ABSTRACT

JANSSEN, BERIT GABRIELA GERDA. Print Quality of Digital Inkjet Printed Nonwoven Fabrics (Under the Direction of Dr. Trevor Little)

Digital Inkjet Printing (DIP) is an increasing market due to its wide range of application, easy handling and flexibility in terms of substrate, ink and design change. The research objectives of this research are (ROI) to define a standardized test print and evaluation method to determine the print quality of DIP nonwoven material as well as (ROII) investigate how changes in print settings and substrate parameter can influence the print quality. Further it is investigated (ROIII) how current crocking standard in the US, as defined by AATCC is applicable to test crocking of DIP nonwoven material on the example of Evolon.

Therefore, no standard test print for DIP of nonwoven or any other fabric exists, a test print is developed based on standards for testing print quality of papers. For the evaluation techniques three methods were investigated on their suitability as a standardized evaluation technique. First evaluation technique is using an image processing program – ImageJ – to evaluate the test print on various substrates by using a computer program. The second evaluation technique is to use the test print, printed without colors on a transparency. The transparency is used as a stencil to evaluate the print. The last method is to measure the content of the print and compare it to the template file. As result a standard test print and evaluation method is defined.

For the second objective the samples printed in first research objective are evaluated and interpreted based on the evaluation method and technique defined in RO I. Results show that the print mode and the ink temperature have a significant influence on the print quality. The fabric weight for a fabric made with the same production method and material however
does not have a visible influence on the print quality. However, while visiting Springs Creative in Rock Hills, South Carolina for printing a set of samples, it is discovered that humidity as well as air pressure in the printing facility can have an influence on the final print quality.

In the third research objective the crocking behavior of DIP nonwoven is investigated and under what circumstances the current valid crocking method is applicable to gain comparable results. During crocking the woven crocking square is rubbed over the surface of the testing specimen. By optical manual evaluation the amount of color transfer is evaluated and grades. During the crocking process the surface of the sample specimen is distorted. For woven material the destruction is not as visible and severe as for the used nonwoven material. By using the same nonwoven as well as other nonwoven material with same material content and production method but different weight for crocking than the sample material the color abrasion differs. Beside different crocking material on different samples also a squared crocking peg instead of a round crocking peg is tested. Using the round crocking peg led to different results compared to using the squared crocking peg on different material and with different crocking fabrics. The overall result is that the current crocking method should be extended by including a nonwoven crocking material and a squared crocking peg for crocking nonwoven.
Print Quality of Digital Inkjet Printed Nonwoven Fabrics

by

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DEDICATION

Dedicated to my family and friends.

For being on my side in one or the other way to walk the path with me and support me along the way.
BIOGRAPHY

Berit Gabriela Gerda Janssen was born on 23\textsuperscript{rd} or December, 1982 in Starnberg am See, Germany. She grew up in Bavaria in a small village, called Bad Bayersoien. Berit graduated from Marien-Realschule (equivalent to secondary school) amongst the 15 best students with a grade of 1.6 in 2000.

In 2000 Berit then started a higher education in Mathematics, Physics and Engineering. After she graduated and spend a year abroad as an Au Pair, she started an apprentice ship as a tailor for traditional Bavarian dresses and leather clothes. In 2007 she began her Bachelor studies in Clothing technologies at the Fachhochschule Albstadt-Sigmaringen which she graduated with a Bachelor of Engineering in 2010. During her Bachelor studies she spend one semester abroad at the Heriot Watt-University Edinburgh, Scottish Boarder Campus - Galashiels, Scotland.

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In January 2014 Berit began her pursuit of a Doctoral of Philosophy at the North Carolina State University.
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INTRODUCTION TO DIGITAL PRINTING

1 Digital printing

Embellishment of textile surfaces through printing has been practiced for centuries but their early examples are not well documented. However, more detailed documentation is available for the development of ink jet printing and digital inkjet printing. A first record, important for the development of ink jet printing can be found in 1686 by Edme Mariotte, who studied the drop formation of a fluid in a nozzle (Mariotte, 1718; Ujiie, 2006). Further contribution to the development of inkjet printing were subjoined by Ebenezer Kinnersley in 1748 and by l’Abbé Nollet in 1749 (Nollet, 1749). Ebenezer Kinnersley describes in a letter to Benjamin Franklin how he investigated electricity in water in 1748 and how he found that it just passes through it (Kinnersley, 1763). l’Abbé Nollet a year later studied the behavior of water under static electricity in a capillary tube (Nollet, 1749; Ujiie, 2006). In 1878 Sir John William Strutt (Lord Rayleigh) published an article “On the instability of jets” in which he mathematically shows how surface tension influences and controls drop formation (Strutt, 1878). 60 years later with the galloping industrialization and technology it brought with it the rise of digital printing began. First only for telegraphs, then for photographs and printing, copy machines of all kind up to the – now everywhere purchasable – desktop printer for the home office. The term “digital printing” as described by Frank Cost (1997) is the production or multiplication of a digital image with either silver halide, thermal, ink jet or electrostatic print mechanism (Cost, 1997). In the following printing methods for printing digital images only a brief description is
included as they have been discussed and presented in prior literature (Carden, 2015; Cie, 2015; Cost, 1997; Fralix, 2000; Ujiie, 2006)

1.1 Digital image

Before printing, a digital image or graphic has to be generated or taken. A digitally generated image consists of a number of pixels in x- and y- direction or vectors. For digital images based on pixels the picture quality is highly dependent on the number of pixels in x- and y- direction. This is not applicable for vector based images, where an image consists of lines and distances between points. The resolution usually can be set in the image or graphic program, which is used to generate a picture.

1.1.1 Pixel based graphics

A pixel is a small block with a certain size and position in a clear defined area. Cameras and monitors are based on pixels where the image quality depends on the dots per inch (dpi). More dpi gives higher resolution and clearer images. A good resolution for printing is said to be about 300 pixels per inch.

Using a photograph from a digital camera the resolution depends on the camera´s capacity. A camera for professional use has around 36.3 Megapixels per picture (Nikon, 2016). This resolution enables pictures in high definition (HD) quality. On a computer, parts of the picture can be enlarged without loss in clearness or quality. Even a picture with 36.3 Megapixels has its limit of enlargement without loss in quality. For printing HD images, depending on the printer, the size is reduced by the printing program, which means the pixel number is decreased and pixel clusters are emerged together to fit the printers resolution. This is called compression
and is usually not reversible. A compressed picture cannot be enlarged as much as an uncompressed picture without loss of sharpness or crispness. Image compression also has its limit therefore too much compression also can decrease the image quality.

1.1.2 Vector graphics

A vector based picture is defined by lines between points on a mathematical base as shown in principle in Figure 1. This enables a nearly infinite amount of enlargement and modification without loss of clearness or crispness. This is why vector images are often used in 3D modeling, animation graphics or company logos, which are resized frequently. The file size also often is very small. Still vector graphics have to be transformed into a bitmap format before printing. In this case, the vector properties are lost and cannot be reversed. Keeping a copy of the original file enables future adjustments in case the graphic has to be changed.

![Figure 1. Principle of Raster Graphic (left) and Vector Graphic (right)](image-url)
1.1.3 File format and graphic data

Before printing, the picture or graphic has to be generated. Here it is important to choose a picture with high resolution to have high quality print. The resolution is determined how many dpi (dots per inch) a graphic contains.

Besides the size and resolution of the image or graphic, the format, such as JPEG, TIFF or PDF is important for the quality of the final print. Depending on the printing software the format can be limited. Joint Photographic Experts Group (Jpg of Jpeg) in general is not recommended for printing large images or pictures. A Jpeg is usually compressed for creating thumbnails or for sending per e-mail, which is irreversible. An image in Jpeg can only be printed in a good quality in the actual file size. Through enlarging a Jpeg picture or graphic it becomes more pixelated as is can be seen in Figure 1. Especially with images generated on screen, which looks good in small scale and then printed in large scales, such as on a fabric with a width of 180cm, the quality can decrease drastically and the final image is very pixelated. PNG means Portable Network Graphics and like JPEG, is good for e-mailing, and for small scale publications (Kabachinski, 2007).

Recommended formats are Tagged Image File Format (TIFF or TIF). This format was created by Aldus Corporation especially for operating environments, such as scanning and large printing. It can store images with any pixel depth in multiple bitmaps which means it can be easily edited without loss of data (Kabachinski, 2007). When modifying a TIFF it is recommended to always have a “master” file, which is the original file, so that if changes are made that are irreversible, a backup file exists.
Another possibility for file format is Portable Document Format (PDF). Even it was
designed by Adobe for a safe and easy way of interactive viewing of text documents, such as
formulas, its ability to store and describe content in a size independent manner, enables it to
some degree to be used for storing and transporting pictures and graphics for digital printing
in large scale (Adobe Inc, 2006).

The file format in this research was mostly TIFF, but also PDF files were used for
comparison of the quality of printed images and graphs.

1.1.4 Print software

The link between PC and printer is the print software, such as Adobe Photoshop®, MS Paint,
RIP Master or MatchPrint. It has to be compatible with the printer´s software to convert the
image into machine language to manage the ink delivery system.

After the image or graphic is generated it has to be loaded into the printing software. Here
print settings, such as number of repeats, placement of print on the substrate in x-direction
based on pre-defined substrate width or determination of print mode, which defines the size of
drops of inks has to be selected. Other settings, such as print head height and print head
alignment for each specific fabric are periodically determined and defined in the “profile”. For
each material the fitting profile can be selected when the material is used for printing.

