Integrating Fabric Formation and Textile Coloration Processes via Digital Inkjet Printing

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Abstract

With rapid progressions in the textile industry, it has become increasingly evident that there is a need for development of a textile printing system which will have the capacity to keep pace with current and future mass customization manufacturing requirements in the printing segment of the textile industry. Digital inkjet printing has the potential to provide such characteristics, in a continuous system combining digital inkjet printing with the fabric formation process. Analyzing various fiber types requires that a specific correlating link be developed to correspond with a given substrate and its respective dye class. Research conducted at Philadelphia University has focused intently on discovering a link for cotton substrates and reactive dye coloration. For future exploration of polyester, research into the design, synthesis and use of special cyclodextrins, (which have the dual capacity to function as suitable hosts for certain colorants, and act as sizing agents), will be the key component for successful integration for the given substrate.

The Future of Textile Production

Currently, digital inkjet printing is being selectively utilized throughout the textile industry, primarily for producing samples as a component in the design process and for small-scale production prints of exclusive design. However, due to its inherently slow application speed, the digital printing process has yet to be adopted and successfully used as a component for full-scale production. Roller screenprinting, which is traditionally used in production, although successful, is a time intensive and relatively inflexible process, causing it to be deficient in the high demand requirements of contemporary quick response textile manufacturing. Therefore, if the fabric production and digital printing processes, which are somewhat compatible in production speeds, could be combined, the resultant integration would include numerous positive outcomes for the textile industry, including dramatically reduced overall fabric handling, which in turn, will enhance agile manufacturing capabilities and provide the ability to produce quick style changes and on demand production.

In attempting to integrate the fabric production and digital inkjet printing processes, several factors must initially be taken into consideration, particularly the presence of sizing agents and a need for dye fixation. In the construction of a woven textile fabric a polymeric coating must be employed on the warp yarns for additional strength and resistance to abrasion during the weaving process.[1] Specifically known as warp sizes, starch, polyvinyl alcohol, and carboxymethyl cellulose are most commonly used when working with a cotton warp. A typical sizing mixture consists of a combination of starch, partially hydrolyzed polyvinyl alcohol, and a small amount of a lubricating agent, such as fat, to ensure a more secure weaving process.[1] More importantly, however, both synthetic and natural sizes must be removed following the weaving process (*via* desizing) to provide access of colorants to the fiber surface in the subsequent dyeing or printing stage. Therefore, to successfully integrate the two processes into a continuous system, a link must be developed to join fabric production and digital printing. However, due to the wide range of dyes being utilized in production today, different links must be discovered to connect varying substrates with their respective dye classes.

Cotton

Cotton is the most widely used of the natural cellulosic fibers and is well known to most consumers, making it a critical area of investigation for integration. Cellulose is a polysaccharide made up of cellobiose units, which combine to form a cellulose molecule, see Figure 1.

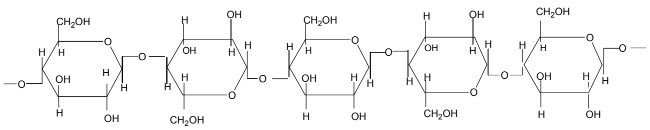


Figure 1. Schematic Diagram of a Cellulose Molecule.[2]

In the simplified diagram of cotton, Figure 2, the hydroxyl (OH) groups are clearly indicated. These hydroxyl groups are critical for several reasons, but most importantly directly pertaining to integration, cellulose fibers absorb water-soluble dyes and finishes, which aids in chemical processing.

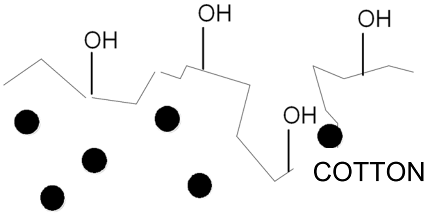
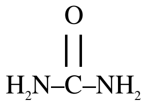


Figure 2. Surface Diagram of Cotton.[4]

Reactive dyes are water-soluble anionic dyes, which react with the hydroxyl groups of cellulose to become covalently bonded to the cellulosic fiber.[1] The chemical reaction between a reactive dye and a cellulosic fiber takes place in the presence of a base, as illustrated in Equation 1.[1] In this investigation, sodium carbonate, Na_2CO_3, is the base being utilized.

$$\text{DYE + H-O-CELLULOSE} \xrightarrow{\text{base (-HCl)}} \text{DYE-O-CELLULOSE + SALT} \quad (1)$$

In addition, urea, depicted in Figure 3, is used in combination with sodium carbonate, to absorb moisture.



$$\begin{array}{c} \text{O} \\ || \\ \text{H}_2\text{N–C–NH}_2 \end{array}$$

Figure 3. Diagram of Urea.

