relation to the optimal value established for standard banknote printing process. The minimal printing nip pressure was the lowest level provided printing. The difference between maximal and medium pressure was equal to the difference between minimal and medium pressure.

Table 1

Samples manufacture peculiarities

Number	Samples nomination	Printing nip pressure	Printing	
			Front side	Reverse side
1	Single sided, minimal	Minimal	Yes	No
2	Single sided, medium	Medium	Yes	No
3	Single sided, maximal	Maximal	Yes	No
4	Double sided, medium	Medium	Yes	Yes

Experimental samples were artificially deteriorated by means of circulation simulator which is the device with automatic control system of drum rotation. Circulation simulator consists of metal drum (280x220x220 mm) with cover lid, locking clamps and rubber lining able to rotate under certain parameters (frequency, clockwise and counterclockwise movement).

During artificial deterioration the wearing agent as the glass beads of two fractions (2 mm diameters (1 kg weight) and 3.3-3.8 mm (1 kg weight)) provided the multiple mechanical damages to the banknotes.

In order to increase banknotes stiffness in the wear imitation processes the stiffening strips were fixed in left and right samples edge. The stiffening strip is 0.5 mm thick plastic of 10 mm width cut out in dog-bone shape with holes for fixing. To fix the stiffening strips the Teflon weights are used.

In the course of the experiments the deterioration characteristics of the samples before and after wet as well as dry deterioration were analyzed. It was decided to choose as deterioration characteristics optical (brightness, color shift), dimensional (weight, thickness) structural (roughness, air permeability), and strength (bursting strength, tensile elongation, Taber-type stiffness) characteristic changes. The characteristic values were determined for the banknotes of all the groups of samples before and after each cycle of deterioration according to the current normative documents. After all deterioration cycles the local damages of the samples were determined including tears along polymer metalized strip, edge tears, dog ears. The complete list of the characteristics is shown in Tables 2-7.

Wet deterioration of the banknotes was performed in cycles (3 cycles 10 min each) with usage of the soiling mixture modeling organic and inorganic compounds being the basic ones during the banknotes soiling at real circulation. The following substances were chosen for soiling mixture:

1. Solid contaminants including white clay as an analogue of the hygrophilous dirt with developed surface morphology;
2. Liquid contaminants including:
   - sun-flower oil and olive oil used for grease substances imitation;
   - 70% alcohol (ethanol) used for increasing substances containing oxygen groups on surface and within paper substrate. Such substances usually cause banknotes yellowing.
   - artificial substance similar by its content to human perspiration (sodium chloride (4.5 g); potassium chloride (0.3 g); ammonium chloride (0.4 g); sodium sulfate (0.3 g); lactic acid, 80% (3.0 mg); urea (0.2 g), distilled water (1000 ml).

Dry deterioration was conducted without usage of any contaminants within one 120 min cycle.

4. Experimental results

4.1. Banknotes characteristics changes as a result of the deterioration imitation

As a result of deterioration imitation the following changes of optical characteristics of the samples occur: color coordinates difference and banknotes lightness and brightness decrease (Tables 2 and 3). The optical characteristics have been measured near water mark in unprinted part of front side and in printed in light colors part of reverse side of banknotes.

The increasing of thickness and mass of the paper as a result of deterioration are especially notable after first deterioration cycle. Air permeability and roughness increase while stiffness, bursting strength and tensile elongation decrease (Tables 4-6). The damages of the paper edge including tears and dog ears occur (Table 7).

Changes for all optical characteristics are less for the samples manufactured under medium pressure values during the printing nip both for single sided and for double sided intaglio printing.

The smallest increasing of sample thickness as a result of deterioration was observed in case of single sided printing with low pressure during the printing nip. This group of samples is highly durable after dry deterioration.

However, by other characteristics the samples printed under low pressure are the worst. Pressure increasing during intaglio printing allows slowing down soil accumulation on the banknotes thus resulting in thickness increase. However at the last soiling stages (3rd deterioration cycle) this has not been observed (Table 4).