When the selection and definition of print settings is done, the software sends the print
information to the printer.
1.2  Digital printing mechanisms

The printing mechanism in all four techniques, as listed by Frank Cost is the same. An image is generated creating a number of small dots next to each other. The methods differ in how the dots are created, such as by placing small amounts of ink, charging areas or developing small areas next to each other. The quality of a print is determined by the used dpi of the picture and the amount of dpi that the printer can print (Cost, 1997).

1.2.1  Silver halide

Silver Hailing is the process of developing a light sensitive photo paper by light beams, directly projected on it instead of light through as with a photo negative. The advantage of silver halide process is a fast and easy method to project a picture on a photo without using chemicals for developing or fixations. Also, the drying process is not necessary anymore. The limitation of this method is that it only can be applied on light sensitive paper or pretreated fabric.

Direct thermal printing, a pretreated heat sensitive material is treated with heat in specific areas. Heat treated area turns black, through which an image or graphic in black and white can be generated. This method can handle up to 300 dpi (Cost, 1997).

1.2.2  Thermal printing

In the thermal printing process heat is applied on a wax plate or colored ribbon. The thermal induction can be controlled in local areas and in 1997, according to Cost, the resolution was about 300dpi (Cost, 1997). Heat can be applied through contact, induction or laser beam. For all methods contact of the print media and the substrate is necessary.
1.2.3 Electrostatic

Through charging selected areas of a dielectric surface, applied toner particles are either attracted or not attracted to charged areas. Charge can be generated through an electric beam or through discharging a photoconductive surface (Cost, 1997). This method is often used in low end fax or printer techniques as well as in creating sales slips in supermarkets or printing short time labels.

Disadvantages of the listed methods by Cost (Cost, 1997) are that they are limited to flat surfaces, which limits their application and further, the resolution is limited due to the size of light beams and applicable areas for charging and heating. These limitations can be overcome by using controlled ink jets, as in various inkjet printing methods.

1.3 Digital Inkjet printing methods

Since the first invention of inkjet printing, much has changed. The first inkjet printing, where simple telegraph machines printing low resolution graphics in black and white whereas nowadays an inkjet printer can print high quality images in a huge color gamut by ejecting ink droplets in the Pico liter per drop range. The ink application is done, as the name indicates, by inkjets. Depending on ink, substrate, printing method and various other parameters the final application and necessary quality of the print is determined.

For forming a drop on the jet nozzle and placing ink on the substrate different techniques can be applied, such as electrostatic for charging the surrounding or single drops in a jet as well as heat or electricity right at the nozzle tip.
1.3.1 Electrostatic

Conductivity is used to create an electrostatic field between nozzle and substrate or charge single drops in a jet to alter its flight path.

1.3.1.1 Electro-hydrodynamic jet printing or e-jet printing

In e-jet printing a high electric field is built up between the inkjet head and the conductive substrate. Depending on the nozzle size very fine drops for high resolution graphs and pictures can be created. With computer controlled power the drop size and amount can be controlled. Challenges in this method are to create a stable electric field to have continuous control over amount of ink, especially when several nozzles are used. A too low conductivity can result in pulsation whereas a field too high causes spraying. This method is used, among others for mass spectroscopy (J.-U. Park et al., 2007).

1.3.1.2 Continuous inkjet printing

Instead of charging the substrate or the surrounding, only selected drops in a continuous inkjet can be charged to alter their flight path. In this method a continuous inkjet is flowing form the nozzle towards a collector that returns unused ink back into the cartridge. With electrostatic charging single droplets in the jet are charged and their path altered so that they leave the print head and form a pattern on the substrate (Calvert, 2001). 1200 droplets per second are possible.

1.3.2 Aerosol jet printing

To create a dense aerosol, ink is placed in an atomizer. From the atomizer the aerosol is pumped into the sheath/center nozzle. The nozzle with the aerosol is located in the center of
the nozzle head. In a sheath nozzle, high pressure gas pushes the aerosol out of the nozzle and onto the fabric. With this method metals, polymers, pigments or bio-materials can be printed in fine lines onto various substrates without contact (Hedges & Marin, 2012).

1.3.3 Drop-on-demand

Generating drop-on-demand can be divided into thermal and piezoelectric or electrical, respectively drop-on-demand (DOD) methods. In thermal DOD drop release is controlled through super heating within $2/10^6$ of a second. Here, a heater vaporized a small volume of ink in the print head right behind the extrusion nozzle. Through the sudden expansion of the liquid ink is ejected (Saunders, Gough, & Derby, 2008).

The ejection mechanism in piezoelectric of electrical print head is caused by a mechanical impulse caused by the rapid shape change of a piezoelectric crystal which has the same effect than the bubble caused by thermal heating, or by a mechanism, such as expanding rapidly a bimetal plate (Saunders et al., 2008). A drop-on-demand printer can eject 1000 drops and more per second (Mishra, Barton, Alleyne, Ferreira, & Rogers, 2010) with a drop density or resolution of up to 2400 dpi.

1.4 Advantages and disadvantages of digital inkjet printing

1.4.1 Advantages

Digital inkjet printing, compared to other printing methods, such as roller printing, is much faster in terms of generating a graphic and printing it onto a substrate. Also, the adjustment and change of graphics or texts can be easily altered with just a few clicks in the program. This
makes digital inkjet printing easy to use on a wide range of applications with fast changing patterns or small production batches. Further in using pigment ink nearly no substrate restriction applies.

1.4.2 Disadvantages

Even if digital inkjet printing is a fast production in terms of the time from design to product, the printing itself is relatively slow, compared to for example roller printing.

Wicking of color can be an issue on untreated material as well as on pretreated material. Here the color wicks along the surface capillaries and causes blurry and un-sharp edges and color mixture. By using less ink this can be prevented, but also the color saturation will be decreased as well as blotchiness increased.

Uneven pretreatment, no pretreatment or low amount of ink can cause blotchy optics in solid area. To overcome this issue the amount of ink per drop can be increased which again can lead to wicking. The evaluation and rating for blotchiness or un-sharp edges solely lies at the producer’s discretionary power therefor not standard test or evolution method for DIP on textiles exist. Choosing the right setting, the right amount of treatment or ink has to be determined experimentally or by experience.

2 Digital Image evaluation

Digital image processing is used in various scientific fields as well as in art. Besides more known techniques, such as video or photo editing for commercial use, like movies or magazines, image processing is also used in science. Here the main focus lays in enhancing, enlarging, clarifying or removing noise from a picture, such as in space photography or medical
application. By manipulating elements of a digital image it is possible to enhance the information content of the picture. For this computers and special computer programs, such as MatLab, Photoshop, Toolbox (Prenhall.com, 2017) or ImageJ as well as programming languages, such as Java, C++ or Python can be used. The selection of program and programming language highly depends on the final purpose and use of the program as well as the programming skills of the program user.

**ImageJ**

ImageJ is a completely Java based program for picture processing and analyzing (Burger & Burge, 2016). It was developed by the NHI in 1997 (ImageJ, 2017) and runs on most common platforms due to its compatible programming language Java (Burger & Burge, 2016). Further it is a public domain program, which does not require any purchase and the source code is publicly accessible. This enables programmers to adjust and modify the program for specific needs. However altering the program always needs good skills in Java. The basic, preprogramed functions and additional plug-ins enable a wide use of ImageJ for scientific use without the need of knowing how to use Java as a programming language.
INTRODUCTION TO DIGITAL INKJET PRINTING ON TEXTILES

3 Digital inkjet printed textiles

3.1 Development of inkjet printing on textiles

The invention as patented by Cummings and Sweets in 1967 for “Fluid droplet recorder with a plurality of jets” (Cumming & Sweet, 1968) pathed the way for applying inkjet printing not only on paper or laminates, but also on fabric. First ink-jet printed fabric like structures where carpets, as produced by Milliken of Spartanburg in South Carolina, USA, in the 1970’s (Ujiie, 2006). The beginning of digital inkjet printing for fabric was around 1993 (Aston, Provost, & Masselink, 1993; Dawson & Ellis, 1994) where first studies were conducted to investigate necessary jet requirement to print on a woven fabric (Dawson & Ellis, 1994) and the overall demand for non-impact applications (Aston et al., 1993) arose, based on available technologies. In the 80’s researchers at universities, such as Georgia Tech and North Carolina State University investigated and tested with some success, printing on fabric by using electrophotography (Ujiie, 2006). Even studies on inkjet printing on textiles rapidly increased over the last decades, in 1995 still inkjet printing for textile was not considered to be a basic printing method as displayed by Malchowski as listed in Table 1 (Malachowski, AATCC, 1995).
Table 1. The basic printing processes used worldwide in 1995 according to Malachowski (1995)

<table>
<thead>
<tr>
<th>Printing method</th>
<th>Use worldwide in 1995 (according to Malachowski, AATCC, 1995)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary Screen Printing</td>
<td>61%</td>
</tr>
<tr>
<td>Flat Screen Printing</td>
<td>19%</td>
</tr>
<tr>
<td>Roller Printing</td>
<td>14%</td>
</tr>
<tr>
<td>Transfer Printing</td>
<td>5%</td>
</tr>
<tr>
<td>Others</td>
<td>5%</td>
</tr>
</tbody>
</table>

Nevertheless printing digital generated graphics on fabric became more and more popular in textile and apparel industries ever since. Today a vast majority of digital inkjet printing (DIP) is available and used.

