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Testing the predictability of water-based flexographic inks on plastic substrates

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Testing the predictability of water-based flexographic inks on plastic substrates

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the School of Printing Management and Sciences in the College of Imaging Arts and Sciences of the Rochester Institute of Technology

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Master's Thesis

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Abstract

The purpose of this thesis was to investigate the applications of surface energy measurements in predicting the ink adhesion of four different Fasson plastic substrates using the flexographic printing process and water-based inks. These four plastic substrates are as follows: Clear P.E.T., Clear Acetate, Polystyrene, Vinyl. These films were identified by Fasson as substrates they believe to have poor adhesion. The aim was to develop a method to predict ink adhesion of these plastic surfaces by correlating a surface energy test on the substrate before printing begins to ink adhesion tests of the finished print.

Water-based inks offer many advantages over traditional solvent-based inks. They are as follows:

1. They are physiologically safer.
2. They don't burn.
3. They don't cause air pollution.
4. They are tasteless and odor less.
5. Water-based inks are less expensive to store, to transport, and to produce.
6. Water is available in large quantities.

The use of water-based inks is becoming more popular not only because of increased government regulations and insurance problems

for solvent ink users, but because water-based inks produce cleaner prints, more consistent colors and faster washups. Water-based inks unfortunately don't wet a surface as good as solvent-based inks. This was the basis for this type of research.

Hypothesis

The following hypotheses are tested in an effort to answer the above research questions.

1.0 There is a significant difference in the ink adhesion as measured by the cellophane tape adhesion test and the taber abraser test between four different plastic subsrates. The four different substrates were Polyethylene Terephthalate (PET), Acetate, Polystyrene, and Vinyl.

2.0 If there is a significant difference, then the surface energy is a factor in predicting the ink adhesion of the four plastic substrates. The surface energy was measured by the contact angle using the static method.

This experiment consists of a pre-test, a test, and two post-tests. The pre-test used was the contact angle test which measures the angle at which a liquid (in this case water) spreads over a surface (in this case the four plastic substrates). The test was the press run which applied the water-based ink onto the four different plastic substrates. After the press run, two post-tests were used to analyze the printed plastic substrates. The cellophane tape adhesion test and

the taber abrasion test were both used to measure the level of ink adhesion of the four plastic substrates.

The research indicates there was a significant difference in both ink adhesion tests between the four plastic substrates.

The regression analysis of the contact angle and the tape adhesion test prove to have a significant correlation. The percentage of variance explained by regression is very small, only 42.5%. This is not large enough to accurately predict ink adhesion.

The regression analysis of the contact angle and the taber abraser test did not prove to have a significant corelation. This research did not indicate that the surface energy is a factor in predicting the ink adhesion of the four plastic substrates using the taber abraser test.

The research indicated that the cellophane tape adhesion test did not accurately predict ink adhesion and the taber abraser test did not predict ink adhesion.

This does not mean the surface energy is not a factor in predicting the ink adhesion of the four plastic substrates, but only that it was not proven in this investigation.

Chapter 1
Introduction

The purpose of this project was to investigate the applications of surface energy measurements in predicting the ink adhesion of four different Fasson Films Division (An Avery Dennison Company) plastic substrates using the flexographic printing process and water-based inks. These four plastic substrates are as follows: Clear Polyethylene Terephthalate (PET), Clear Acetate, Polystyrene, Vinyl. These films were identified by Fasson as substrates they believe to have poor adhesion. The aim was to develop a method to predict ink adhesion of these plastic surfaces by correlating a surface energy test on the substrate before printing begins to ink adhesion tests of the finished print.

The need for this type of investigation is based on present environmental and economic conditions. Our society no longer accepts the free emissions of Volatile Organic Copounds (VOC's) solvents into the atmosphere. "The clean air act of 1970 and its 1977 amendment require individual states to improve air quality within their borders to standards established by the U.S. Environmental Protection Agency." [1] Water-based inks can help achieve compliance with regulations by limiting the amount of solvent emissions from flexographic printers. The solvent recycling of V.O.C.'s is possible but is an expensive proposition. The use of water-based inks provides a comparible reduction in V.O.C.'s but without the capital investment. Water-based inks offer the following advantages over solvent-based inks:

They are physiologically safe.

Some solvent vapors are considered dangerous to the health of the worker. There are some V.O.C's that may be absorbed through the skin. In this case, even if the air concentration is below U.S.O.S (United States Occupational Exposure Standard) levels, significant exposure to the skin may be dangerous.

They do not burn.

Most organic solvents are fire hazards. This is because the solvent evaporates into the air out of the ink, it sometimes mixes with air to form explosive mixtures. If there is not proper ventilation, these solvents will collect and if ingnited will cause an explosion. Water-based ink users need less protective measures and therefore recieve reduced insurance premiums.

They do not cause air pollution.

When water evaporates from the ink the by-product is harmless. Solvent-based inks release large amounts of V.O.C.'s into the air. These V.O.C's are harmful in certain concentrations. Some of these V.O.C.'s are as follows: alcohols, esters, glycols, ketones, and aromatic hydrocarbons.

They are tasteless and odorless.

This allows easier protection for product and packing. Some solvents if they stay in the ink film can cause a strong objectionable odor. Odor causing substances are found in some of the Volatile Solvents. This can be very irritating to the consumer especially in food packaging.

Water-based inks are less expensive to store, to transport and to produce.