Table 2

Optical characteristics change as a result of deterioration. Color shift

Characteristics	Group	Optical					
	Name	Color difference ΔE^*_{ab} (front side)			Color difference ΔE^*_{ab} (reverse side)		
Deterioration	Type	Wet					
	Number of cycles	1	2	3	1	2	3
Type of samples	Single sided, minimal	4.49	5.67	6.09	4.10	5.47	6.78
	Single sided, medium	4.76	6.08	7.33	3.71	4.69	5.27
	Single sided, maximal	4.56	5.53	6.61	3.90	5.82	6.30
	Double sided, medium	4.73	6.01	7.12	3.98	4.65	5.35

Table 3

Optical characteristics change as a result of deterioration imitation. Brightness

Characteristics	Group	Optical					
	Name	Brightness TAPPI (front side), %			Brightness TAPPI (reverse side), %		
Deterioration	Type	Wet					
	Number of cycles	1	2	3	1	2	3
Type of samples	Single sided, minimal	9.98	11.77	14.10	7.39	9.85	11.25
	Single sided, medium	9.19	12.48	14.77	6.07	7.49	8.49
	Single sided, maximal	9.65	12.86	14.25	8.04	10.21	11.77
	Double sided, medium	9.75	11.17	13.80	6.69	7.64	9.06

Table 4

Dimensional characteristics change as a result of deterioration imitation

Characteristics	Group	Dimensional			
	Name	Increased thickness, mm			Increased weight, %
Deterioration	Type	Wet			
	Number of cycles	1	2	3	3
Type of samples	Single sided, minimal	0.007	0.008	0.008	7.71
	Single sided, medium	0.009	0.008	0.012	5.91
	Single sided, maximal	0.007	0.010	0.012	6.93
	Double sided, medium	0.003	0.007	0.008	5.08

Table 5

Structural characteristics change as a result of deterioration imitation

Characteristics	Group	Structural					
	Name	Roughness, ml/min		Air permeability, ml/min			
Deterioration	Type	Wet	Dry	Wet			Dry
	Number of cycles	3	1	1	2	3	1
Type of samples	Single sided, minimal	3486	4036	0	5	17	201
	Single sided, medium	3373	4217	0	5	14	243
	Single sided, maximal	3326	4239	0	5	22	165
	Double sided, medium	3990	4343	0	0	7	229

Table 6

Strength characteristics change as a result of deterioration imitation

Characteristics	Group	Strength					
	Name	Bursting strength, *H*		Tensile elongation, %		Taber-type stiffness, g*cm	
Deterioration	Type	Wet	Dry	Wet	Dry	Wet	Dry
	Number of cycles	3	1	1	2	3	1
Type of samples	Single sided, minimal	47.50	32.60	9.00	5.70	0.40	0.40
	Single sided, medium	58.15	48.40	11.40	9.00	0.40	0.45
	Single sided, maximal	47.80	45.30	9.10	8.70	0.40	0.40
	Double sided, medium	59.25	39.80	10.50	7.20	0.40	0.40

Generally it may be seen that there is no pressure value under the conditions of single sided intaglio printing that allows obtaining the highest samples durability by all the characteristics. Double sided intaglio printing provides samples with the best optical, structural and dimensional indices and the indices of local damages but comes second after single sided printing by the strength characteristics (Table 6). Thus it is impossible to correctly evaluate intaglio printing parameters influence on banknotes durability on the basis of individual characteristics. Thereby the task to order to determine complex quality characteristic arises [5].

4.2. Determination of the complex banknote paper quality index

Complex banknotes durability characteristic was formed as a result of solving a multicriteria problem of choice by convolution of many criteria to one generalized criterion creating utility function [5]. From the point of view of utility function theory the optimal solution for the multicriteria problem of choice is the alternative with maximal value of utility function $F(x_i)$.