3.2 Printing on a nonwoven with MS JP5\textsuperscript{evo}

Independent if for a desktop printer, an industrial printer for posters or an inkjet printer for textiles the principle of creating a picture on the substrate’s surface is the same. In following the process of printing on a selected nonwoven with the MS JP5\textsuperscript{evo} printer from MS Printing, Italy is described.

3.2.1 Printer set up

Before the printer can start printing, the print start point hast to be defined. Each substrate has its own width and is placed differently on the conveyor. To avoid printing on the belt
instead of the substrate the start point has to be typed into the printer manually. After the printer receives the print data from the software its starts printing.

The printing sledge with the print heads and its nozzles starts moving from one side to the other side and back. In either one or both directions (uni or bi drop application) moving the nozzle drop the ink on the substrate according to the image or pattern and the chosen print mode. The belt moves the substrate according to pattern or image in the y-direction. Same as with any other inkjet printing mechanism, a picture is generated by placing a certain amount of dots per inch next to each other. The more dots in an inch the clearer the image, but also the smaller the dots have to be, to ensure clear color separation. For the available printer in this research the maximum amount of dpi is 600 in x and y direction with drop sizes ranging from 4 pl to 72 pl (1pl = Pico liter = 0.000,000,001 ml = 1e⁻⁹).

3.2.2 Printing process

Selection of printing substrate depends on the end use, such as interior, hygiene, apparel or signage. Based on the substrate properties, such as material, absorbency and finishing the fitting print mode has to be chosen. In a print mode the amount of ink per application is defined. Assuming print mode “A” has drop sizes 4, 7 and 12 Pico liter (pl). Therefore the maximum drop size is 12 pl (which is 1ml=1 000 000 000pl) it is suitable for very fine material with a high spreading and absorbent rate, such as paper. Printing with this print mode on a thick and absorbent material such as a fluffy carpet, the color saturation and print quality will be very low. Further, as soon as the print head is not working properly, due to dried ink or clogged nozzle, banding is highly visible. In “C” mode the drop sizes possible are 4, 7, 11, 14, 16, 21
and 24. This mode is suitable for material with moderate absorbency, such as treated woven cotton or polyester fabric. The absorbency properties of cotton fabric depends on the capillary action of the fabric structure as well as absorbency of the material itself, whereas the absorbency properties of polyester fabrics mostly comes from the fabric structure or fiber finish. In this print mode the amount of ink placed on the substrate is much higher as much as in print mode “A”. The color saturation in fabric is higher as well as the risk of wicking or spreading of ink and a blurry image. Further, the chance for print failures as mentioned in section below is much higher. Occurrence of banding due to clogged nozzles or dried ink on nozzle is lower since the amount of ink from other nozzles is high enough to cover for reduced or missing ink. The highest amount of ink is used in print mode “H”. Here the drop sizes vary from 4 to 72pl, which nearly completely erases the risk of banding but also gives the highest risk of other image faults defined in section below. “H” print mode is suitable for heavy material high absorbency rate.

The printer, used in this research has the 8 main print modes (A to H), with several sub print modes for A to E. In the sub print modes the distance between each drop and the speed of ink jetting is defined. For example D2 HQ means that the ink sledge is moving slower and ink droplets are placed more accurately and dense than in a print mode with higher speed. Which print mode is most suitable for used material, has to be determined by testing and evaluation of the print on the actual fabric.

The ink absorption and spreading depends not only on the amount of ink placed on the substrate but also on the material, fabric formation and fabric pretreatment prior to printing. Which material, production method and additional treatments are used depends mainly on the
desired end use of the product but certainly also on which ink wants and can be used for the printing process.

Using an absorbent material, such as cotton fiber causes more spreading and absorption through the fiber structure. This can be directly influenced by fabric production, such as weaving very fine cotton yarn or producing a very dense and thin nonwoven fabric by needle punching or hydroentangling, treating the fabric, such as by mercerizing the cotton fabric, coating it with paste or solution to increase ink adhesion, such as a cationic pretreatment (El-Shishtawy & Nassar, 2002), as well as treating with plasma or other radiation to influence liquid absorbency properties (Li & Jinjin, 2007). There are many possibilities but the decision regarding which is most suitable depends highly on the material and desired properties of the end product.

When designing the picture or text to print on the substrate it has to be kept in mind that monitors, cameras and TV’s using RGB (red, green, blue) color mode, whereas printer and scanner are using CMYK (cyan, magenta, yellow, key color). Each picture made with a digital camera has to be transformed into CMYK color mode. This can cause a different display of colors on the PC monitor but result in original and desired colors on the substrate. A picture designed in Adobe© Photoshop with cyan, magenta and yellow defined as 100% in a 4 color mode are displayed as pure color on the pc monitor but will not be printed in pure color on the substrate. This is due to the preset setting in the Photoshop program, which mixes cyan color with at least 2% of red and yellow with 2% blue, causing yellow to be green and cyan to be purple on the substrate. Switching to multicolor mode in the Photoshop program enables us to remove the presetting and print pure color. Then, it is crucial to have the same number of layers
as colors in the printer, named in the exact same order with the right names otherwise, the print program is not able to locate and assign the right colors to the right print nozzles. Nevertheless, a test print always should be done prior to final printing.

Depending on the quality of test print several adjustments at the printer can be made to influence the outcome.

- Change ink temperature. A change in ink temperature during printing can increase or reduce spreading of ink on the substrate as well as change color saturation.

- Change print mode. Even fist evaluation is satisfying a change in print mode one above or below can create even a better print.

- Uni- and Bi- directional ink application. In Uni- directional mode ink is only applied when ink sledge is moving in one direction, either back or forth, causing slower print speed but reduces ink spreading. In Bi- directional mode ink is applied every time the ink sledge is moving over the substrate in both ways, back and forth. This enables a higher print speed.

After printing is done and the quality of the print is satisfying the ink on the substrate has to be fixed or cured. Depending on the ink and the substrate the right fixation method has to be chosen. Reactive dyes need more temperature for activation than some pigments dyes. Also, a water soluble ink should not be fixed with hot steam, hence it can cause color bleeding. Therefore, the ink already had to be chosen depending on the heat resistance of the fabric the maximum heat for fixating the ink on the fabric is to be set below the fabric’s onset temperature before heat damage occurs.
For this research a Polyester/Polyamide 70/30% fabric, called Evolon®, by Freudenberg was used. With a DSC the onsets of melt temperatures for both material where determining prior to selection of ink and fixation method. Based on the result pigment ink was most suitable. Printing with a Disperse ink set was also tried and determined as not suitable due to its high fixation temperature which exceeded the melting temperature of the PA content. Therefore a part of presented research is about determining best printing and fixation setting, several print modes, ink temperatures and fixation temperatures were used.

3.3 Inks for digital inkjet printing

Dyes for coloring objects and fabric have been used for over 2000 years. Ever since the modernization and industrialization in the last century the technology and knowledge about dyes and dyeing increased and changed how we use dye today. Besides the initial use of dyes for coloring a complete fabric or yarns, today dyes can be used in ink form for printing a pattern instead of former different methods of embroidery. Depending on the substrate, dyeing method and dye have to be selected (Maute-Daul, 1995).

For printing different inks in form of a thick paste, screen and rotatory printing together with aqueous state for inkjet printing are commonly used. Depending on substrate, the end product and its specifications as well as fixation or curing temperatures, the ink or dye can be selected.

3.3.1 Reactive ink

Reactive dyes, as the name states, are dyes that color the material through reacting with it due to the influence of additional chemicals and/or environmental aspects, such as light, heat
or radiation. For dyeing, the material is put into a dye bath with desired color. Through chemical, heat and/or light the dyeing reaction is triggered and the material gains its color. Reactive dyes tend to have very good color fastness and good to very good light fastness. On the other hand reactive dyes are very expensive to purchase and satisfactory dyeing requires a number of steps prior to and after printing. The dyeing process takes a lot of time and a high amount of dye gets lost during the process (Rivlin, 1992). Also, the substrate has to be washed as post treatment to remove chemicals or dye residues.

Reactive ink works in the same manner, but instead of a whole bath the ink is placed locally on a substrate. After drying the reactive ink on the substrate is activated and forms covalent bonds with the material (Christie, 2015).

3.3.2 Disperse ink

During the dyeing process the finely disperse color particles merge into the fiber. This takes place under great heat (higher than 100°C) and is mainly used for Polyester. After the dyeing process the pigments are trapped in the fiber and therefore the substrate has a good colorfastness against abrasion and washing. On the other hand, the colorfastness to light is lower for regular disperse inks/dyes, whereas so called “high-energy” disperse ink can improve lightfastness. Another disadvantage is that the process requires high heat and time. Disperse dye and inks are mostly used for Polyesters and Acetates but also can be used for other material.

3.3.3 Acid ink

Acid dyes or direct dyes are used for material with repeating chain moieties which have ionic attraction towards the dye molecules. Repeating moieties are found in amide fibers,
urethane or fibers containing peptide. When the dye or ink is placed on the substrate it directly react with the material. A pre-treatment of the fabric can increase the colorfastness and other properties. In after treatments the wash fastness and humidity fastness can be increased (Ujiie, 2006).

