PRELIMINARY COMMUNICATION

ACTA GRAPHICA 241

Analysis of Printing Substrate, Ink Age and Number of IR Drying Influence on Electrical Resistance of Conductive Inks

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Abstract:

As a result of availability of new technologies, functional printing as a segment has become one of the most interesting directions of research and development in graphic technology. Conductive inks are not a novelty and they already have broad possibilities in production of everyday products. There is still a big market for the broadening of their use, as well as a possibility of further enhancing their properties. This paper analyzes the influence of printing substrate, age of ink and the number of IR drying on the electrical resistance of the conductive inks. In the paper, subject of analysis was the change of electrical resistance in the line that was 9 cm long and 10 typographic points wide. The semi-automated screen-printing machine was used for printing. Three types of printing substrates were used; uncoated, coated and recycled paper. Two types of inks were used; newly opened ink and ink that was out of date for half year. After the printing, prints were dried using the IR dryer. Prints were dried once, and then additional three times. After the first and last drying, multimeter was used to measure electrical resistance of the lines. Analysis of the data shows that the older ink produces prints with higher electrical resistance. There are also notable differences in the electrical resistance based on the printing substrate.

Keywords:

conductive inks, printing substrate, screen-printing, IR drying, electrical resistance.

1 Introduction

As a result of availability of new technologies, functional printing as a segment has become one of the most interesting directions of research and development in graphic technology. Conductive inks are not a novelty and they already have broad possibilities in production of everyday products. There is still a big market for the broadening of their use, as well as a possibility of further enhancing their properties.

Tendency of functional print developing is to achieve more wider application of these printing inks, so that products that exist today could be further advanced, and that the new ones could be made. This paper addresses the change in electrical resistance of prints as well as the idea of conductive inks. The influence of printing substrate, the age of the ink and the number of IR drying on the electrical resistance of the conductive inks will be analyzed. It is important to determine whether the electrical resistance is identical on different printing surfaces. Considering the fact that used printing ink is relatively expensive, it's useful to see if it is still useable after the expiration date, since it is very short, barely six months.

The idea that the length of drying influences the electrical resistance will be tested. The hypothesis is that longer IR drying lowers the electrical resistance of the ink. The electrical resistance of the printed lines will be measured with multimeter, in order to check whether increasing the number of drying reduces electrical resistance. The results will be analyzed using descriptive, inferential and multivariate statistics, and presented graphically.

2 Theoretical Framework and Problem Approach

Functional printing provides certain functionality to printed material. It can be sensitivity to the temperature, light, a certain part of electromagnetic radiation, electrical conductivity, etc. Product that was produced in that way has the added function and added value, and is commonly used in technologies that are fast developing (Cui et al., 2010).

Many products which can be easily produced on a large scale and possess outstanding electronic properties, have great potential for the convenient fabrication of flexible and low-cost electronic devices by using a simple screen-printing technique (Wu et al., 2014). But it's a well-known long-term material problem of thin film organic electronics, namely the solution processing of an opaque electrode (Frantz et al., 2015), which could be in future replaced by paper. The widespread usage of paper and cardboard offers largely unexploited possibilities for printed electronics applications. Reliability and performance of printed devices on comparatively rough and inhomogeneous surfaces of paper does however pose challenges (Dogome, Enomae and Isogai, 2013). Therefore paper media can be used as low cost, but comparably high performance substrate for metal nanoparticle inks in printed electronics applications (Öhlund et al., 2012). This is especially applicable in production of solar cells.

Solar cells of the new generation could be based on this technology since production and materials required for optimal operation are cheaper than conventional technologies used in production of solar cells. (Lennon et al., 2008; Lennon et al. 2009).

Aliaga et al. (2015) in their paper analyzed the effects of the presence of printed electronics on the paper waste streams and specifically on paper recyclability. The analysis is based on a case study focused on envelopes for postal and courier services provided with these intelligent systems. Results show that differences between new and recycled papers shouldn't cause problems or restrict the use of recycled paper in current applications.