This absorption is indicated in Equation 1, as no water is given off as a product of the reaction.[1] The resultant covalent bond provides good washfastness properties, and is much stronger than the weak hydrogen bonds formed between direct dyes and cellulose, making reactive dyes the preferred choice when working with cotton. Furthermore, since a base, in this case Na_2CO_3, is required for the dye to bond with the cotton substrate, and is typically applied to the fabric as a pretreatment solution prior to digital printing, the link to integrating the fabric formation and coloration processes is based upon the sodium carbonate/urea solution.

Since it has been established that the covalent bonding of reactive dye with cotton occurs when the substrate is pretreated with sodium carbonate and urea, the physical property which must be explored for integration is an ability to protect the cotton yarns from abrasion and breakage during the weaving process, i.e., the solution must be investigated to determine if it will additionally perform as a warp size. To determine such properties, three groups of 100% cotton, 20/2 N_{ec} yarns were treated with various solutions, listed in Chart 1. Two of the groups of yarn were padded with their respective solutions, using a lab-scale padding unit, such that solution uptake was 80% of the weight of the dry yarns. The control yarn samples were not treated with any solution, and cornstarch was used to mimic the traditional starch sizing currently used in woven production on the second group of yarns. In addition to the sodium carbonate and urea used in Solution C, thickener and silica were added to the solution for increased viscosity. Following application, the samples were dried in a Tsuji Senki Kogyo tenter oven at 130ºC for two minutes. After all of the yarns were conditioned under standard temperature and relative humidity for twenty-four hours, half of the yarns were tested for single end strength using a Testmetric SDL constant rate of extension tensile testing machine, in accordance with ASTM Test Method #2256. Using a CSI Flex Tester, the remaining yarns were then subjected to an abrading force of one pound for ten cycles, proportional to that which would be incurred on an active loom. These yarns were tested for single end yarn tenacity, as previously noted, following abrasion to determine a change in tenacity similar to that which occurs during the duration of weaving. The average change in tenacity and standard deviation values for the corresponding formulas are shown in Table 1.

Chart 1: Average Change in Single End Yarn Tenacity
(as a result of simulated weaving)

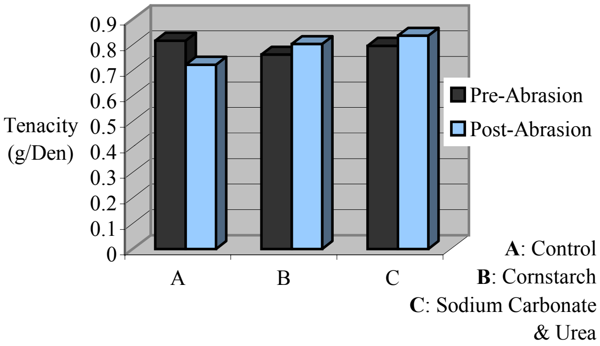


Table 1. Tenacity (g/Den) Data for Cotton Substrate

Sample	Average Change in Single End Tenacity	Standard Deviation
A: Control		
Pre-Abrasion	0.82 g/Den	0.07 g/Den
Post-Abrasion	0.72 g/Den	0.09 g/Den
B: Cornstarch		
Pre-Abrasion	0.76 g/Den	0.18 g/Den
Post-Abrasion	0.80 g/Den	0.09 g/Den
C: Sodium Carbonate & Urea		
Pre-Abrasion	0.80 g/Den	0.14 g/Den
Post-Abrasion	0.84 g/Den	0.07 g/Den

The results demonstrate promising data for future integration. The control samples were clearly abraded during simulated weaving, reducing the average single end tenacity. The two remaining samples however, demonstrated an increase in tenacity following abrasion, although within a minimal range. Although it is not theoretically feasible to state that the yarns actually increased in strength after abrasion, the results from the sample pool averaged an increase in strength for both the cornstarch and sodium carbonate/urea solutions. This increase in strength most likely results from the small sample pool tested, and further testing will take place to ensure more concrete results. In addition, the high standard deviation values for the yarn samples tested prior to abrasion create some speculation of tensile strength, which might be a cause of discrepancy in the average change in strength following abrasion. Regardless, the ability of the yarns to maintain a relatively high level of strength, despite an abrading force, may result from the breakdown of the applied solution rather than the yarn itself during the simulated weaving process. Most importantly, the sodium carbonate/urea formula performed well for resistance to abrasion, which is a key component for integration.