3.3.4 Vat

Indigo was the first vat dye available. The colorant was extracted from plant but nowadays it is produced synthetically and mainly used in dyeing jeans fabric. Vat dyes are mostly used for coloring cellulose material, but also can be used for protein based or polymer based material. In all cases the insoluble colorant is put in a solution to transform it into its soluble form. For this the dye is put in a reduction agent and then reduced at appropriate temperature. In the next step the dye substrate is added and dyed at dyeing temperature for the chosen colorant and material. During the dyeing process the color pigment emerges into the fiber where it is then mechanically trapped. After the dyeing time has passed, the substrate is rinsed and colorant is oxidized. In this step, the dye is cured or fixed in and on the substrate. In last dyeing step the substrate is washed with soap or surfactant and water which not only increases the wash fastness of the dye but also sets the final shade (Christie, 2015; Reif, 1953; Rivlin, 1992).

3.3.5 Pigment inks

Pigment dyes where first developed in the 1930 but were only in low use until 1960s where the required technologies reached a level that pigment dyes could be used in a fast and easy manner (AATCC, 1995). Pigment printing is the application of a colored print paste on a fabric.
The print paste contains besides the color pigments also consist of binder, thickener and specialized chemicals (AATCC, 1995). The color pigment, as the name indicates gives the color, the binder makes sure the dye stays on the substrate by adhesion (Hussain et al., 2015; Warburton, 1976), and specialized chemicals can impart additional properties to the printed or dyed area. Depending on the substrate the binder can be chosen and changed easily, since the color fastness is determined by the adhesion of the binder on the fiber. Compared to other dyes, pigment ink or dye has a low curing or fixation point, which makes a curing or fixation relatively easy (AATCC, 1995). In comparison to other reactive dyes and inks as described above, pigments are more durable (Gulrajani, 2010). Since no chemical reaction takes place during printing or dyeing pigment prints, pigments can be used on a wide range of fabric types including blended materials. Another advantage is that with fewer processing steps the production speed is much higher compared to other dyes or inks.

### 3.4 Advantages and Disadvantages of digital inkjet printing for textiles

Comparing the different inks and dyes for inkjet printing it becomes clear that each of them has its advantages and disadvantages. Depending on the substrate and the requirements on the end product the best-fit ink has to be carefully selected. Choosing the wrong ink for a substrate can result in poor dyeing properties, such as blotchy images as well as poor washing stability. Further, as presented above, all inks, except pigment ink have to be washed or chemically post treated to ensure good color adhesion and remove excess dyeing chemicals. Pigment ink on the other hand can be used on every substrate without washing or chemical treatment after printing. Due to dry heat, such as in a heat press the binder is cured and ensures good pigment
adhesion to the fibers. This makes pigment ink a solution for fast and easy printing for quick, small scale production. However, digital inkjet printing is still a comparable young technology and the experience of using digital inkjet printing is not as widespread as using other printing and dyeing methods.

3.4.1 Advantages

In comparisons to roller printing or screen printing, digital inkjet printing offers advantages in various areas.

Design

Digital inkjet printing as discussed above has the advantage of fast and easy adjustment in a print design. In comparison to other common textile printing methods, such as roller printing or screen printing, a change in the design does not need the production of a new roll or screen. By changing the digital image or picture all necessary steps for a change or adjustment in digital inkjet printing is done. In screen or roller printing for each change in color or pattern a new pattern roll or screen has to be produced, which is not only very time consuming, but also expensive.

A quick color change in digital inkjet printing is simply done by a few mouse clicks in the digital printing file, whereas in roller or screen printing the equipment has to be washed and cleaned before new ink paste can be processed. Further, each color in the print head can be controlled separately, which enables an additional possibility of adjusting color saturation. For this it can be chosen from pre-programmed printing modes in which the drop size range is
stored. Besides up to 16 colors in one print head, also additional inline fixation agent and other chemical can be directly printed during the process.

With drop sizes ranging from 4 Pl to 72 Pl and up to ca. 2400 dpi very small and fine detailed graphics and pictures can be printed (Pakistan Textile Journal, 2016). Small and fine details are also possible to print with screen or roller printing and therefore not an outstanding advantage.

Cost

As mentioned in previous section, a change in design in digital inkjet printing simply is done digitally. In roller or screen printing for each design change new screens or rolls have to be made, which can create huge expenses. Further, a color change in digital inkjet printing also is just a few clicks in the digital file whereas in roller or screen printing the rolls or screen have to be washed and cleaned before new paste can be used. These features make digital inkjet printing most suitable for printing small batch sizes, fast changing designs and colors.

3.4.2 Disadvantages

Digital inkjet printing not only has advantages, but also disadvantages in comparison to roller or screen printing, such as speed, equipment and current experience and knowledge about handling an managing digital inkjet printing.

Speed

In roller printing, the speed is measured in meter per minute or meter per hours. Here the substrate runs between the rolls. The width of the substrate is not important. In digital inkjet printing the print head moves from left to right and back over the whole width of the printing
area. Here the print speed is measured in m². Depending on number of colors, nozzles, drops and speed of the print head the print speed can change. In 2006 Kobayashi (Kobayashi, 2006) predicted that digital inkjet printing has have to reach a printing speed of at least 200m²/h to be able to replace common rotary screen printing methods. The average printing speed of digital inkjet printing at that time was around 30 m²/h (Kobayashi, 2006). However in the AATCC review in 2009 by Kerry King digital inkjet printers with printing speed of up to 250m²/h where described (King, 2009).

**Equipment**

For digital inkjet printing a computer is used, in which the print file is designed and the printer controlled. To be able to process and handle new file types and size the software of the computer must be able to process graphics and be compatible with the printer software. The software types that are compatible with a free software printer are called Raster Image Processing (RIP) software. Also, the printer software has to be updated regularly.

As every computer, with increasing age and advancing technology the performance decreases due to full storage and old hardware. To keep the physics of a computer up to date, hardware parts can be replaced, whereas most times a complete computer replacement is necessary.

Both aspects often bring new designed user surfaces and interfaces, which take time for the operator to learn which also reduces the production speed.

Additionally the preparation of the printer and software after a color change is very time consuming. Here, for every new set of colors and inks a new color profile in the print software has to be established. Old profiles can be used for existing color or ink sets.
Cost

Even though the costs for digital printing can lower handling and setup costs, ink for digital inkjet printing is still expensive compared to printing pastes used in roller or screen printing.

Knowledge

One major disadvantage is the low amount of experience and knowledge about how to properly handle digital inkjet printing technology. Whereas in roller or screen printing experience taught how to adjust color paste thickness or amount of color on the fabric to control and adjust color saturation or color bleeding in digital inkjet printing only a very small amount might exist. This puts the responsibility of influencing and controlling the final print quality in the hands of the ink and fabric manufacturer, where the print quality, such as color bleeding can be manipulated by the ink viscosity and/or fabric treatment for printing.

3.5 Determining Quality of the Print

The quality of the final print not only depends on the chosen ink but also how it behaves and interacts with the substrate. To determine the print and ink quality various parameters and aspects rule into the process. As displayed in Figure 2 besides the solely interaction of ink and substrate also the print head height, the substrate density, belt stickiness or testing method can influence the quality and quality evolution of a print.
Figure 2. Ishikawa diagram for Quality of Digital Inkjet Printing on Nonwoven
3.6 Crocking (AATCC 8)

In 1989 Gore analyzed the current AATCC 8 Method for determining colorfastness of dyed fabrics. He states the confusions caused by the vague descriptions and what can be done wrong during the test procedure based on the lack of description in the document. He further describes that at the beginning in 1928, the crocking was done with a cloth and finger of the testing person. Through the differences in finger size the crocking area was different. Further depending on gender and arm length the force applied on the crocking fabric was majorly different from test to test and tester to tester. With a test row the applied force could vary from very strong to comparable weak, when the tester got tired and was not able to press as hard as the beginning. To erase the problem of area and pressure a standardized peg and with a specific unit of force on top of it was developed. Another problem was the length and speed of rubbing on the fabric. With a longer rubbing distance potentially more color could be loosened and taken up from the crocking fabric. Further differences in speed could result in increased or decreased abrasion heat, additionally influencing color abrasion. To reduce the error in this topic it was defined for one stroke per second and the length was determined by the rotational device. Still in a manual Crockmeter the speed of rotation and with its potential pressure difference on the crocking specimen can vary. If a tester is turning the device’s handle faster the arm on which the peg is mounted could jump which causes irregularities in pressure over the crocking area and further resulting in biased results. With an electric device this could be prevented, still the arm could be misplaced in the rail guide during testing without notice and testing results would be wrong.
Another aspect on the testing machine itself is the peg that could influence the crocking results. If the peg is uneven, that part that sticks out causes more abrasion on the specimen falsifying the results. To smoothen the peg’s surface it can be polished with a fine grained sandpaper. A too smooth sandpaper on the opposite side of the peg, supposed to hold the crocking specimen in place, does not do its job and the specimen can move, causing folds during crocking resulting in uneven abrasion. Likewise a too smooth sandpaper also an incorrect placement and handling of the specimen holder can have influence on the test result. If placed in the wrong position according to the end points of the crocking path the peg can hit the edges of the specimen holder, which causes it to jump and as mentioned earlier, causes irregular and deceptive results. If the clamp, which is holding the crocking fabric in place on the peg is too loose, the crocking fabric also can fold while crocking or moves forth and back influencing the final crocking result on the crocking fabric and the crock specimen. By using a defined sandpaper under the crocking sample, the specimen cannot move during the testing process. To fasten the peg clamp it can be put around a round tube, pen or stick, which slightly smaller diameter than the peg. The clamp then can be bend together to cause enough hold on the fabric on the peg.