Nanotechnology is becoming vitally important in many industrial fields, especially in fabrication of electronic devices. Many papers are putting emphasis on its multi-disciplinary nature and convey the enormous impact that nanotechnology will progressively make on materials, product and process research and therefore on the manufacturing technologies, industry and the economies of countries throughout the world (Corbett et al., 2007). The fabrication of electronic devices requires the printing of small, narrow and thin conductive lines (Florian et al., 2015), which can be printed in different printing techniques (Sowada et al., 2015). The electro-conductive ink can be printed using screen-printing technique, ink jet technique, digital printing, pad printing, and offset printing depending on the type of printing substrate. Screen-printing is a common useful method for fabricating electrodes or signal wires of electronic devices (Nomura et. al., 2014). Commonly used as electrically conductive inks are those with the silver, gold, palladium, mercury or copper particles. Each of said particles have different physicochemical properties, and depending on the purpose of future print the most appropriate is selected. Printing of any metal nanoparticles is an attractive method for direct patterning conductive metal lines thanks to low-cost, low-waste, and simple process (Park et al., 2007). Gizachew et al. (2011) emphasized the influence of annealing temperature on printed line resistance. Drying, as well as sintering, is associated with the conductivity of the printed conductive patterns

(Huang, 2014). When the temperature of substrate increases, a significant reduction of ink spreading was observed which leads to increased conductivity. Conductivity was also related to the dispersion state of the ink (Woo et al., 2013; Mun et al., 2011). It is important to emphasize that drying and sintering of printed metal nanoparticles can be made not only by conventional heating, but also by e.g., electrical, microwave, plasma, laser and flash lamp annealing such as IR lamp (Tobjörk et al., 2012). When the electricity passes through the lines that were printed with conductive inks, electrical resistance occurs. It is a ratio of voltage and electric current, and the conductivity of conductive inks is reciprocal to their electrical resistance. Regarding the temperature, the resistance of metals increases with increasing temperature. (Bakshi and Bakshi, 2008).

The question developed from those facts; how do the conductive inks act when we treat them with different temperatures. Since the viscosity of the ink decreases with the increase of temperature, which changes its physical and chemical properties, printed layer can be dried by various methods, as mentioned above. IR radiation is one of the most commonly used methods for drying (Tobjörk et al., 2012). IR dryers radiate in on of three ranges; Shortwave (air penetrates into the paper 0.8 - 2 mm), middle wave (air penetrates into the paper 2-4 microns) and long wave (not suitable for drying because the air penetrates into the paper 4 microns - 1mm). However, with the many advantages, IR drying has a high cost, both initial and in the application because it requires a lot of power consumption (Şahïnbaşkan and Köse, 2010).

3 Experimental Research

3.1 Methodology of research

For the purpose of this paper the printing form for screen printing with print surfaces in the form of lines that are 9 cm long and 10 typographic points thick. Screen printing mesh had a liniature of 90 lines/cm, with a thread diameter of 48 microns. Threads were strained at an angle of 0 degrees. As a photosensitive layer, Fotecoat 1010 diazo emulsion for double hardening was used. The emulsion is pale-purple in color and with medium viscosity. It has a short exposure time. The resulting film had a good resistance and could be used with a broad range of printing inks. Prints were made using the semi-automatic screen-printing machine. Three substrates were used; uncoated, coated and recycled paper.

As printing ink, CRSN2442 Suntronic Silver 280 Thermal Drying Silver Conductive Ink was used, both new one and one that was used for two years. The ink is intended for screen-printing technique. It can te printed on the classical substrates and flexible ones. It dries quickly and provides a low electrical resistance. It can be used in all types of screen-printing machines (manual, semi-automatic, automatic) and does not need to be diluted. Increase in drying temperature reduces its electrical resistance. Resistance also depends on the liniature, emulsion thickness, printing speed, squeegee hardness and drying conditions. The ink can be used for six months after opening.

Finished prints were dried once with the IR dryer at 130° C. Electrical resistance was measured after the prints were dried. The prints were then dried three more times at the same temperature. Resistance was measured again, using the Velleman DVM1200 multimeter. Twenty five prints of each ink on each type of paper were made. Overall, 300 measurements were made.

3.2 Descriptive Statistics of measured values

In the first step, descriptive statistics of measured values was made. It was used to determine normality of data and their convenience for further statistical analysis and interpretation. Descriptive Statistics of measured values of printed lines on three types of substrate with new ink, dried once and four times.