In contrast to organic solvents, the exhaust air does not require cleaning by expensive equipment.

Water is available in large quantities.

A factor of increasing importance in view of the ongoing oil crisis. Along with these advantages, there are some weakness. Compared to alcohol and other solvents, water needs three to eight times the amount of heat for vaporization.[2] Water evaporates slower and has a higher surface tension. This effects its ability to wet and adhere to certain non-porous substrates.

Insurance companies are taking a closer look at solvent ink users, resulting in higher premiums. Apart from government regulations and insurance problems, water-based inks are becoming more popular because of their ability to produce cleaner prints, more consistent colors and faster washups. The use of water-based ink systems is presently the only acceptable alternative.[3] However, research and development in this area has until recently been limited. This thesis project will be a contribution to the search for much needed knowledge in this field.

Ink adhesion, in general, means different things to different people. To some, it means simply that a given tape applied to the printed surface does not lift the ink, and in such a test, the release properties of the ink may be a factor which should not be ignored. To others, good ink adhesion means that the ink will not separate from the substrate under various kinds of use conditions. In this experiment both of these factors were tested to determine the level of ink adhesion. The cellophane tape adhesion test was used to determine the resistance of the ink to be pulled from the surface of the substrate. The abrasion resistance was determined by using the taber abraser which will duplicate various kinds of use conditions.

The printing of the substrates was done at Rochester Institute of Technology's School of Printing Flexography Lab. The testing of the substrates were done at the Fasson plant in Cleveland, Ohio. Fasson Corporation is a company which specializes in the development of pressure-sensitive adhesive materials. The Fasson Roll Materials Division and the Fasson Specialty Materials Division apply Adhesives to a wide variety of papers, plastic films, foils, and cloth. They supply pressure-sensitive base materials in roll form to roll label printers for conversion into labels and packaging components. These pressure-sensitive laminates are the second most popular substrates used in printing. Among the end-uses of these laminates are consumer product primary labels, printed stickers, coupon promotional labels, medical and general industrial applications.

Definition of Terms

Terms used in this study, are defined as follows:

Abrasion- Process of wearing away the surface of a material by friction.

Abrasion Test- A test designed to determine the ability to withstand the effects of rubbing and scuffing.

Acetate- A family of solvents also known as esters; example normal propyl acetate. One of, or the family of, cellulose acetate films.

Adhesion- The state in which two surfaces are held together by interfacial forces; measure of the strength with which one material sticks to another.

Anilox Roll- A mechanically or laser engraved steel and chrome or ceramic coated metering roll used in flexographic presses to control a desired volume of ink from the ink fountain to the rubber or photopolymer printing plates to the substrate.

Contact Angle- Measures the surface tension or holdout of a substrate when wetted by a fluid substance such as water.

Doctor Blade- A thin flexible blade mounted parallel to and adjustable against an engraved anilox roll, for the purpose of scraping off excess ink.

Dyne- The unit of force in the centimeter-gram-second system of units.

Evaporation- The changing from the liquid to the gaseous or vapor stage, as when the solvent leaves the printed ink film.

Hydrocarbons- Materials composed entirely of carbon and hydrogen. General term for family of petroleum solvents.

Ink, flexographic- Fast drying fluid inks used in flexographic printing.

Ink Fountain- The ink pan or trough on a flexographic press.

Ketones- A class of organic compounds generally colorless, volatile liquids, as acetone, methyl ethyl ketone, etc.

Organic- Refers to the compounds in the field of chemistry containing carbon.

P.E.T.- Polyethylene Terephthalate- A polyester film.

Polystyrene-A thermoplastic material derived from the polymerization of styrene.

Solvent- The medium used to dissolve a substance.

Substrate- A foundation material on the surface of which a substance may be deposited by printing, coating, etc.

Surface Tension- A measure of the binding force holding together the molecules at the surface of a substance so that they form a kind of "skin". Measured in dynes/cm.

Vehicle- Carries the colorant from the ink reservoir to the substrate.

Viscosity- The measure of flow characteristics in a liquid.

V.O.C.- (Volatile Organic Compound)- An organic compound that is easily passible from a liquid into a gaseous state under normal temperatures and pressures.

Zahn cup- A device for measuring viscosity.[4]

Endnotes

[1] "Troubleshooting Guide for Waterborne Flexo Inks," Paper,Film & Foil Converter, February 1989, pp. 62-63.

[2] Heinz-Ulrich Werther, Ph.D., "Water-Based Printing Inks:Limitations and Opportunities," FLEXO, September 1991, pp. 36-39.

[3] Ibid., pp. 36-39.

[4] Flexographic Technical Association, Flexography- Principles & Practices Fourth Edition (New York, New York: FTA 1991), pp. 509-539.

Chapter 2

Theory

Flexography is a process of direct rotary printing that uses relief image plates made of rubber or a photopolymer material. These plates are attached to plate cylinders which are linked by a cell-structured ink metering (anilox) roll, a fountain roll, and an ink pan. The fountain roll delivers ink from the ink reservoir to the metering roll which supplies a thin film of ink to the plates that print on any substrate, absorbent or nonabsorbent.

Over the years flexography has gained a wide acceptance in branches of printing which previously were the exclusive domain of the other three major printing methods; letterpress, offset, and gravure. Among the reasons for this has been its ability to print on almost any kind of substrate, paper, cardboard, plastic, or metal. Flexography is used to print on packaging materials such as beverage containers, milk cartons, labels, and flexible material (films and foils). Due to the economic advantages of flexography, it has been a strong contender to its closest competitor; gravure.