Table 7

Local damages as a result of deterioration imitation

Characteristics	Group	Local damages			
	Name	Total length of tears per banknote, mm	Average length of one tear, mm	Total length of tears along the polymer strip, mm	Average quantity of dog ears per banknote, items
Deterioration	Type	Dry	Dry	Dry	Dry
	Number of cycles	1	1	1	3
Type of samples	Single sided, minimal	56.3	10.7	14.7	2.6
	Single sided, medium	28.4	3.8	7.9	2.6
	Single sided, maximal	63.9	16.9	27.4	2.7
	Double sided, medium	33.8	4.4	4.8	1.6

Table 8

Utility functions of the alternatives - types of banknote paper

Criteria	Group of characteristics	Optical	Dimensional	Structural	Strength	Local damages	Total
	Number of criteria	12	4	7	6	4	33
Utility function		By the groups of characteristics					Complex
Type of samples	Single sided, minimal	0.90	0.72	0.74	0.80	0.45	0.77
	Single sided, medium	0.97	0.69	0.74	1.00	0.81	0.87
	Single sided, maximal	0.89	0.64	0.75	0.90	0.36	0.77
	Double sided, medium	0.97	1.00	0.93	0.91	0.93	0.95

Utility function was determined by additive convolution [5] on basis of Tables 2-7:

$$F\left(x_i\right)=\sum_{j=1}^{k}\omega_j\frac{x_{ij}}{x_{max\ j}}+\sum_{j=k+1}^{m}\omega_j\frac{x_{min\ j}}{x_{ij}}+\sum_{j=m+1}^{n}\omega_j\left(1-\frac{x_{ij}}{x_{max\ j}}\right) \quad (1)$$

where i is the alternative number $X=\left\{x_i \mid i=\overline{1,l}\right\}$ (here- types of samples (Table 1)), j is criterion number, x_{ij} is individual j criterion value for i alternative, l is alternatives quantity (here $l=4$), n is criteria quantity (here $n=33$), ω_j is weight of j criterion, $\sum_{j=1}^{n}\omega_j=1$, $x_{max\ j}$ and $x_{min\ j}$ are the basic individual criteria values as maximal values for the stimulators $x_{max\ j}=\max_i x_{ij}$, $j=\overline{1,k}, x\in S$ and minimal values for destimulators $x_{min\ j}=\min_i x_{ij}$, $j=\overline{k+1,n}, x\in D$, $D=D^{'}\cup D^{0}$:

$$x_{0j}=\begin{cases} x_{max\ j}\ ,\ j=\overline{1,k}, x\in S \\ x_{min\ j}\neq 0,\ j=\overline{k+1,m}, x\in D^{'} \\ x_{min\ j}=0,\ j=\overline{m+1,n}, x\in D^{0} \end{cases}.$$

Utility function (1) was formed by normalization of individual criteria of the alternatives matrix for avoiding probable situation when lacking value of individual utility function in relation to one criterion may be compensated by increasing values of individual utility function in relation to the other criterion. Besides it was taken into consideration the separation of criteria for stimulators (to be maximized) and destimulators (to be minimized) and destimulators presence with basic value of $x_{min\ j}=0$:

$$x_{ij}^{'}=\begin{cases} \dfrac{x_{ij}}{x_{max\ j}},\ j=\overline{1,k}, x\in S \\ \dfrac{x_{min\ j}}{x_{ij}},\ j=\overline{k+1,m}, x\in D^{'} \\ 1-\dfrac{x_{ij}}{x_{max\ j}},\ j=\overline{m+1,n}, x\in D^{0} \end{cases}. \quad (2)$$

It is necessary to note here that under our research the stimulators are the bursting strength, tensile elongation and Taber stiffness. All other criteria are the destimulators.

The Table 8 shows the values of the utility functions of the alternatives – the types of samples obtained under different technological modes of intaglio printing for different groups of characteristics according to the equation (1) with supposition of equal weight of all criteria.

Formed utility functions show that in totality of characteristics the most durable are the samples obtained under medium pressure during the printing nip at double side intaglio printing.