Table 1. Number of valid cases

Between-Subjects Factors		
		N
Drying	1x	75
	4x	75
Type	Uncoated	50
	Coated	50
	Recycled	50

Table 1 shows number of valid cases of measured values of printed lines on a three types of substrate (uncoated, coated and recycled paper) printed with a new ink. All printed lines are dried once and four times.

Table 2 shows a descriptive statistics of measured values of printed lines on a three types of substrate (uncoated, coated and recycled paper) with new ink. Also all printed lines are dried once and four times.

Table 2. Descriptive Statistics of measured values of printed lines on a three types of substrate with a new ink, dried once and four times

Descriptive Statistics				
Dependent Variable: Resistance				
Drying	Type	Mean	Std. Deviation	N
1x	Uncoated	3,8400	,08165	25
	Coated	4,8200	,30551	25
	Recycled	6,1800	,18028	25
	Total	4,9467	,98795	75
4x	Uncoated	3,3400	,08165	25
	Coated	3,9200	,15000	25
	Recycled	4,5400	,11547	25
	Total	3,9333	,50707	75
Total	Uncoated	3,5900	,26515	50
	Coated	4,3700	,51319	50
	Recycled	5,3600	,84177	50
	Total	4,4400	,93321	150

Standard deviation or absolute measure of dispersion shows that there are low percent deviations in electrical resistance of printed lines, in comparison to average values of the electrical resistance for all three types of substrate and both drying times. It shows us that the variability is low. Lowest variability was in the case of line that was printed on recycled paper and dried once (,92%). while the highest was in the case of line that was printed on coated paper and dried once (6,34%) which shows Table 2.

Furthermore, Figures 1 and 2 show that there is difference in arithmetic mean of measured values of electrical resistance in the lines printed with new ink on all three types of substrate (uncoated, coated and recycled paper), in both cases of drying.

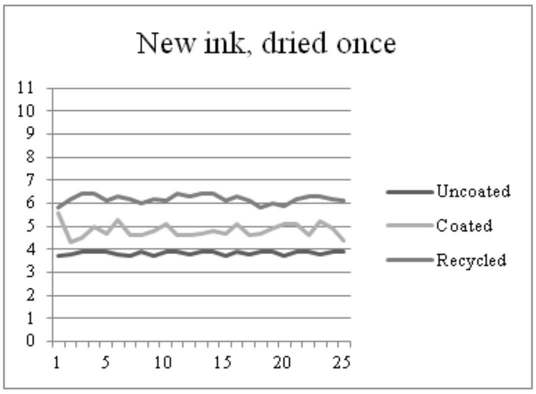

Figure 1. Arithmetic means of measured electrical resistance of the lines printed with new ink on three types of substrate, dried once

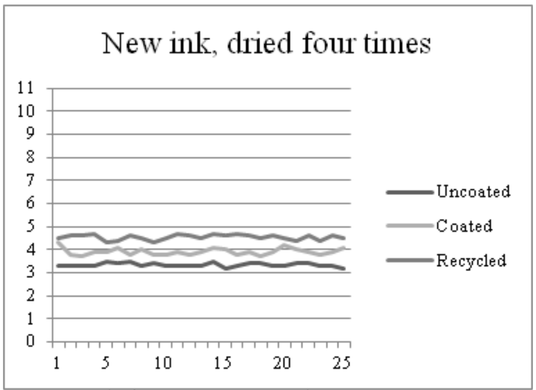

Figure 2. Arithmetic means of measured electrical resistance of the lines printed with new ink on three types of substrate, dried four times

Descriptive Statistics of measured values of printed lines on three types of substrate with old ink, dried once and four times.

Table 3. Number of valid cases

Between-Subjects Factors		
		N
Drying	1x	75
	4x	75
Type	Uncoated	50
	Coated	50
	Recycled	50

Table 3 shows number of valid cases of measured values of printed lines on three types of substrate (uncoated, coated and recycled paper) printed with old ink. All printed lines are dried once and four times.