Unfortunately, flexography has usually been looked at as a "cheap" printing process. This is mainly because flexography has always been associated with uncomplicated jobs in such areas as package and label printing, forms printing, and other non-process color jobs. The development of the photopolymer plate material for flexography changed many peoples negative view of the process. This breakthrough allowed more demanding jobs to be run with flexography at an accetable quality level.

The one characteristic which makes flexography and gravure different from letterpress and offset is their ink formulation. The low viscosity ink of flexography and the way in which the ink is distributed from the printing forms to the substrate, makes this simpler than offset and letterpress.

However the hydrocarbon solvents used in flexography and gravure for ink formulations are carcinogenic and, therefore hazardous to the health and environmentally unacceptable, even if recovering the solvents is part of the process. The introduction of water-based inks on the other hand, raises questions about runability (a measure of how trouble-free the printing process is being executed).

From a physical chemistry point of view large differences exist between hydrocarbon solvents and water in terms of wetability of the various physical surfaces available to flexography. This is a challenge for ink manufactures to formulate a water-based ink which meets the same print quality demands during press runs as are being placed on hydrocarbon solvent-based inks. Conversely, creating printing surfaces which are compatible with water-based inks without sacrificing print quality, is a challenge for companies like Fasson.

Although this experiment was not aimed in formulating water-based inks and compatible printing substrates, it was aimed at determining ink adhesion of the plastic substrates under the set of conditions outlined in chapter four in order to have a foundation for characterizing surface tension tests which may serve as indication of ink adhesion of the printing surfaces in question.

One problem with water-based inks is that they don't adhere to plastic films as well as solvent-based inks. When printed on porous substrates such as paper, water-based inks dry by penetrating into the stock. When printing on a non-porous substrate, water-based inks ability to wet on the surface is most important.

A water-based ink is composed of a colorant, a vehicle, and other additives. The colorant is dissolved into a solution of non-volatile resins that are dissolved into the vehicle. The colorants used in water-based inks are basically the same as those in solvent inks. The same basic dyes and pigments can be used, but caution is necesary to insure there is no bad reaction. The vehicle can be composed of primarily water such as in water-based inks or can be composed of solvents such as in solvent-based inks. The vehicle is a necessary waste in this process because it is used to supply fluidity to solid colorants and vehicle components. The vehicle is a by-product of the printing process because it is released into the air after the ink dries. It never becomes part of the final product. The vehicles used in water-based inks are vastly different from those in solvent inks.

The difference in formulations between water-based inks and solvent-based inks are as follows:

Water-based Inks	Solvent-based Inks
13% Pigment	11% Pigment
27% Resin	19% Resin
5% Waxes/Amine/etc.	1% Waxes/Amine/etc.
5% Solvent	70% Solvent
50% Water [1]	

The percentage of solvent in solvent-based inks is 70%, which is a large proportion compared to only 5% solvent in water-based inks. These solvents are components of the vehicle of the ink. A water-based ink releases primarily water into the air, only 5% solvent. A solvent-based ink releases primarily harmful solvents into the air. There are basically three phases to the use of a water ink. They are as follows:

1. Liquid Phase- In this phase the components-pigments, resins, slip additives, amines, etc. are in a fluid, pourable, printable form.
2. Printing and Drying Phase- Once applied to the substrate, it must dry and cure within seconds.
3. Functional Phase- Once the ink has been dried it must show some end properties such as gloss, scuff, rub and tape adhesion.

It is well known in the printing industry that the surface energy of a substrate and the surface tension of the ink plays an important role in ink adhesion in flexography. The term "surface energy" is used to describe the reactivity of the surface of the solid substrate.

Sometimes surface tension is used interchangeably with surface energy, which is understandable in as much as both terms are used to refer to the same force with which the molecules at the surface of a substance cling to each other.

Surace tension is expressed in units of force per unit of width (not area) and is analogous to web tension. We can use the same units for both. Web tension is usually given in lbs./inch of width. Since surface tension forces are so much smaller, it is much more convenient to express them in dynes/cm. For example, the surface tension of water is 72 dynes/cm or its equivalent, .00000403 lbs./inch.[2]

"When a liquid comes in contact with a solid, the liquid may wet the solid very well, and thus spread completely across the surface, or not so well, with less tendency to spread across the surface."[3] Spreading and wetting are both terms used to describe the tendency of a liquid to spread itself over a solid. Spreading describes the tendency of the molecules of a liquid to be attracted to the molecules at the surface of a solid, rather than cling to one another. For a liquid to wet a surface, the liquid must have a surface tension that is less than the surface energy of the solid. In the case of water-based inks, water has a high surface tension thus causing wetting problems.

The contact angle is an important thermodynamic quality that describes the interaction between a solid and a liquid interface.

The contact angle is the angle formed by the tangent to the point of contact at the solid/liquid interface. The techniques for measuring contact angles is based on the static method.