After performing textile material tests to determine yarn strength pre- and post- weaving, the next stage in the direction of integration is digital inkjet printing. Initial steps have been taken in this direction, including weaving 100% cotton plain weave fabric on a 400-end Sumagh sample loom, using 20/2 N_{ec} yarn, identical that which was previously used for single end strength analysis. The woven fabric was divided into three samples, and treated with identical solutions to those used in Table 1. Once padded, using a lab-scale padding unit, such that solution uptake was 80% of the weight of the dry fabric, the three fabrics were dried in an identical manner as the yarn samples, 130ºC for two minutes in the Tsuji Senki Kogyo tenter oven. The samples were then digitally printed using reactive dyes on a Mutoh Full Color Inkjet Printer, with 100% pure color stripes of Cyan, Magenta, Yellow and Black, manufactured by CIBA Specialty Chemicals, INC., as shown in Figure 5.

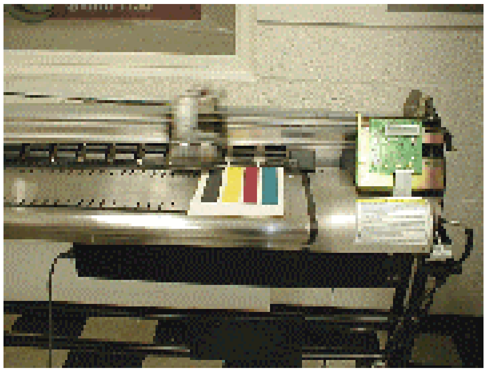


Figure 5. Mutoh Full Color Inkjet Printer.

The resultant samples were subjected to after-treatment procedures, including steaming at 103ºC for eight minutes and soaping-at-the-boil, in an uncovered stainless steel kettle, with water and Synthrapol, a commonly used textile detergent. These after-treatment procedures are required to improve the bonding between the dye and the fiber and finally, to remove any unbonded dye and dyeing assistants from the substrate.[1] As a result of the after-treatment procedures, the untreated control fabric and cornstarch treated fabric failed to retain any of the reactive dye applied during digital printing. This failure occurred because the necessary chemical reaction, refer to Equation 1, did not take place to covalently bond the cellulose and the reactive dye, which is required to lock the color into the cotton structure. Therefore, these two fabric samples were not treated for colorfastness properties. The remaining sodium carbonate/urea sample was, however, conditioned at standard temperature and humidity levels and tested for Colorfastness to Light (AATCC Test Method #16), Colorfastness to Laundering (AATCC Test Method #61), and Colorfastness to Crocking (AATCC Test Method #116), in an effort to determine if the sodium carbonate/urea solution being used in the research of cotton did in fact covalently bond with the reactive dyes. Results are shown in Tables 2-4.

In analyzing the results from the three AATCC test methods illustrated in Tables 2, 3 and 4, it is evident that the printed samples treated with the sodium carbonate/urea solution demonstrate excellent colorfastness properties to laundering, light and crocking. Furthermore, the results indicate that the reactive dyes did in fact bond with the cellulose structure as indicated in Equation 1.

Table 2. Results from AATCC Test Method #16

Sample		**AATCC #16 Colorfastness to Light**	
		20 hours	**40 hours**
A: Control		N/A	
B: Cornstarch		N/A	
C: Sodium Carbonate/Urea Formula with Thickener and Silica	**Cyan**	5	5
	Magenta	4-5	4
	Yellow	5	4-5
	Black	4-5	4

Table 3. Results from AATCC Test Method #61.

Sample		**AATCC #61 Colorfastness to Laundering**
A: Control		N/A
B: Cornstarch		N/A
C: Sodium Carbonate/Urea Formula with Thickener and Silica	**Cyan**	5
	Magenta	5
	Yellow	5
	Black	5

Table 4. Results from AATCC Test Method #116.

Sample		**AATCC #116 Colorfastness to Crocking**	
		Wet	**Dry**
A: Control		N/A	
B: Cornstarch		N/A	
C: Sodium Carbonate/Urea Formula with Thickener and Silica	**Cyan**	4	5
	Magenta	3	5
	Yellow	4	5
	Black	4	5

At this point in time, positive results for integrating the fabric formation and coloration processes for a cotton substrate are promising. Future work in this area will include expanded testing for strength and comprehensive testing for edge acuity, a critical printing property, following digital inkjet printing.