Table 4. Descriptive Statistics of measured values of printed lines on three types of paper with old ink, dried once and four times

Descriptive Statistics				
Dependent Variable: Resistance				
Drying	Type	Mean	Std. Deviation	N
1x	Uncoated	4,2800	,06455	25
	Coated	7,1560	,37537	25
	Recycled	10,3000	,15546	25
	Total	7,2453	2,48609	75
4x	Uncoated	3,5000	,08165	25
	Coated	4,9200	,34400	25
	Recycled	6,5160	,17720	25
	Total	4,9787	1,26055	75
Total	Uncoated	3,8900	,40064	50
	Coated	6,0380	1,18423	50
	Recycled	8,4080	1,91832	50
	Total	6,1120	2,26976	150

Standard deviation or absolute measure of dispersion also shows that there are low percent deviations in values electrical resistance of printed line from the average values in all three types of substrate and both times of drying. It shows us that the variability is low. Lowest variability was in the case of line that was printed on uncoated and recycled paper and dried once (1,51%). while the highest was in the case of line that was printed on coated paper and dried four times (6,99%) which shows Table 4.

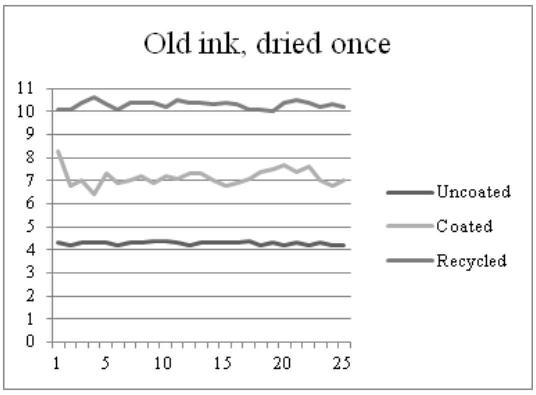

Figure 3. Arithmetic means of measured electrical resistance of the lines printed with old ink on three types of substrate, dried once

It was concluded from the results that the measured values are appropriate for the further statistical interpretation and analysis of variance. One Way ANOVA test was used. In the Figures 3 and 4, differences in arithmetic mean of measured values of electrical resistance in the lines printed with old ink on all three types of substrate (uncoated, coated and recycled paper), in both cases of drying.

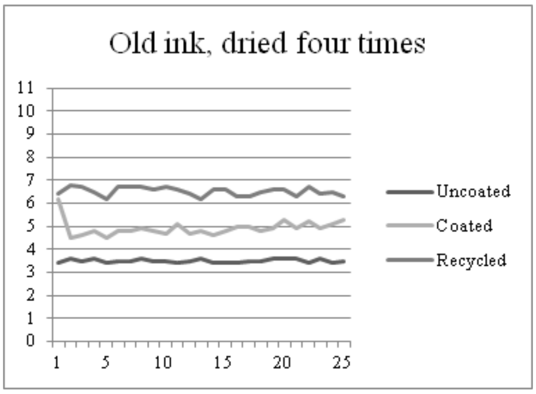

Figure 4. Arithmetic means of measured electrical resistance of the lines printed with old ink on three types of substrate, dried four times

4 Results Discussion

4.1 New ink

Univariate Analysis of Variance

Before testing the difference of effects among drying time and type of paper on the resistance of the lines printed with a new ink, Levene's Test of Equality of Error Variances of type of drying time and type of paper was conducted. This test was used to assess the equality of variances for a variable calculated for two groups, drying time and type of paper. It tests the null hypothesis that the population variances are equal regarding the result

Table 5. Levene's Test of Equality of Error Variances of type of drying time and type of paper

Levene's Test of Equality of Error Variancesa			
Dependent Variable: Resistance			
F	df1	df2	Sig.
12,112	5	144	,000
Tests the null hypothesis that the error variance of the dependent variable is equal across groups.			
a. Design: Intercept + Drying + Type + Drying * Type			

of p-value, which is less than significance level of .05 as Table 5 shows. It can be concluded that the average values of the tested groups are not equal.

Below are the results of tests of Between-Subjects Effects of type of drying time and type of paper (Table 6). Observing the level of statistical significance of p-value (less than ,05), it can be concluded that the independent variables of drying time and type of paper are significant; they influence in the change of electrical resistance of the printed lines. It is interesting to point out that the difference in values of electrical resistance of the lines printed with new ink is around 66,6% with the different drying time and type of substrates. The biggest difference in value of electrical resistance is between the lines printed on the uncoated paper and dried four times and the lines printed on recycled paper and dried once.