Gore further describes aspects that influence crocking results that are cause by the laboratory as well as the testing person itself. One aspect is the condition of the testing sample as well as the crocking fabric. Humidity and temperature dictated by annual season and daily weather highly influence crocking results. To avoid those influences Gore suggests executing crocking tests only under elaborated lab conditions. Further, the orientation of the warp and weft yarns in the crocking fabric as well as in the crocking sample have to be aligned tilted,
whereat the warp or weft yarn of the crocking fabric should be aligned parallel to the testing direction.

Gore states that the tester has to be aware of all possible mechanical and environmental influences on the test process and conditions to be able to avoid errors during the test procedure or incorrect results. In addition to make sure, prior to testing a calibration run should be done with an in-house fabric and the results compared with results done with the same fabric earlier under monitored and observed correct conditions and procedure.

Further to avoid misunderstanding, misinterpretation or lack of description clarification of the document the Committee on Crocking is advised to considered the point, mentioned and discussed by Gore to improve the procedure and reduce and eliminate future errors (Gore, 1989).

A similar approach on the drawbacks in the AATCC 8 Test method valid in 1989 is undertaken by Patton (Patton, 1989) in the same year or the same AATCC issue in March 1989. Whereas Gore (Gore, 1989) only discusses errors resulting from unclear or missing description in the test method document, Patton based his report on the collection of data about the problems with the test procedure and results from companies and laboratories which lead to the revision of the test method in 1986 (Patton, 1989). He further discussed how recent adjustments in the document prevent errors and faulty results.

One reported problem is the sample holder. As mentioned by Gore, a misplaced sample holder can lead the peg hit the edges and influence the results. By widening the opening in the sample holder this was able to prevent this issue, but also an additional sample holder was implemented. If the crocking sample is thick and/or fluffy, the initial sample holder would bulk
up the specimen in the opening, changing the surface and abrasion on the fabric on the peg. By using two metal clamps on each end in the crocking direction this issue was solved.

Gore clearly states in his article that the weft and warp yarns of the crocking fabric should be oblique to the yarns in the sample. Patton on the other hand states that this is an actual aspect that negatively influences the results. Due to the stretch in diagonal direction of warp and weft the result on the crocking fabric was not round, as the peg, but elongated. The issue was addressed and corrected by stating the mounting of the crocking fabric on the peg in a way that the warp and weft are parallel or perpendicular along the crocking direction, respectively. The crocking sample on the other hand has to be cut with cutting edges oblique to warp and weft.

Most changes and adjustments discussed by Patton (Patton, 1989) as well as Gore (Gore, 1989) are still applicable in the current valid AATCC 8 test method in 2016 (AATCC 8-1996, 1996).

Both articles were issued in the same year in the same journal in the same month. Based on the revision of these two articles the practical guide by Gore as well as the revision of the newly revised test method it becomes clear that the crocking method was not fully established for universal application for testing. Since 1986 the standard was revised an additional 5 times. Even the use and awareness of possible applications of nonwoven increases in the last decades the last revised version form 2011 does not include or mention the application of the test method for printed or dyed nonwoven. The only kind of fabric mentioned in AATCC 8 are woven and knitted material in section 6.2.9 “[…] Position specimen normally with the long dimension oblique to the warp and filling. […]” (AATCC 8-1996, 1996, p. 1) and section 7.2 “Cut specimens […] to warp and filling or wales and courses.” (AATCC 8-1996, 1996, p. 1).
In 2011 Pan et al. (K. Pan, Guan, & Wu, 2011) compared the Chinese and American standards for color fastness in terms of colorfastness to light, perspiration and crocking. They found that those standards do not vary much in terms of basic setup and use of equipment from each other but still enough to show some significant differences in results. The smallest difference however, was found in the testing procedure and result for crocking. The Chinese test standard enabled beside a round peg, also a squared crocking finger. This attempt was briefly discussed by Gore (Gore, 1989) and found to be not be suitable and was not implemented in the crocking standard due to its difference in amount of abrasion compared to a round crocking finger.

As mentioned above, the AATCC 8 test method is specifically designed for testing color abrasion for woven material as well as yarns, but not for nonwoven material. In general the colorfastness in nonwoven against crocking was not from huge interest since the invention and classification of the abrasion test. Few attempts have been made for testing abrasion and determining abrasion properties of printed or dyed nonwovens.

Hussain et al. used a theoretical approach to calculate the effect of binder concentration and curing time and temperature on the dye adhesion on spunbond polypropylene nonwoven. For this trial, samples were printed with pigment ink, containing different concentrations of binder. For each parameter, binder concentration, curing time and curing temperature, each three samples were produced and tested. With statistical software the test outcome for different production parameter, others than actual tested was predicted. As result the authors state that with the used materials and method a theoretical approach can be used to predict test results (Hussain et al., 2015). No replication study for other polymer material, than polypropylene and
binder, others than based on aqueous acrylic dispersion could be found to date. Further research about crocking in nonwoven was not published in openly accessible journals.

Although the interest in increasing nonwoven crocking is present, as patents such as US 3,867,187 from 1975 show where a fiber with a polypropylene fiber with a certain amount of N,N'-alkylenbeis(alkanamide), which is coated after spinning is described (Borenstein, 1975) no other patent directly addressing the issue of nonwoven crocking could be found. The resulting fiber and fabrics have an increased soiling and crocking characteristics (Borenstein, 1975). Polypropylene is used in nonwoven production and therefore this invention is highly applicable to nonwovens. Researchers at Procter and Gamble in 2012 developed a substrate with increased crocking behavior. In this research also nonwoven material is tested and showing increased crock fastness (Warner, Robertson, Li, & McCurry, 2012). However it does not mention if it was investigate prior if the crocking method is actually appropriate for testing nonwoven material.

As the reviewed literature shows, there is a lack of knowledge about crocking behavior of nonwoven as well as a lack of specification about nonwoven crocking properties. The methods of dyeing a nonwoven made from man-made fibers, by putting color pigments into the polymer batch or hopper during spinning, already makes synthetic fibers much more color resistant against abrasion as natural dyed fibers. Even color application after fibers spinning and fabric production, such as printing is increasing in the use of nonwovens, still the current valid test method in 2011 does not clearly state if the method is only applicable for woven material or also for nonwovens.
3.7 Print sharpness

Research about determining print quality of digital inkjet printed textiles mainly focuses on the woven fabrics. Here the interaction of yarn twist and weaving construction (H.-S. Park, 2006) as well as fabric finish on liquid migration and print quality (Kim, 2006) was investigated and described for determining print quality of digital inkjet printed woven fabric. Y. E. Kim describes the importance of pretreatment of textiles for digital inkjet printing to ensure good printing quality for woven textiles (Kim, 2006) whereas Park studied the ink migration on coated and uncoated polyester fabrics with different weaving patterns (H.-S. Park, 2006). Hamada et al. investigated the influence of ink placement of aqueous and solvent inks on synthetic nonwovens on the liquid migration and print quality (Hamada, Bousfield, & Luu, 2009).

Reviewed research in the literature only focuses on aspects such as coating, finishing, weaving pattern, or fabric density, but none can provide a guideline to evaluate print quality of digital inkjet printed textiles to directly compare it to other prints. Further, no standard is available to evaluate the print clearness or sharpness of digital inkjet printed textiles. Depending on the use of a final print, for example a banner, which is placed above crowded or a in an exhibition booth the sharpness can either be low or has to be very accurate, respectively.

A standard to test and evaluate the print quality of digital inkjet printing could be designed according ASTM 1944-98 for evaluating digital inkjet prints on paper. ASTM 1944-98 is designed to determine the Quality of printed pictures on a substrate in digital inkjet printing (ASTM F1944-98, 2008).
3.7.1 Text evaluation

3.7.1.1 Feathering

Feathering occurs when the letters of a text do not have clear edges but fine stripes along the fibers. Through feathering, the letters can be connected by ink-bridges and to test feathering, several lines of Text in different sizes are printed (Figure 3 -1).

3.7.2 Image bleeding

If two contrasting colors are printed in the same area such as yellow text on a solid black (Figure 3 - 2) area or black text on a solid yellow area (Figure 3 - 3) they can bleed into each other. This is due to wicking and causes blurry text and blotchy color.

3.7.3 Solid color defects evaluation

3.7.3.1 Solid fill

To examine if the color on the substrate is evenly distributed and has the same density some solid filled squares are printed. The solid filled squared can have any color, but for proper evaluation the basic colors used in the printer are used.

A solid black area (Figure 3 - 5) is also printed to evaluate solid fill as well as bronzing. When black ink reacts with the substrate it can cause a bronze shimmering.

With printing solid filled areas it also can be observed if ink causes swelling of fibers in the substrate or if the substrate gets a wave pattern after the ink dried.
3.7.3.2 Banding

Banding is an image defect of inconsistent color density in form of bands. Through banding a picture or picture area looks blotchy. To evaluate for banding in printing the solid area as printed for solid (Figure 3 - 4 and 5) fill testing are examined.