Polyester

In addition to investigating the potential for integration of fabric formation and coloration processes for cotton substrates, polyester, a popular fiber used in both the apparel and home furnishings industries, also carries potential for future integration.[3] Polyester, a hydrophobic fiber, is typically dyed with disperse dyes, which are also hydrophobic, and thus have a good affinity for the fiber.[1] It is known that the treatment of starch with a bacterial enzyme produces oligosaccharides, known as cyclodextrins, depicted in Figure 6.

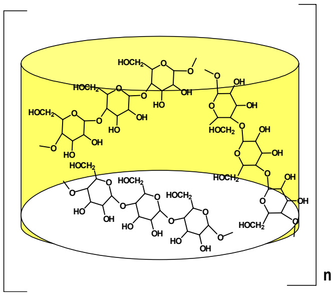


Figure 6. Representation of cyclodextrin structure.

These cyclodextrins have a polar, hydrophilic exterior and a relatively hydrophobic interior, a dual feature, which enables the cyclodextrin to serve as a host for hydrophobic compounds in a hydrophilic medium and the key that is required to successfully link the fabric formation and digital printing processes for polyester substrates.

A future approach to combining the weaving and fabric printing steps will take advantage of the unique properties of cyclodextrins. In this regard, future research will include the design, synthesis and use of special cyclodextrins (CDs) that function simultaneously as warp sizes and latent colorants. To achieve this, it will be necessary to determine 1) the number of cyclodextrin units that must be linked together to give the viscosity needed in an effective warp size and 2) the size of cyclodextrins required for the types of dyes to be employed. It is envisioned that the structures represented in Figure 6 could be used as warp sizes for natural and synthetic fibers and then dissolved away with hot water, leaving dye on the fiber surface. By using end-functionalized polyethylene oxide (PEO) oligomers to form soluble PEO-CD-ICs (inclusion compounds), blocking the PEO ends so CDs cannot slip off, linking the threaded CDs with epichlorohydrin, and finally removing the bulky PEO end-groups, it is possible to obtain a chain of CDs of the type shown schematically in Figure 7. It is believed that this group of units would serve as a warp size and simultaneously bind various dyes to the fiber surface.

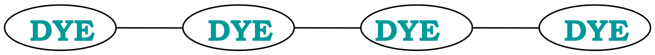


Figure 7. Representation for linked cyclodextrin units containing dye molecules.

Simulated Production

Once a link has been successfully discovered that will transcend separate fabric formation and coloration processes, for both 100% cotton and 100% polyester substrates, a small production facility will be put together using a sample loom and a desktop digital inkjet printer. The simulated production will provide manufacturing productivity data, which will be compared in relative capacity to real-time manufacturing speeds currently in use. Should the two processes be successfully combined, a decrease in manufacturing time will dramatically increase productivity and reduce handling costs associated with individual processes. Such integration possesses the potential to be the future of textile production.

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Biographies

Hitoshi Ujiie is an assistant professor of textile design at Philadelphia University. His specialization is in digitally produced textile design and he has established Ion Design, a digital fabric-printing studio in New York. As an inkjet fabric-printing specialist, he has offered his services as a consultant to many software and hardware companies. He has produced numerous textiles for the national and international home furnishing market place. Previously, he coordinated the Textile Program at Parsons School of Design.

Deanna Wood is a graduate Fashion Apparel Studies student at Philadelphia University, focusing on Advanced Apparel Manufacturing. She received her Bachelor of Science degree in Textile Design, from Philadelphia University, in May 2002, having concentrated on knitwear design. Her current research, funded by the National Textile Center, examines current apparel manufacturing productivity, and how it may be improved by combining fabric formation and textile printing processes.

Brian George, an Assistant Professor at Philadelphia University, School of Textiles & Materials Technology since 1999, received a Ph.D. in fiber and polymer science in 1999 and a B.S. in textile science in 1994, both at NC State. Brian's research interests include instructional methods, nonwovens, recycling, and fiber extrusion.

Muthu Govindaraj, an Associate Professor and Director of Textile Graduate Programs at Philadelphia University since 1995, earned a Ph.D. in mechanical engineering at the University of Liberec (Czech Republic) in 1982. He also earned a MTech. in textile engineering at the University of Madras (India). Muthu was also a machine design engineer in industry in India, a post-doctoral research associate at NC State and an assistant professor at Cornell. His research interests include fabric mechanisms and on-line control systems for textile and apparel machinery.