The static method is a optical technique in which the tangent at the solid/liquid interface is estimated as a small drop of liquid is put onto a surface. This technique is also referred to as the sessile drop technique. The contact angles are measured directly at the interface with the aid of an optical protractor, or indirectly from photographs or images of the drop. To calculate the contact angle, measure the height (h) of the drop and the diameter (d) of the surface of contact of the drop. Then use the following formula to determine the contact angle:[4]

$$\tan(c/2) = 2 \times h/d$$

This method has been applied to measure receding contact angles. The receding angle is much less sensitive to surface characterization than the advancing angle. Advancing contact angles are usually difficult to measure with the static technique. The advancing contact angle relates to the wetting of the substrate, while the receding contact angle relates to the adhesion of the fluid to the substrate.

Flexography is a printing process that has gained wide acceptance in the graphic arts industry. Among the reasons for this are its ability to print on almost any kind of substrate. The use of water-based inks in flexography is gaining acceptance over solvent-based inks by many flexographic printers. The reasons for this are that solvent-based inks are carcinogenic and, therefore hazardous to the health of the worker and the environment. Water-based inks solve this problem by replacing the solvent vehicle with a primarily water vehicle. The water is released into the air without any harmful effects to the environment.

The ability of an ink to spread and wet a surface is important for ink adhesion. For a liquid to wet a surface, the liquid must have a surface tension that is less than the surface energy of the surface. In the case of water-based inks, water has a high surface tension thus causing wetting problems. The contact angle is an important quality that describes the interaction between a surface and a liquid. The technique used to measure contact angle is based on the static method.

Endnotes

[1] Scott Maloney, "The Beginner Flexographer: Getting the Best from Waterborne Inks," FLEXO, June 1991, pp. 44-45.

[2] James V. Marra, "Transfer, Spreading and Adhesion of Ink on Plastic Films," FTA Proceedings, 1989, pp. 53-54.

[3] Ibid., pp. 53-54.

[4] Dr. F.J. Micale, "The role of Wetting of Water Based Inks in Flexographic Printing," FTA Proceedings, 1989, pp. 59-68.

Chapter 3

Review of Literature

Although water-based flexographic inks have been around for almost 20 years, serious research has been done only in the past 12 years. [1] In the early years, the main reason for printers interest in water-based inks was the growing concern for the environment. Government agencies and insurance companies were taking a harder look at solvent ink users resulting in higher premiums and increased regulations.

As more printers switched to water-based inks, the quality of the ink improved dramatically. These improvements resulted in a cleaner print, more consistent colors, and faster washups. So in addition to saving the environment, water-based inks provide savings in insurance premiums and in running costs. This is why there is a need for this type of research.

The purpose of this thesis was to investigate the applications of surface energy measurements in predicting the ink adhesion of four different Fasson plastic substrates using the flexographic printing process and water-based inks.

The article "Value-Added Packaging: Ink-Anilox-Substrate Connection," stresses the role of ink in the flexographic process and the importance of surface tension.

"Flexographic inks are the one part of the printing equation that brings all the parts together...The first job of a printing ink is to deliver color on a printed sheet, and color is being demanded more than ever for packaging." " For an ink to print smoothly, it must have less surface energy or tension than the substrate. This "wetting out" of the ink and substrate is often determined by using the angle of contact measurement." [2]

Water-based inks have many advantages but also some weaknesses. The article "Water-Based Printing Inks: Limitations and Opportunities," explains how these inks offer a safe substitute for solvent-based inks. Flexographic printers hope these products will satisfy the many demands for safety in the workplace and for safety in the workplace and for a cleaner environment. [3]

In order to make proper tests on the surface of the plastic substrates, it is necessary to understand the properties and ways of testing ink adhesion. The book Flexography-Principles and Practices published by the FTA is a very good source for explaining the basics of flexography as well as describing the many tests available. [4]

"Water ink adhesion and print quality are dependent upon a suitable substrate surface. The surface must be free from contaminates and should have a higher surface-energy level than the water inks that will be used to print it." [5]

This was the basis for my investigation. The purpose was to find a way to predict the ink adhesion of the substrate by using the measurements of the surface energy before the printing of the substrate.

Endnotes

[1] Mike Buystedt, "The Beginner Flexographer: Ink Manufacturers are Quite Serious About Waterbase Inks," FLEXO , November 1991, pp. 42-42.

[2] Roger L. Proteet, "Value-Added Packaging: Ink-Anilox-Substrate Connection," FLEXO, Febuary 1991, pp. 27-33.

[3] Heinz-Ulrich Werther, Ph.D., "Water-Based Printing Inks: Limitations and Opportunities," FLEXO, September 1991, pp. 36-39.

[4] Flexographic Technical Association, FLexography-Principles and Practices-Fourth Edition (New York: FTA, 1991)

[5] "Troubleshooting Guide For Waterborne Flexo Inks," Paper, Film & Foil Converter, Febuary 1989.

Chapter 4

Statement of the Problem

Originally, the purpose of this investigation was to investigate the applications of surface energy measurements in predicting the ink adhesion of four different Fasson foil substrates using the flexographic printing process and water-based inks. Unfortunately all the foil substrates failed the ink adhesion tape test not because of poor ink adhesion but because of the failure of the substrates. It was difficult to determine if the ink was removed from the substrate because the foil laminate lifted off the paper lining with every tape pull test. The purpose and rationale for the study was not changed, only the substrates to be studied were changed. The foil was replaced by four plastic substrates: Polyethylen Thriphalate, Acetate, Polystyrene, and Vinyl.