3.7.4 Image defects

3.7.4.1 Image bleeding

Through wicking the colors in an image can bleed into each other causing blurry edges and unclear pictures. To evaluate image bleeding two pictures with high contrast color and sharp edges are printed as well as small stripes in gray and black (Figure 3 - 6).

3.7.4.2 Spraying

A moving print head can cause spraying which is the dislocated placement of ink around the outside of an image. It can cause a halo effect around a picture. For testing on spraying the area around the pictures and stripes in area 6 (Figure 3) are investigated.

3.7.5 Other defects

3.7.5.1 Drop Volume

To evaluate if the print head has a consistent drop volume over a distance the thinnest possible line of at least 1 inch length is printed several times over the picture. As printed around area 1, 3 and in area 7 in Figure 3.

3.7.5.2 Skew

To evaluate if a pictures is printed with all sides in the relationship to the edges as placed, skew is determined. For this a 25.0 cm long stripe (Figure 3 - 8) is printed along the edge of
the test print and the distances of the stripes edges to the edges of the substrate are measured. This can also be used to determine the color gamut of the printer on the substrate.

Figure 3. Test print picture as designed by author
Besides ASTM F1944-98 also ISO/IEC-13660 can be used to evaluate the print quality for hardcopy outputs. For testing and evaluating DIP prints for textiles no standard or guideline to test or evaluate digital inkjet printing for nonwoven or textiles could be found.

For color intensity and trueness evaluation a microspectrophotometer (MSP) can be used. An MSP measures the absorption or transmission spectrum of colored liquid or solid.

3.8 Quality prediction based on liquid movement in porous media

The spreading behavior of liquid in porous structure depends on various properties in the liquid as well as in the solid material. Depending on the surface tension and interfacial tension, viscosity, pore size and distribution wetting and wicking takes place in a porous media, such as a woven textile assembly. To predict and determine spreading different mathematical approaches can be applied, as studied by various researchers.

3.8.1 Surface tension

Surface tension is a liquids’ inherent force to keep it in a structure with the smallest possible surface area. It enables liquids to form elastic drops and bubbles (Foundation of Science, 1966). Through the interaction of molecules in all direction in the liquid it is in an equal state, whereas the imbalance on the surface causes tension. The surface tension also means that there is free energy, which is referred to surface free energy (Patnaik, Rengasamy, Kothari, & Ghosh, 2006).

Using different techniques like tensiometry, such as Wilhelmy plate method or Pendant drop method as well as a goniometry method, such as measuring the contact angle with the Sessile drop method, the surface tension of static liquids and solids can be determined. In
goniometry, surface tension is calculated by using the contact angle of a liquid to a solid. In tensiometry, pressure differences as well as measuring forces, radii and angles are used to calculate surface tension and indirect calculate the contact angle (Patnaik et al., 2006).

3.8.1.1 Wilhelmy Plate Method

With the Wilhelmy plate method the surface and interfacial tension of liquids and solids can be determined. Here a plate, usually made from platinum-iridium for liquid surface tension or a liquid with known surface tension, respectively is used. The plate, which is designed to enable good wetting if in contact with a liquid, is put into the liquid. The very fine and exact scale holding the plate, measures the drag caused by the lamella crawling up on the plate’s sides.

![Diagram of forces on the three-phase contact line](image)

*Figure 4. Forces on the three-phase contact line (as seen at Holz & Rau, 2016)*
The dragging force $F_{tens}$ caused by the weight of the liquid on the sides of the plate is now measured with the scale. With optical evaluation the contact angle $\Theta_C$, meniscus and meniscus height $L$ can be measured. On the three-phase contact line, as displayed in Figure 5 the $F_{tens}$ can be divided into a perpendicular $F_\perp$ and parallel $F_\parallel$ forces (Equation (1)).

$$
F_\perp = F_{tens} \cdot \cos \Theta_C \\
F_\parallel = F_{tens} \cdot \sin \Theta_C
$$

The gravitational force $F_G$ drags the plate down and is measured by the fine scale. $F_G$ is equal to the weight of the amount of liquid in the meniscus. Based on this, the Wilhelmy Equation (2) can be applied to determine the surface tensions $\gamma$ of a liquid (Holz & Rau, 2016).

$$
\gamma = \frac{F_{tens}}{L} = \frac{F_\perp}{L \cdot \cos \Theta_C} = \frac{F_G}{L \cdot \cos \Theta_C}
$$

This method can be used to determine the surface tension of a liquid, by using a platinum-iridium plate. For determining the surface tension of a material a liquid with known properties can be used. However the method is not applicable when using absorbent material, such as an Evolon® nonwoven. Here, the absorbent rate is too high, so that the electric fine scale cannot
adjust quick enough to give exploitable values. Further, by testing a high absorbent material the problem occurs that the amount of water is too much so that the scale reaches its limit and breaks.

3.8.1.2 Pendant Drop Method

In the pendant drop method, the surface tension of a liquid is determined based on optical evaluation and the use of the Young-Laplace Equation (Holz & Rau, 2016; Pellicer, García-Morales, & Hernández, 2000; Tadros, 2013). For this a drop on the tip of a needle is formed between a camera and a light source. Through optical evaluation the radii $R_x$ and angles of the drop can be determined using the Laplace pressure and the Young-Laplace Equation (3).

$$\Delta P = (P_{int} - P_{ext}) = \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right)$$

where $\Delta P$ is the Laplace-pressure, describing the pressure difference between the inside and the outside of curved surface caused by surface tension of the drop, $P_{int}$ is the internal pressure, $P_{ext}$ is the external pressure, $\gamma$ the surface tension and $R_1$ and $R_2$ the horizontal and vertical radii, respectively (Holz & Rau, 2016; Tadros, 2013).

The pendant drop method is only suitable to determine a liquid’s surface tension.

3.8.1.3 Sessile Drop Method

In the Sessile drop method, the contact angle of a drop of liquid on a solid surface is measured. Similar to pendant drop method the measurement is done optically. A liquid drop is placed on a solid surface between a light source and a camera. After the contact angle is
measured, the surface tension between the solid and the liquid can be calculated using Young-Dupré Equation (4). If a drop of water put on a smooth, homogeneous, impermeable and non-deformable surface (Patnaik et al., 2006) forming a bubble and does not ingress into the fabric the surface tensions of the substrate and the liquid are in equilibrium, as described by Young-Dupré Equation.

\[ \gamma_{SL} - \gamma_{SA} = \gamma_{LA} \cos \theta \]

where \( \cos \theta \) is equilibrium contact angle, \( \gamma_{SL} \) is the surface tension between solid and liquid, \( \gamma_{SA} \) the surface tension between solid and air and \( \gamma_{LA} \) the surface tension between liquid and air (Holz & Rau, 2016; Patnaik et al., 2006). The bigger the angle becomes the lower the interface tension becomes and the more likely spreading, wicking or wetting occurs (Patnaik et al., 2006; Pellicer et al., 2000).
The units is for expressing surface tension is dyne/cm and is a unit of force in the centimeter-gram-second system (CGS) or N/m and its derivations in SI unit. Surface tension of liquids and solids play an important role in capillaries and capillary action. Impurities, additives as well as the change in temperature can influence the surface energies (Morrison, 2013a; Patnaik et al., 2006).

Similar to the Wilhelmy-plate method the Sessile-drop methods has its limits of application. It cannot be used for material with low surface tension, such as highly absorbent substrates and/or very low viscous liquids. When a drop of liquid is put on to the surface the liquid will be absorbed before a contact angle can be determined.

3.8.2 Viscosity

As viscosity of a fluid it is referred to the resistance of the liquid or gas against flow as well as applied stress or shear rate (Morrison, 2013b; Viswanath, 2007). Dynamic viscosity, also
called shear viscosity, is the flow behavior of a liquid under shear or stress and is important for applications, such as fiber spinning. In the process of wicking or wetting in fabrics or fibers, no or nearly no pressure, shear or stress is applied. Therefore dynamic viscosity with its related mathematical consideration will not further be discussed.

The SI units of viscosity are Pascal second (Pas) and its derivation such as millipascal seconds (mPas) or poise as well as centipoise (cP). The conversion of 1 mPas = 1 cP but 1 Pas = 10 P (Tadros, 2013).

To determine the viscosity of a Newtonian liquid U-tube viscometer, such as a Ostwald or Ubbelhode viscometer can be used (Tadros, 2013) as sketched in Figure 6. The principle of such a viscometer is to determine the time a liquid needs to flow through a pipe (B) with certain diameter. For this test the U-shaped flask is filled with a liquid. It then is sucked up into the sphere (C). After removing the suction device the time is measured how long it takes for the liquid to sink from level (1) to level (2). With gained data as well as volume and density the viscosity of a liquid can be calculated.
Surface tension and interfacial tension of liquids–solids as well liquids–liquids are independent to viscosity. For example, a liquid with low viscosity, such as mercury (see Table 2) can have high surface tension, whereas Glycol has a much lower surface tension but higher viscosity. Whereas distilled water has the lowest viscosity but higher surface tension than Propylene Glycol.
Table 2. Comparison of Viscosity and Surface tension for selected liquids

<table>
<thead>
<tr>
<th></th>
<th>Viscosity (Engineering ToolBox, 2016)</th>
<th>Surface tension (Surface-tension.de, 2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pas or *10 P</td>
<td>mN/m @ 20°C</td>
</tr>
<tr>
<td>distilled H₂O</td>
<td>0.00089</td>
<td>72.8</td>
</tr>
<tr>
<td>Hg</td>
<td>0.0015</td>
<td>425.41</td>
</tr>
<tr>
<td>Propylene glycol</td>
<td>0.042</td>
<td>33.9</td>
</tr>
</tbody>
</table>

For liquid movement, such as ink or dye in a fabric, the viscosity and surface tension of the liquid in correlation with the surface tension and structure as well as the ab- and ad-sorption properties of the substrate are crucial.