Table 6. Tests of Between-Subjects Effects of type of drying time and type of paper

Tests of Between-Subjects Effects						
Dependent Variable: Resistance						
Source	Type III Sum of Squares	do	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	125,560a	5	25,112	860,983	,000	,968
Intercept	2957,040	1	2957,040	101384,229	,000	,999
Drying	38,507	1	38,507	1320,229	,000	,902
Type	78,690	2	39,345	1348,971	,000	,949
Drying * Type	8,363	2	4,182	143,371	,000	,666
Error	4,200	144	,029			
Total	3086,800	150				
Corrected Total	129,760	149				
a. R Squared = ,968 (Adjusted R Squared = ,967)						

Estimated Marginal Means, Drying time

In the next step, estimates of dependence of resistance of a lines printed with a new ink on a drying time (Table 7) was calculated. Estimated marginal means (4,947 for dried once and 3,933 for four times dried) are equal to the means from Table 2. There is no difference between means.

Observing the level of statistical significance of p-value (less than ,05), it can be concluded that the independent variable of drying time is significant, because the observed arithmetic means of values of electrical resistance in lines that are dried once and dried four times, are not the same. Also, mean difference shows that the difference in the value of electrical resistance in lines printed with new ink and dried once is 1,013mΩ more than the same line that was dried four times (Table 8).

Table 7. Estimates of dependence of dependent variable (resistance) on drying time

Estimates				
Dependent Variable: Resistance				
Drying	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1x	4,947	,020	4,908	4,986
4x	3,933	,020	3,894	3,972

F-test was conducted to determine the significance of independent variables; both times of drying, and their influence on electrical resistance of printed lines (Table 9). Level of statistical significance of p-value (less than ,05) shows that the change of drying time is significant, because the arithmetic means of observed groups are not the same.

Type of paper

The dependence of resistance of lines printed with new ink on a type of paper was also calculated (Table 10). Estimated marginal means (3,590 for uncoated paper, 4,370 for coated paper, and 5,360

Table 8. Pairwise Comparison of dependent variable (resistance) on drying time

Pairwise Comparisons						
Dependent Variable: Resistance						
(I) Drying	(J) Drying	Mean Difference (I-J)	Std. Error	Sigma	95% Confidence Interval for Differencea	
					Lower Bound	Upper Bound
1x	4x	1,013*	,028	,000	,958	1,068
4x	1x	-1,013*	,028	,000	-1,068	-,958
Based on estimated marginal means						
*. The mean difference is significant at the ,05 level.						
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).						

Table 9. Univariate tests of the effects of drying times to the resistance of printed lines

Univariate Tests						
Dependent Variable:Resistance						
	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	38,507	1	38,507	1320,229	,000	,902
Error	4,200	144	,029			
The F tests the effect of Drying. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.						

for recycled paper) are equal to the means from Table 2. There is no difference between means.

Level of statistical significance of p-value (less than ,05) shows that the change of printing substrate (type of paper) is significant, because the arithmetic means of observed groups are not the same. Mean Difference also shows that the electrical resistance of the lines printed with new ink on uncoated paper is lower for ,780mΩ in comparison

Table 10. Estimates of dependence of dependent variable resistance on type of paper

Estimates				
Dependent Variable: Resistance				
Type	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Uncoated	3,590	,024	3,542	3,638
Coated	4,370	,024	4,322	4,418
Recycled	5,360	,024	5,312	5,408

to coated paper, and for 1,770mΩ in comparison to recycled paper. The resistance of printed lines on coated paper is lower for ,990mΩ in comparison to recycled paper (Table 11).

F-test was conducted to determine the significance of independent variables; all three types of substrates (papers) and their influence on electrical resistance of printed lines (Table 12). Level of statistical significance of p-value (less than ,05) shows that the change of printing substrate (paper) is significant, because the arithmetic means of observed groups are not the same.

Values in Table 13 and the profile plots on Figure 5 can confirm us the results of previous Pairwise Comparisons Tests that the influence of change in printing substrate (paper) and drying time is significant, when we observe the change in electrical resistance of printed lines.