Research Questions

The research questions answered by this investigation are:

1. Is there a change in ink adhesion between the four different plastic substrates?

2. Does one have better ink adhesion qualities than another?

3. Can tests of the surface energy of the plastic substrates before the printing help us predict how well the ink will adhere to the plastic substrates?

Hypothesis

The following hypotheses are tested in an effort to answer the above research questions.

1. There is a significant difference in the ink adhesion as measured by the cellophane tape adhesion test and the taber abraser test between four different plastic subsrates. The four different substrates were Polyethylene Terephthalate (PET), Acetate, Polystyrene, and Vinyl.
2. If there is a significant difference, then the surface energy is a factor in predicting the ink adhesion of the four plastic substrates. The surface energy was measured by the contact angle using the static method.

Delimitations

It is necesary to establish a set of limits or boundaries in a investigation. The scope of the study is described below.

The water-based ink used was suppied by Werneke Ink Company. The actual chemical structure was not changed for the study. No solvents were added to the ink during the press run, the ink came straight out of the container.

The substrates run in this experiment were produced by Fasson in roll form. They each consist of a facestock, adhesive, and a liner. Only one of the substrates is top coated or print treated and the other three substrates are not treated. The names of the four substrates being tested are as follows:

1. 2 mil Clear PET/65# (ID#60111)

Facestock: 2 mil clear polester

Adhesive: S-333 is a permanent, emulsion acrylic adhesive

Liner: A 65# semi-bleached, super calendered, kraft stock.

2. 2 mil Clear Acetate/50# (ID#60097)

Facestock: A 2 mil cast acetate film with good clarity. Suitable for indoor point of purchase displays and some tamper evident applications.

Adhesive: S-730 is a permanent solvent acrylic adhesive

Liner: A 50# semi-bleached super calendered kraft stock.

3. 2.6 mil White Semi-gloss Polystyrene (ID#72216)

Facestock: 2.6 mil white semi-gloss polystyrene film, corona treated for printability.

Adhesive: S-1000 is an aggressive, all temperature, permanent, emulsion acrylic adhesive.

Liner: A 50# semi-bleached super calendered, kraft stock

4. 3.4 mil White Flexible Vinyl/63# (ID#86272)

Facestock: A 3.4 mil opaque white flexible vinyl film

Adhesive-S-475 is a permanent, emulsion acrylic adhesive

Liner-A 63# machine finish, bleached, coated liner

The type of printing press used in this experiment was the Mark Andy 6 unit Narrow Web Press.

This research will not print the rest of the process colors in our study, yellow, magenta, and cyan.

Limitations

In a investigation there are certain factors that cannot be controlled. The following are factors which may impact on the reliability and validity of the study: This research will not print the rest of the process colors in our study, yellow, magenta, and cyan.

1. This research will not control the chemical make-up of the water-based ink being used.
2. This research will not add any solvent to the water-based inks to improve performance.
3. This research will not control how the ink volume of the anilox roll may effect the printability.

Chapter 5
Methodology

This chapter will describe the experimental design of the study, the instrumentation and equipment used as part of the experimental design, and the procedures used for collecting and analyzing data. This experiment consists of a pre-test, a test, and two post-tests.

The pre-test used was the contact angle test which measures the angle at which a liquid (in this case water) spreads over a surface (in this case the four plastic substrates).

The test was the press run which applied the water-based ink onto the four different plastic substrates.

After the press run, two post-tests were used to analyze the printed plastic substrates. The cellophane tape adhesion test and the taber abrasion test were both used to measure the level of ink adhesion of the four plastic substrates.

Pre-test

In order to test hypothesis 2.0 (the surface energy is a factor in predicting ink adhesion) it was necesary to first run the contact angle test. This test is better known as the static method of measuring contact angle. This method is an optical technique in which the tangent at the solid/liquid interface is measured as a small drop of liquid is put onto a surface. The contact angles are measured directly at the interface with the aid of an optical protractor. For this experiment the four plastic substrates were used as the solid and distilled water as the liquid. A surface wettability tester made by Lorentzen and Wettre was used to test the contact angle of the substrates. Distilled water at 23 degrees and having a surface tension of at least 72 dyne/cm was used.

From each of the four substrates, 15 samples were cut into strips. The strips measured 100 +- mm x 15 +- mm. It was important that the samples were clean, free of folds, wrinkles, blemishes, and other defects. A small drop of distilled water was placed on the plastic film. The height (h) of the drop and the diameter (d) of the surface of contact of the drop were measered using the optical protractor.

The formula tan (c/2) = 2 x h/d (c= contact angle) was used to calculate the contact angle of the specific sample.

This procedure was used for all 15 samples and for all four plastic substrates. Only the contact angles for each substrate were recorded.

Test

Flexographic printing applied the water-based ink onto the four different plastic substrates. This uniform coating of ink on the substrate was used for both of the ink adhesion tests. The apparatus and material used to print the four substrates are as follows:

1. A Mark Andy six unit narrow web press was the printing press used to apply the ink onto the substrate.
2. The four substrates printed were PET, Acetate, Polystyrene, and Vinyl.
3. The flexographic ink used was a black process ink made by Werneke Ink Company.
4. A 200 pyrimid cell anilox roll was used.
5. The plates used were photopolymer plates .067 thick on compressilbe backing.
6. A doctor blade was used.