3.9 Capillaries and Pores

Capillaries are referred to as round tubes with a small, constant diameter (Foundation of Science, 1966). Pores on the other sides are channel like structures interpenetrating an object, such as vessels and veins in the human body or roots of a tree interpenetrating the soil. Pores can be viewed as numerous interconnected capillaries with different shapes and diameters, creating a network (Dullien, 1992; Turbak & Technical Association of the Pulp and Paper Industry, 1993). Through the hollow structure of the pores and capillary action, liquids, such as blood or water can flow through them parallel, along and opposite to the forces of gravity. Capillary action, which is in general the travel of a liquid through a tube, pore or capillary caused by differences in surface tension between air/gas, liquid and solid (Kissa, 1996; Turbak & Technical Association of the Pulp and Paper Industry, 1993).
3.10 Capillary action

Capillary action is the travel of a liquid through a tube or pore caused by differences in surface tension between solid-air and solid-liquid (Kissa, 1996). The capillary action reaches an equilibrium when the forces (F) or surface tension (γ) between solid - liquid \( (F_{SL} / \gamma_{SL}) \) and solid - air \( (F_{SA} / \gamma_{SA}) \) are equal to the forces between the liquid - air \( (F_{LA} / \gamma_{LA}) \) and the contact angle \( \cos \theta \). This equation is called the Young-Dupré Equation (4), as displayed above.

Common effect of cohesion – attraction of molecules of a liquid is higher to each other than to the solid – as in mercury (Hg). Sticking a glass capillary tube vertically into a container of Hg the meniscus is below the surface. Where on the other hand, sticking a glass capillary vertically tube into a container with water \( (H_2O) \) the liquid in the tube will rise above the surface due to capillary action caused by the higher attraction of the water molecules to the glass than to each other, called adhesion. With decreasing diameter of the capillary the level of water rise increases and vice versa. Through the cohesive or adhesive properties of a liquid to the capillary walls a meniscus is formed. Here, the surface is either higher on the wall than in the middle, forming a bowl like structure for liquids such as water, alcohol and other liquids, whereas in Hg the meniscus bends upwards (Pople, 1987) as displayed in (Figure 7 Schematic of capillary rise).

Capillary pressure occurs at the meniscus of a liquid in a capillary. The surface tension of the curved liquid causes a pressure difference \( \Delta P \) across the curved liquid-air interface, described by the Laplace equation (5) for an ideal condition in a cylindrical tube.
where \( r \) is radius, \( \gamma_{LV} \) the surface tension and \( \Delta P \) the pressure drop (Kissa, 1996; Szymkiewicz, 2013; Turbak & Technical Association of the Pulp and Paper Industry, 1993).

With the Hagen-Poiseuille Equation (6) the pressure drop in a Newtonian and incompressible fluid is described. It is assumed that the liquid flows laminar through a long and cylindrical pipe with constant cross section (Morrison, 2013). The volume flow rate is inversely related to the length the liquid flows.

\[
Q = \frac{dV}{dt} = \frac{\pi r^4 \Delta P}{8\eta l}
\]
where $Q$ is the volume rate $dV$ over the time $dt$, $\Delta P$ is the pressure drop over distance, $l$ is the distance covered by the liquid front during time $t$, $p$ is pressure drop across the distance $l$, $r$ is the radius.

Based on Hagen and Poiseuille’s equation, Richard Lucas (Lucas, 1918) in 1918 and Edward W. Washburn (Washburn, 1921) in 1921 independently to each other derived an equation (7) for flow rates in dependence of time in perpendicular capillary while neglecting the inertia of the flow (N. Pan & Zhong, 2006).

$$\frac{dl}{dt} = \frac{r \gamma \cos \theta}{4\eta l}$$  \hspace{1cm} (7)

where $\eta$ is the viscosity of the liquid, $\gamma$ the surface tension and $r$ the radius of the capillary tube, $l$ the height or distance the liquid travels and $\cos \theta$ the contact angle (N. Pan & Zhong, 2006).

Combining Equation (5) and (6) and integrating the final equation as described by Turbak (Turbak & Technical Association of the Pulp and Paper Industry, 1993) a further simplified version of the Washburn equation emerges as shown in Equation (8).

$$h = k_0 t^{0.5}$$  \hspace{1cm} (8)

where, $h$ is the height, $t$ the time and $k$ a constant.
3.11 Capillary action in porous media

Porous media, as the name suggest is a material penetrated with pores. A pore is a tube that interpenetrates the material throughout from one side to the other or only into the material with a dead end. A pore is not a regular tube, such as a capillary with constant diameter, but with constantly changing form and diameter. In contrast capillaries, as described above, are regular tubes with constant diameter and round shape. Liquid movement in porous media such as nonwovens is, besides surface tension, due to capillary action (ASTM D6767-14, 2014), even pores are different to capillaries.

The irregular shape and diameter of pores makes it hard to predict wicking, wetting or spreading in nonwovens. To estimate liquid movement average pore size, distribution and diameter can be measured.

For determining pore size and pore distribution a porometer is used, where a sample is wetted with a liquid with known surface tension. The sample is then put into porometer and air pressure is applied on one side. The liquid stays inside the pores until applied pressure exceeds the surface tension and capillary action holding the liquid in the substrate. Based on applied pressure and known surface tension the pore diameter can be calculated using, Young-Laplace Equation (see Equation (10)).

\[ D = \frac{4 \gamma \cos \theta}{P} \]
where D is the diameter of the pore, \( \gamma \) the surface tension of the liquid to the solid, \( P \) the pressure and \( \theta \) the contact angle. In the case of very small to no surface tension, \( \gamma \to 0 \) complete wetting occurs, resulting in \( \theta \to 0 \); or \( \cos \theta = 1 \) (ASTM D6767-14, 2014).

### 3.12 Wetting

Wetting is the process of replacing a solid-air interface with a solid-liquid interface in a porous structure (Kissa, 1996), such as sponges or fabrics, by capillary action, adsorption, absorption, spreading or immersion (Kissa, 1996; N. Pan & Zhong, 2006; Patnaik et al., 2006). Wetting is necessary to enable wicking (Patnaik et al., 2006).

As described by Pan et al. (N. Pan & Zhong, 2006) as well as Turback (Turbak & Technical Association of the Pulp and Paper Industry, 1993) with Young’s equation (4) for surface energy and contact angle, the grade of wetting can be determined such as no wetting with high surface energy and contact angle (a), partly wetting a contact angle (in Figure 8 smaller than 90°) (b) and complete wetting with no contact angle (c) as shown in Figure 8 (N. Pan & Zhong, 2006).

![Figure 8. Drop on a smooth surface with (a) high contact angle resulting in no Wetting, (b) partly wetting or mostly wetting and (c) completely wetting](image)

*Figure 8. Drop on a smooth surface with (a) high contact angle resulting in no Wetting, (b) partly wetting or mostly wetting and (c) completely wetting*
3.13 Wicking

Wicking is the specific term for spontaneous wetting through capillary action in a porous structure (Karaguzel, Tafreshi, & Pourdeyhimi, 2008; Kissa, 1996; N. Pan & Zhong, 2006). Assuming wicking in a capillary, the pressure difference at the meniscus of the liquid can be described with the Young-Laplace Equation for pressure drop (N. Pan & Zhong, 2006).

\[ \Delta P = \gamma_{LA} \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (10) \]

where \( \Delta P \) is the pressure difference, \( \gamma_{LA} \) is the interface tension between liquid and air and \( R \) the radii of the curved interface. In a circular tube \( R_1 \) and \( R_2 \) are equal and equation (10) can be rewritten as shown in Equation (11).

\[ \Delta P = \frac{2\gamma_{LA}}{R} \quad (11) \]

where \( R \) is calculated as shown in Equation (12); \( \cos \theta \) being the contact angle and \( r \) the capillary radius. In porous structures made from fibers the capillary diameter and radii are not uniformly distributed. Therefore an average radius \( r_e \) is used, which has to be determined (N. Pan & Zhong, 2006).

\[ R = \frac{r}{\cos \theta} \quad (12) \]
To determine wetting and wicking behavior, possible liquid movement can be calculated using physical data, that are easy to obtain and applying a theoretical approach, such as Washburn equation (Turbak & Technical Association of the Pulp and Paper Industry, 1993).

Gillespie in 1958 derived his equation for spreading of liquid in paper from D’Arcy’s law, which describes the flow of a liquid in a porous medium. Through testing and comparing spreading of liquid in different papers Gillespie formed an equation describing the spreading radii in dependency to spreading rate, volume and height of the paper.

\[
R^2(R^4 - R_0^4) = \frac{3\beta}{2} \left( \frac{3V}{2\pi h} \right)^2 t \tag{13}
\]

where \( R \) is the radius of the stain at a certain time, \( t \) the spreading time, \( h \) the height of the paper, \( V \) the volume of liquid and \( \beta \) the spreading rate.

\[
\beta = \frac{b q_s \gamma \cos \theta}{c_s^3 \eta} \tag{14}
\]

where \( \beta \) is calculated as shown in Equation (14); \( b \) being a substrate constant, \( q_s \) the permeability of the substrate, \( \gamma \) the surface tension, \( \eta \) is the liquid’s viscosity, \( \cos \theta \) the advancing contact angle and \( c_s \) the saturation concentration of the liquid in the substrate.