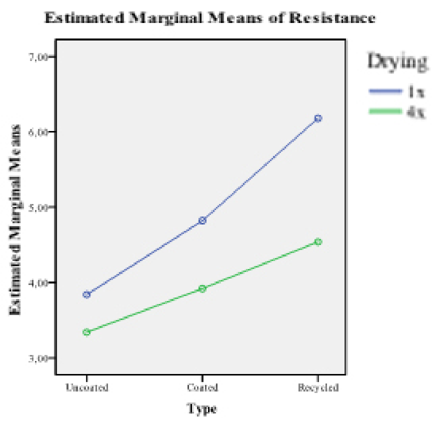

Figure 5. Profile Plots f Estimated Means of Resistance of new ink

Table 11. Pairwise Comparison of dependent variable resistance on type of paper

Pairwise Comparisons						
Dependent Variable:Resistance						
(I) Type	(J) Type	Mean Difference (I-J)	Std. Error	Sig.a	95% Confidence Interval for Differencea	
					Lower Bound	Upper Bound
Uncoated	Coated	-,780*	,034	,000	-,848	-,712
	Recycled	-1,770*	,034	,000	-1,838	-1,702
Coated	Uncoated	,780*	,034	,000	,712	,848
	Recycled	-,990*	,034	,000	-1,058	-,922
Recycled	Uncoated	1,770*	,034	,000	1,702	1,838
	Coated	,990*	,034	,000	,922	1,058
Based on estimated marginal means						
*. The mean difference is significant at the ,05 level.						
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).						

Table 12. Univariate tests of the effects of drying time to the resistance of printed lines

Univariate Tests						
Dependent Variable:Resistance						
	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	78,690	2	39,345	1348,971	,000	,949
Error	4,200	144	,029			
The F tests the effect of Type. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.						

Table 13. Estimates of dependence of dependent variable resistance on drying time and type of paper

3. Drying * Type					
Dependent Variable:Resistance					
Drying	Type	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1x	Uncoated	3,840	,034	3,772	3,908
	Coated	4,820	,034	4,752	4,888
	Recycled	6,180	,034	6,112	6,248
4x	Uncoated	3,340	,034	3,272	3,408
	Coated	3,920	,034	3,852	3,988
	Recycled	4,540	,034	4,472	4,608

4.2 Old ink

Univariate Analysis of Variance

Like in the first part, before testing the difference of effects among drying time and type of paper on the resistance of the lines printed with an old ink, Levene's Test of Equality of Error Variances of type of drying time and type of paper was conducted. Test was used in this case to assess the equality of variances for a variable calculated for two groups, drying time and type of paper. It tests the null hypothesis that the population variances are equal regarding the result of p-value which is less than significance level of .05, as Table 5 shows. It can be concluded that the average values of the tested groups are not equal. Below are the results of tests of Between-Subjects Effects of type of drying time and type of paper (Table 15). Observing the level of statistical significance of p-value (less than ,05), it can be concluded that the independent variables of drying time and type of paper are significant; they influence in the change of electrical resistance of the printed lines. It is interesting to point out that the difference in values of electrical resistance of the lines printed with old ink is around 87,8% with the different drying time and type of substrates. The biggest difference in value of electrical resistance is between the lines printed on the uncoated paper and dried four times and the lines printed on recycled paper and dried once. The same conclusion was in the analysis of prints that were made with new ink.

Table 14. Levene's Test of Equality of Error Variances of type of drying time and type of paper

Levene's Test of Equality of Error Variancesa			
Dependent Variable:Resistance			
F	df1	df2	Sig.
8,427	5	144	,000
Tests the null hypothesis that the error variance of the dependent variable is equal across groups.			
a. Design: Intercept + Drying + Type + Drying * Type			

Table 15. Tests of Between-Subjects Effects of type of drying time and type of paper

Tests of Between-Subjects Effects						
Dependent Variable: Resistance						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	759,803a	5	151,961	2799,971	,000	,990
Intercept	5603,482	1	5603,482	103247,690	,000	,999
Drying	192,667	1	192,667	3550,005	,000	,961
Type	510,719	2	255,359	4705,158	,000	,985
Drying * Type	56,418	2	28,209	519,766	,000	,878
Error	7,815	144	,054			
Total	6371,100	150				
Corrected Total	767,618	149				
a. R Squared = ,990 (Adjusted R Squared = ,989)						

Estimated Marginal Means, Drying time

In the next step, estimates of dependence of resistance of a lines printed with a new ink on a drying time (Table 16) was calculated. Estimated marginal means (7,245 for dried once and 4,979 for four times dried) are equal to the means from Table 2. There is no difference between means.