The procedures for printing onto the four test substrates are as follows:

1. The Mark Andy printing press was made ready for printing. The ink, substrate, and printing plate were installed in the press.
2. When the press was made ready, the press was brought up to operating speed of 50 f.p.m. and viscosity was checked to see if it was running between the suggested 18 to 25 sec.(#2 Zahn). The actual running viscosity during the press run was 21 seconds.

3. When the plate roll was adjusted for proper ink film thickness and the press operator felt the press was running at normal conditions, 15 samples were taken from through out the run.
4. This same procedure was repeated for all four plastic substrates.

Post-test

An important characteristic of an ink is its ability to adhere to a substrate. There are two ink adhesion tests in this experiment that were used to determine the level of ink adhesion for each of the four plastic substrates. The two tests used were the cellophane tape adhesion test and the taber abrasion test. Both of these tests were carried out after the four substrates were printed with water-based ink using the flexographic printing process. These tests followed specific standards outlined by the American Society for Testing and Materials (ASTM). These standards consist of the procedures and materials needed to carry out a reliable test.

<u>Standard Test Method for Measuring Adhesion by the Cellophane Tape Test</u>

The cellophane tape adhesion test was used for assessing the adhesion of the ink to substrate by applying and removing adhesive tape over cuts in the ink film. This test checks the bond of ink to substrate compared to the bond of the adhesive on the tape to the ink surface. This test method is used to determine what adhesion level a particular substrate is. The specific test used in this experiment was Method B, the cross cut tape test.

The apparatus and materials used in this test are as follows:

1. A cutting tool such as a sharp razor blade, scalpel, knife or other device having a cutting edge or edges angled between 15° and 30° that will make either a single cut or several cuts at once. It is of particular importance that the cutting edge be in good condition.

2. A cutting guide such as a steel or other hard metal straightedge or template to ensure straight cuts.

3. A tempered steel ruler graduated in 0.5 mm for measuring individual cuts.

4. A one-inch (25 mm) wide semitransparent pressure-sensitive tape with an adhesion strength agreed upon by the supplier and the user is needed. Because of the variability in adhesion strength from batch-to-batch and with time, it is essential that tape from the same batch be used when tests are to be run in different laboratories.

5. A rubber eraser found on the end of a pencil.

6. A light source is helpful in determining whether the cuts have been made through the film to the substrate.

7. An illuminated magnifier to be used while making individual cuts and examining the test area.

Before the procedures for this test were carried out it was necesary to wait at least 24 hours after the press run. After drying, select an area on the substrate free of blemishes and minor surface imperfections.

The substrate was placed on a firm base and under the iluminated magnifier and eleven parallel cuts were made spaced 1mm apart. All cuts were made about 3/4 inches (20 mm) long.

The ink film was cut through to the substrate in one steady motion using just sufficient pressure on the cutting tool to have the cutting edge reach the substrate. When successive single cuts were made with the aid of a guide, the guide was placed on the uncut area.

After making the required cuts the substrate was brushed lightly with a soft brush to remove any detached flakes or ribbons of coatings. The additional eleven cuts were made at 90 degrees to and centered on the orginal cuts. The area was brushed as before and the incesions were inspected for reflection of light from the substrate. If the substrate had not been reached another grid in a different location would be made.

Two complete laps of tape were removed and discarded. An additional length was removed at a steady (that is not jerked) pace and cut into a piece about 3 in. (75mm) long. The center of the tape was placed over the grid and in the area of the grid was smoothed into place by a finger. To ensure good contact with the film the tape was rubbed firmly with the eraser at the end of a pencil. The color under the tape indicated when good contact had been made.

Between 60-120 seconds of application, the tape was removed by seizing the free end and rapidly (not jerked) pulling it off at as close to an angle of 180 degrees as possible.

The grid area was inspected for removal of coating from the substrate. The adhesion was rated in between the following scale:

0 % removal of ink (100 % adhesion of ink to substrate)

100 % removal of ink (0 % adhesion of ink to substrate)

The removal of ink was rated by using this scale between 0% and 100%. Zero percent indicated no removal of ink from the substrate or indicated 100% adhesion of ink to substrate. One hundred percent indicated a total removal of ink from the substrate or indicated there was no adhesion of ink to substrate.

The percentage removal was recorded for each 15 samples and for each of the four plastic substrates.

Abrasion Resistance of Organic Coatings by the Taber Abraser

Good ink adhesion is defined as the ability of a ink not to separate from the substrate under various kinds of use conditions. The taber abraser test was used for assessing the adhesion of the ink to the substrate by subjecting it to abrasion. This abrasion resistance was used to duplicate the various use conditions.

The number of cycles of abrasion to wear the ink through to the substrate determines the level of ink adhesion. A low number of cycles shows the ink separated from the substrate quickly. A high number of cycles shows the ink separated from the substrate at a slower pace. As the number of cycles increases so does the ability of the ink to adhere to the substrate. The apparatus and materials used in this test are listed as follows:

A taber abraser tester was used in this experiment.

From each of the four plastic substrates, 15 samples were cut. The samples were covered with a uniform coating of ink that was applied to the substrate by a flexographic press. They were cut into squares 4 in. (100 mm) x 4 in. (100mm) with rounded corners and with a 1/4 in. (6.3 mm) hole centraly located on the sample. It was important that the samples were clean, free of folds, wrinkles, blemishes, and other defects.

An abrasive wheel with resilient calibrase wheels number cs-10 was used.

A resurfacing medium, an s-11 abrasive disk, was used for resurfacing the abrasion wheels.