5. Conclusions

1. Durability of the experimental samples of the Ukrainian hryvnia banknotes different by intaglio printing parameters (single side intaglio printing with low pressure of printing nip; normal pressure of printing nip; high pressure of printing nip as well as double side intaglio printing) were analyzed comparing the optical, dimensional, structural, and strength characteristic changes after wet and dry deterioration.

2. Under the conditions of single side intaglio printing there is no pressure value allowing obtaining the highest samples durability by all the characteristics. Double sided intaglio printing provides samples with the best optical, structural and dimensional indices and the indices of local damages but comes second after single side printing by the strength characteristics.

3. As it is impossible to correctly evaluate intaglio printing parameters influence on banknotes durability on the basis of individual characteristics the complex quality index was determined on basis the utility function considering large quantity of durability characteristics.

Utility functions obtained for every alternative (mode of intaglio printing) allow concluding that samples printed under medium pressure of printing nip during double side intaglio printing are the most durable by the totality of all the characteristics. This means that double side intaglio printing application makes it possible to increase significantly banknotes durability

References

1. **Van Renesse, R.L.** 2005. Optical document security. Third edition. Artech House. 368p.
2. **Crane, T.** 2011. Some observation on technological developments in durable substrates, Int. Rev. on Cash Management 9: 9.
3. **Kipphan, H.** 2001. Handbook of Print Media. Technologies and Production Methods. Springer. 1207p. http://dx.doi.org/10.1007/978-3-540-29900-4.
4. **Holik, H.** 2006. Handbook of paper and board. Wiley-VCH. 505p. http://dx.doi.org/10.1002/3527608257.
5. **Kyrychok, T.** 2013. Algorithm for solving multicriteria problem of choice of banknote deterioration characteristics using the utility function, Research Bulletin of National Technical University of Ukraine Kyiv Polytechnic Institute 1: 68-75.

T. Kyrychok, P. Kyrychok, S. Havenko, E. Kibirkštis, V. Miliūnas

SLĖGIO ĮTAKA BANKNOTŲ PATVARUMUI SPAUSDINANT GILIASPAUDE

R e z i u m ė

Dėl didelio slėgio kontakto zonoje (iki 1000 kN/m) spausdinant giliaspaude, banknoto struktūra yra suspaudžiama ne tik prispaudimo cilindro, bet ir dažų įsigėrimo metu. Šis poveikis sumažina banknoto ištepliojimą dažais, padidina jo atsparumą, kas pagerina patvarumą. Buvo nagrinėtos skirtingais giliaspaudės parametrais atspausdintų (esant vienpusei ir dvipusei spaudai su žema, vidutine ir didele kontakto zona) eksperimentinių bandinių patvarumo charakteristikos. Remiantis naudingumo funkcijomis, gautomis kiekvienam atvejui (skirtingiems giliaspaudės rėžimams) nustatyta, kad dvipuse spauda ir esant vidutinei kontakto zonai atspausdinti bandiniai pasižymėjo didžiausiu patvarumu. Todėl dvipusė giliaspaudė sudaro galimybę padidinti banknotų patvarumą.

T. Kyrychok, P. Kyrychok, S. Havenko, E. Kibirkštis, V. Miliūnas

THE INFLUENCE OF PRESSURE DURING INTAGLIO PRINTING ON BANKNOTES DURABILITY

S u m m a r y

Due to high pressure during the printing nip (up to 1000 kN/m) intaglio printing seals the banknote substrate structure both by pressing and by ink penetration into the paper. This effect decreases banknotes soiling and increases their strength resulting in durability increase. Durability characteristics of the experimental samples of banknotes different by intaglio printing parameters (single side intaglio printing with low, medium and high pressure of printing nip as well as double side intaglio printing) were analyzed. On basis of utility functions obtained for every alternative (mode of intaglio printing) it was concluded that samples printed under medium pressure of printing nip during double side intaglio printing are the most durable by the totality of all the deterioration characteristics. Thus double side intaglio printing makes it possible to increase banknotes durability.

Keywords: intaglio printing, banknotes, durability, pressure, utility functions.

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