Observing the level of statistical significance of p-value (less than ,05), it can be concluded that the independent variable of drying time is significant, because the observed arithmetic means of values of electrical resistance in lines that are dried once and dried four times, are not the same. Also, mean difference shows that the difference in the value of electrical resistance in lines printed with old ink and dried once is 2,267mΩ more than the same line that was dried four times (Table 17).

Table 16. Estimates of dependence of dependent variable resistance on drying time

Estimates				
Dependent Variable:Resistance				
Drying	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
1x	7,245	,027	7,192	7,299
4x	4,979	,027	4,925	5,032

Table 17. Pairwise Comparison of dependent variable resistance on drying time

Pairwise Comparisons						
Dependent Variable:Resistance						
(I) Drying	(J) Drying	Mean Difference (I-J)	Std. Error	Sig.a	95% Confidence Interval for Differencea	
					Lower Bound	Upper Bound
1x	4x	2,267*	,038	,000	2,191	2,342
4x	1x	-2,267*	,038	,000	-2,342	-2,191
Based on estimated marginal means						
*. The mean difference is significant at the ,05 level.						
a Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).						

F-test was conducted to determine the significance of independent variables; both times of drying, and their influence on electrical resistance of printed lines (Table 18). Level of statistical significance of p-value (less than ,05) shows that the change of drying time is significant, because the arithmetic means of observed groups are not the same.Type of paper

Table 18. Univariate tests of the effects of drying time to the resistance of printed lines

Univariate Tests						
Dependent Variable: Resistance						
	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	192,667	1	192,667	3550,005	,000	,961
Error	7,815	144	,054			
The F tests the effect of Drying. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.						

The dependence of resistance of lines printed with new ink on a type of paper was also calculated (Table 19). Estimated marginal means (3,890 for uncoated paper, 6,038 for coated paper, and 8,408 for recycled paper) are equal to the means from Table 4. There is no difference between means.

Table 19. Estimates of dependence of dependent variable resistance on type of paper

Estimates				
Dependent Variable:Resistance				
Type	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Uncoated	3,890	,033	3,825	3,955
Coated	6,038	,033	5,973	6,103
Recycled	8,408	,033	8,343	8,473

Table 20. Pairwise Comparison of dependent variable resistance on type of paper

Pairwise Comparisons						
Dependent Variable:Resistance						
(I) Type	(J) Type	Mean Difference (I-J)	Std. Error	Sig.a	95% Confidence Interval for Differencea	
					Lower Bound	Upper Bound
Uncoated	Coated	-2,148*	,047	,000	-2,240	-2,056
	Recycled	-4,518*	,047	,000	-4,610	-4,426
Coated	Uncoated	2,148*	,047	,000	2,056	2,240
	Recycled	-2,370*	,047	,000	-2,462	-2,278
Recycled	Uncoated	4,518*	,047	,000	4,426	4,610
	Coated	2,370*	,047	,000	2,278	2,462
Based on estimated marginal means						
*. The mean difference is significant at the ,05 level.						
a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).						

Level of statistical significance of p-value (less than ,05) shows that the change of printing substrate (type of paper) is significant, because the arithmetic means of observed groups are not the same. Mean Difference also shows that the electrical resistance of the lines printed with old ink on uncoated paper is lower for 2,148mΩ in comparison to coated paper, and for 4,518mΩ in comparison to recycled paper. The resistance of printed lines on coated paper is lower for 2,370mΩ in comparison to recycled paper (Table 20).

F-test was conducted to determine the significance of independent variables; all three types of substrates (papers) and their influence on electrical resistance of printed lines (Table 21). Level of statistical significance of p-value (less than ,05) shows that the change of printing substrate (paper) is significant, because the arithmetic means of observed groups are not the same.