A vacuum pick-up assembly, consisting of a vacuum unit, a variable transformer suction regulator, a nozzle with bracket attachment, and a connection hose with adaptor.

The procedures to test the samples using the taber abraser are as follows:

The test sample was mounted on the turntable and the abrading heads were placed on the test substrate. The vaccum pick-up nozzle was put in position and the counter was set to zero.

After the vaccum was turned on, the taber abraser was started.

The test sample was subjected to abrasion until wear through of the ink to the substrate was observed. When the point of wear through was determined, the taber abraser was stopped.

The number of cycles of abrasion to wear through was recorded for the sample substrate.

These procedures were repeated for each of the 15 samples and for each of the four plastic substrates.

Chapter 6

The Results

The purpose of this thesis was to investigate the applications of surface energy measurements in predicting the ink adhesion of four different Fasson plastic substrates using the flexographic printing process and water-based inks. These four plastic substrates are as follows: Clear P.E.T., Clear Acetate, Polystyrene, and Vinyl. These films were identified by Fasson as substrates they believe to have poor adhesion. The aim was to develop a method to predict ink adhesion of these plastic surfaces by correlating a surface energy test on the substrate before printing begins to ink adhesion tests of the finished print.

The contact angle test was performed on 15 samples of each of the four plastic substrates. The contact angle measurements were obtained by using the Lorrentzen and Wettre Surface Wettability Tester. The procedures for this test are explained in Chapter Five. This test measures the angle of contact of a liquid when it is droped on a solid surface in degrees. The results of the contact angle for all four plastic substrates are listed on Table 1. This table also shows the computed average contact angle for each substrate. These measurements were used to determine the correlation between contact angle and ink adhesion.

Ink adhesion was defined as the ability of an ink to resist tape removal and the ability to resist abrasion. These two factors of ink adhesion were tested by using the cellophane tape adhesion test and the taber abraser test. Both of these tests were performed on the four substrates after the water-based ink was applied by the flexographic printing process. These results were used to determine the correlation between contact angle and ink adhesion.

The cellophane tape adhesion test was used to test the bond of the ink to the substrate by applying and removing an adhesive tape over a set of cuts in the ink. This was measured as a percentage of ink removed from the substrate by the tape. The procedures for this test are explained in Chapter 5. This test was performed on 15 samples of each of the four plastic substrates. The results of the tape adhesion test for all four substrates are listed in Table 2. This table also shows the computed average percentage of removal for each substrate.

The taber abraser was used to test the ability of a ink to resist abrasion and from separating from the substrate. This was measured by the number of cycles of abrasion to wear through the ink to the substrate. The procedure for this test are explained in Chapter 5. This test was performed on 15 samples of each of the four substrates. The results of the test for all four substrates are listed in Table 3. This table also shows the computed average number of cycles for each substrate.

The purpose of this chapter was to provide results of the tests and try to test the hypothesis by using the statistical design outlined in the previous chapter. The results of the three tests performed will be given in data tables on the following pages. The statistic results will be given and explained at the end of the chapter.

Table 1

Contact Angle Measurements

	Clear P.E.T.	Clear Acetate	Polystyrene	Vinyl
1.	81.20°	65.74°	79.40°	99.49°
2.	87.11°	63.57°	78.19°	100.39°
3.	89.08°	60.14°	73.74°	102.68°
4.	84.55°	61.21°	72.65°	101.53°
5.	88.18°	62.37°	76.53°	96.21°
6.	86.53°	57.22°	77.32°	95.29°
7.	88.12°	63.04°	72.27°	93.18°
8.	87.38°	69.28°	73.74°	99.69°
9.	87.01°	64.16°	81.49°	97.63°
10.	82.11°	61.47°	77.77°	99.69°
11.	85.27°	64.30°	72.51°	98.65°
12.	85.91°	61.71°	72.65°	99.99°
13.	87.01°	61.93°	78.26°	101.12°
14.	87.11°	63.22°	74.04°	96.21°
15.	86.30°	60.80°	79.22°	97.38°
Average	86.19°	62.68°	75.99°	98.61°

Table 2

Ink Adhesion by Cellophane Tape Test

	Clear P.E.T.	Clear Acetate	Polystyrene	Vinyl
1.	99%	50%	0%	98%
2.	98%	54%	0%	99%
3.	98%	48%	0%	100%
4.	97%	47%	0%	100%
5.	98%	48%	0%	99%
6.	97%	46%	0%	98%
7.	98%	45%	0%	99%
8.	99%	44%	0%	100%
9.	98%	47%	0%	97%
10.	97%	48%	0%	98%
11.	98%	49%	0%	100%
12.	99%	43%	0%	99%
13.	97%	48%	0%	98%
14.	98%	50%	0%	100%
15.	99%	47%	0%	99%
Average	98.00%	47.60%	0.00%	98.93%

Table 3

Ink Adhesion by Taber Abraser Test

	Clear P.E.T.	Clear Acetate	Polystyrene	Vinyl
1.	3	15	43	8
2.	5	14	47	10
3.	5	16	49	9
4.	5	15	50	8
5.	6	14	47	9
6.	6	13	47	9
7.	6	14	50	8
8.	3	16	49	10
9.	5	12	45	10
10.	4	16	51	9
11.	5	16	48	10
12.	4	16	54	9
13.	6	16	52	9
14.	5	14	50	9
15.	6	14	52	10
Average	4.93	14.67	48.93	9.13

A one-way analysis of variance[1] with a 95% confidence level was used to test the hypothesis 1 as measured by the cellophane tape adhesion test. Since the calculated F value (496.48) was greater than the critical F value (2.79), the hypothesis was accepted. Therefore ink adhesion is not the same for all four plastic substrates.

The Sheffe Test[2] was used to determine which differences between the four substrates were significant. All the differences between the substrates were significant except between PET and the Vinyl. The Vinyl had the highest ink removal percentage (98.93 %) and PET was (98.00%).

The following chart will show the results of the Sheffe Test. A Yes response on the chart means the two substates are significant. A No response on the chart means the two substrates are not significant.

	PET	Acetate	Polystyrene	Vinyl
PET		Yes	Yes	No
Acetate			Yes	Yes
Polystyrene				Yes

As shown by the chart above, the difference between PET and Vinyl is not significant. The other 5 differences between substrates is significant.

A one-way analysis of variance with a 95% confidence level was used to test Hypothesis 1 as measured by the taber abraser test. Since the calculated F value (2,130.5) was greater than the critical F value (2.79), the hypothesis was accepted. Therefore ink adhesion is not the same for all four plastic substrates.

The Sheffe Test was used to determine which differences between the four substrates were significant. The following chart will show the results of the Sheffe Test. A Yes response on the chart means the two substates are significant. A No response on the chart means the two substrates are not significant

	PET	Acetate	Polystyrene	Vinyl
PET		Yes	Yes	Yes
Acetate			Yes	Yes
Polystyrene				Yes

As shown by the chart above, all the differences between the substrates are significant.

A regression analysis[3] with a 95% confidence level was used to find a linear relationship or correlation between contact angle and the Tape Adhesion ink test.

The two equation variables in this experiment are X and Y. The cellophane tape adhesion test is variable X and the contact angle test is variable Y.

The correlation coefficient (R) of this test was .425.

Since the t tested value (3.1) is larger than the t critical value (1.771), the correlation coefficient (R) is significant. R-square is the coefficient of determination, that is, the square of the correlation coefficient. R-square is defined as the percentage of variance explained by regression.

The regression equation is $X= 102 + 2.02Y$

In this case only 42.5% of the variability among the contact angle and the tape adhesion test can be explained on the basis of the linear relationship. A strong prediction can not be made of how contact angle is related to ink adhesion, although there is evidence that a high contact angle will result in poor ink adhesion (high ink removal).

A regression analysis with a 95% confidence level was used to find a linear relationship or correlation between contact angle and the Taber Abraser ink adhesion test.

The two equation variables in this experment are X and Y. The cellophane tape adhesion test is variable X and the contact angle test is variable Y.

The correlation coefficient (R) of this test was .345.

Since the t tested value (1.325) is smaller than the t critical value (1.771), the correlation coefficient (R) is significant. R-square is the coefficient of determination, that is, the square of the correlation coefficient. R-square is defined as the percentage of variance explained by regression. In this case only 11.9% of the variability among the contact angle and the taber abraser test can be explained on the basis of the linear relatinship.

There is no significant relationship between the contact angle measurements and the taber abraser tests.

Endnotes

[1] Shirley Dowdy, and Stanley Wearden, Statistics For Research. (New York: John Wiley & Sons, 1991) pp. 45-67.

[2] Ibid., pp. 83-102.

[3] Ibid., pp. 124-143.

Chapter 7

Summary and Conclusions

The purpose of this thesis was to investigate the applications of surface energy measurements in predicting the ink adhesion of four different Fasson plastic substrates using the flexographic printing process and water-based inks. These four plastic substrates that were used are: Clear P.E.T., Clear Acetate, Polystyrene, Vinyl. These films were identified by Fasson as substrates they believe to have poor adhesion. The aim was to develop a method to predict ink adhesion of these plastic surfaces by correlating a surface energy test on the substrate before printing begins to ink adhesion tests of the finished print.

Hypothesis

The following hypotheses are tested in an effort to answer the research questions outlined in Chapter 4.

1. There is a significant difference in the ink adhesion as measured by the cellophane tape adhesion test and the taber abraser test between four different plastic subsrates. The four different substrates were Polyethylene Terephthalate (PET), Acetate, Polystyrene, and Vinyl.

2. If there is a significant difference, then the surface energy is a factor in predicting the ink adhesion of the four plastic substrates. The surface energy was measured by the contact angle using the static method.

The research indicates there was a significant difference in both ink adhesion tests between the four plastic substrates.

The regression analysis of the contact angle and the tape adhesion test prove to have a significant correlation. The percentage of variance explained by regression is very small, only 42.5%. This is not large enough to accurately predict ink adhesion.

The regression analysis of the contact angle and the taber abraser test did not prove to have a significant corelation. The research did not indicate that the surface energy is a factor in predicting the ink adhesion of the four plastic substrates using the taber abraser test.

The research indicated that the cellophane tape adhesion test did not accurately predict ink adhesion and the taber abraser did not predict ink adhsion.

In this study, surface energy is not a factor in predicting the ink adhesion of the four plastic substrates. This is a point that other researchers might varify or disprove after further investigation.

Further investigation is recommended using similar testing and methods except for a larger number of plastic substrates. The substrates choosen should all be non-treated and non-top coated plastic substrates. Another test that would determine surface energy in addition to the static contact angle test should be used.

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