Table 21. Univariate tests of the effects of drying time to the resistance of printed lines

Univariate Tests						
Dependent Variable:Resistance						
	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	510,719	2	255,359	4705,158	,000	,985
Error	7,815	144	,054			
The F tests the effect of Type. This test is based on the linearly independent pairwise comparisons among the estimated marginal means.						

Table 22. Estimates of dependence of dependent variable resistance on drying time and type of paper

3. Drying * Type					
Dependent Variable:Resistance					
Drying	Type	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
1x	Uncoated	4,280	,047	4,188	4,372
	Coated	7,156	,047	7,064	7,248
	Recycled	10,300	,047	10,208	10,392
4x	Uncoated	3,500	,047	3,408	3,592
	Coated	4,920	,047	4,828	5,012
	Recycled	6,516	,047	6,424	6,608

Values in Table 22 and the profile plots on Figure 5 can confirm us the results of previous Pairwise Comparisons Tests that the influence of change in printing substrate (paper) and drying time is significant, when we observe the change in electrical resistance of lines printed with old ink.

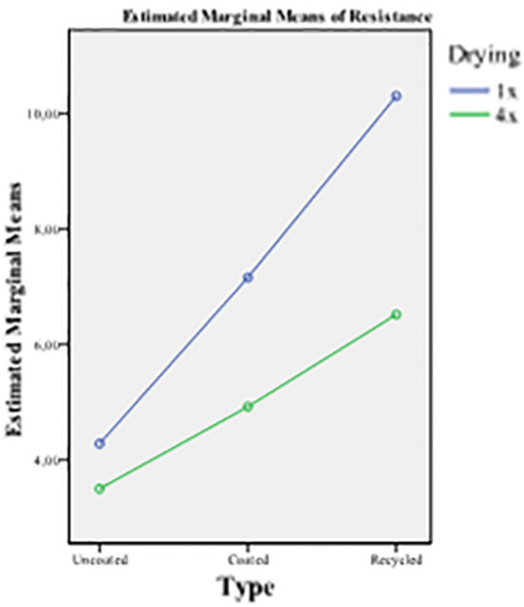

Figure 6. Profile Plots of Estimated Marginal Means of Resistance of old ink

5 Conclusion

The main purpose of this paper was analysis of influence of drying, printing substrate and ink age on the electrical resistance of conductive inks. Using the One Way ANOVA test was tried to see whether there is a connection between the resistance and change of printing substrates together with change in number of drying. All the results for new ink show that all independent variables (ink age, substrate, drying) are significant; values of statistical significance of p-value are less than ,05. It was noticed that there is a significant difference in values of electrical resistance of the lines printed with new ink (around 66,6%) with the different drying time and type of substrates. The biggest difference in value of electrical resistance is between the lines printed on the uncoated paper and dried four times and the lines printed on recycled paper and dried once. Change of drying time is also significant, because the arithmetic means of observed groups are not the same. Difference in the value of electrical resistance in lines printed with new ink and dried once is 1,013mΩ more than the same line that was dried four times. Electrical resistance of the lines printed with new ink on uncoated paper is lower in comparison to coated paper and recycled paper. The resistance of printed lines on coated paper is lower in comparison to recycled paper. All the results for old ink also show that all independent variables (ink age, substrate, drying) are significant; values of statistical significance of p-value are less than ,05. Difference in values of electrical resistance of the lines printed with old ink is around 87,8% with the different drying time and type of substrates. The biggest difference in value of electrical resistance is between the lines printed on the uncoated paper and dried four times and the lines printed on recycled paper and dried once. The same conclusion was in the analysis of prints that were made with new ink. Difference in the value of electrical resistance in lines printed with old ink and dried once is 2,267mΩ more than the same line that was dried four times. Electrical resistance of the lines printed with old ink on uncoated paper is lower in comparison to coated paper and recycled paper. The resistance of printed lines on coated paper is lower in comparison to recycled paper.

It can be concluded that there is significant influence of ink age, printing substrate and drying time on the electrical resistance of printed lines. Differences in the electrical resistance between the prints that were dried once and four times is still not big enough, so the investment in the IR drying is not necessary. Same applies to the difference between uncoated and coated paper. Only recycled paper could benefit from four times drying. Regarding the new ink, it is not necessary to dry the print four times using any substrate.

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