The data required to calculate \( \beta \) are hard to determine, which can complicate the prediction of liquid spreading in paper. Even more difficult is the ascertainment those data for calculating \( \beta \) for spreading of liquid in a woven fabric assembly as investigated by Kissa (Kissa, 1981).
Assuming that liquid spreading in paper and fabric comes from the same physical aspects of solid and liquid, Kissa in 1981 tested if Gillespie’s calculation can also be applied on woven fabric assemblies. For this, Kissa derives Gillespie’s equation on a different attempt in assuming a constant pressure based on Darcy’s law (Equation (15)) (Kissa, 1981).

\[ A = K \left( \frac{\gamma}{\eta} \right)^u V^m t^n \]  

(15)

where \( A \) is the spreading area, \( V \) the volume of the drop, \( t \) the time of spreading, \( \gamma \) surface tension, \( \eta \) viscosity of liquid and \( K \) a constant. \( u, m \) and \( n \) are constants and determined for non-absorbent materials as 0.33 for \( u \) and \( n \) and 0.67 for \( m \), respectively (Kissa, 1981). \( K \) can be calculated as shown in Equation (16).

\[ K = \frac{27\pi b q_s \cos \theta}{8h^2 c_s^2} \]  

(16)

where parameters are equal to those for \( \beta \) in Equation (14).

3.14 Solid Volume Fraction

By measuring the weight and the volume of a nonwoven and setting it in relation to the average density of the fibers the solid-volume fraction in % (SVF) can be determined.
\[ \mu = \frac{M/V}{\rho_f} \] (17)

The SVF gives the ratio of fiber volume to total volume in a substrate.

### 3.15 Discussion

In 1986 Kawase et al. (Kawase, Sekoguchi, Fuj, & Minagawa, 1986a), studied the spreading of liquids in woven textile assemblies regarding the regular spreading in several untreated material and further the influence of softening agents on capillary spreading in fabric assemblies. Based on the finding of Kissa (Kissa, 1981, 1996) Gillespie’s equation (Gillespie, 1958) was used to initially calculate spreading in the woven textile assembly and then further tested on its validity on applying it on concluding that for defined two phases I and II (Phase I is equal to (b) and phase II equal to (c) in Figure 8, respectively) of spreading the equation can be used to calculate spreading in fabrics (Kawase et al., 1986a). Softening agents such as, dodecyltrimethyl ammonium chloride and a commercial variety, decrease absorption and increase interfacial surface tensions (Kawase et al., 1986a).

Another method to determine wetting in a porous structure, such as a nonwoven is to measure the demand absorbency or rate of fluid uptake, measuring the contact angle of a liquid on the structure and applying Young-Dupré Equation (Turbak & Technical Association of the Pulp and Paper Industry, 1993) as well as measuring radial spreading of a liquid in dependency of amount of liquid applied (Karaguzel et al., 2008).
As shown above wicking and wetting in textiles is affected by fiber properties such as absorption and adsorption behavior, diameter and cross-section as well as fabric formation, structure and fabric density creating capillaries. The liquid properties, such as surface tension and viscosity affect liquid motion in textiles (Karaguzel et al., 2008; Kissa, 1996; Patnaik et al., 2006).

Besides the capillary size and distribution in porous media, such as fabrics, also the direct interaction between liquid and material are important to know when investigating wetting and wicking in porous media (Hsieh, 1995; Kissa, 1996; Turbak & Technical Association of the Pulp and Paper Industry, 1993; Washburn, 1921). Kissa (Kissa, 1996) here classified the liquid-solid interaction in four categories.

1. Only capillary – no material interaction
2. Both, capillary and material interaction such as absorption
3. Capillary and interaction with fiber finish or surface additive
4. Capillary action, ab- and ad-sorption (Kissa, 1996, p. 664)

In the case of absorption and diffusion, the penetration of the fluid into the fiber can cause swelling of the fiber. This again changes the capillary size and also can influence the surface tension, which further leads to increased complications in calculating wetting and wicking by initial data (Kissa, 1996; Mao & Russell, 2008).

3.16 Conclusion

Based on reviewed literature the liquid spreading behavior in textile assemblies is difficult to calculate and predict. Already, determining the contact angle can be challenging when the porous substrate has big pores, high absorbent rate or the liquid a comparable low surface
tension. When no drop can be formed on the substrate surface a determination of the contact angle by the Sessil Drop method cannot be executed. In these cases, the Pendant Drop or the Wilhelmy-Plate Method can be used. With correct data for the liquid and the substrate different mathematical approaches can be used to calculate liquid spreading in substrate such as those investigated in this research in addition to others by Turbak et al. (Turbak & Technical Association of the Pulp and Paper Industry, 1993), Pan et al. (N. Pan & Zhong, 2006), Kawase et al. (Kawase et al., 1986a, 1986b), Gillespie (Gillespie, 1958) and for different fabrics and liquids by Kissa (Kissa, 1981, 1996).

4 Problem Statement, Research Objectives and Approach

4.1 Problem Statement

During research, literature review, and preliminary testing several issues in determining print quality of digital inkjet printing where determined. Even the interest in digital inkjet printing for textile, such as nonwoven is increasing constantly, current standards such as crocking are not adjusted. Further the lack of new standards and research hinder a meaningful and factual determination of print quality of digital inkjet printed fabrics. In addition, predicting print quality based on substrate and ink properties is possible but the amount of data and the difficulties to determine them, make those methods not practical for commercial use.

4.2 Research Objectives

Based on reviewed literature three Research Objectives (RO) where formulated.
4.2.1 1st Research Objective (RO I)

As shown in 3.7, currently no standard for evaluating and comparing DIP prints on textiles is available. In RO I based on ASTM F1944-98 standardized test and evaluation method for DIP nonwoven will be established (ASTM F1944-98, 2008).

4.2.2 2nd Research Objective (RO II)

Based on reviewed literature it is clear that the print quality is influenced by the interaction of substrate and ink, such as surface tension, viscosity and porosity. The prediction of print quality is often very laborious due to difficulties gaining all required date for predicting and testing. RO II investigates how a change in process parameter during the digital inkjet process influences the final quality of the print based on known substrate properties. Based on the findings a guideline will be established on how to change certain process parameters to achieve certain effects on the substrate.

4.2.3 3rd Research Objective (RO III)

As discussed in 3.6 crocking is a method for determining color abrasion of dyed and printed woven textiles. Nonwoven fabrics were not included in the American, European or Asian standard. By testing and comparing digital inkjet printed woven and nonwoven fabrics made from same or similar material, it will determine if the current AATCC crocking standard is applicable for testing DIP nonwovens with pigment ink. If the currently available methods yields highly different results for woven and nonwoven fabrics suggestions for improvement or adjustment, respectively will be made.
PRELIMINARY TESTS AND RESULTS

5 Crocking in digital printed Nonwoven

Crocking is a test for determining the color fastness of a woven or knitted fabric to rubbing against a white, bleached woven cotton fabric under defined pressure (AATCC 8-1996, 1996). During crocking color from a printed or dyed fabric surface is transferred to another. The color transfer takes place because there is color available on the surface. In dyed fabrics the available color is usually less than in printed fabrics (Society of Plastics Engineers, Technical Conference, & Society of Plastics Engineers, 2015). Color fastness is an important subject in printing and dying fabrics.

In digital inkjet printing (DIP), when ink is jetted on the surface it forms, depending on the amount of ink, clusters. By applying heat the binder in pigment ink or the reactant in reactive ink is activated and the ink solidifies and is bind to the fibers. Still the clusters break up, when the fiber in it or around it gets disoriented or ripped out. The current crocking standard only is defined for woven or knitted material.

Research such as from Hussain et al. (Hussain et al., 2015) statistical showed that the crock fastness of printed PP nonwoven can be influenced by varying the amount of binder in the ink and the time and temperature of the fixation method according to amount of binder. Investigations and inventions also had been made to improve crocking behavior of fabrics treating wool fabric with plasma (Chi-Wai, Kwong, & Chun-Wah, 2004) or cationic treatment of cotton fabric (Tabba & Hauser, 2000) before or irradiation treatment of pigment – printed fibrous sheets (Lawton & Woodruff, 1963) after printing.
Preliminary tests investigated how fixation/curing time and temperature as well as ink temperature during printing influence the crocking of untreated DIP nonwovens.

5.1 Crocking

During the crocking process of nonwoven, a woven crock fabric is rubbed over a certain area of a nonwoven. As visible in Figure 9 the woven crock fabric cracks open fibers on the surface of the nonwoven and rolls them up, forming ribbons or bands on the surface. The used nonwoven fabric was not pretreated. The only chemicals or substances added onto the fabric where the pigment ink which adheres only through the binder. Through the braking of fibers on the surface, also the ink clusters (Figure 14) break up and distributed over the crocking area. On the other side, as it can be seen in Figure 10 the woven crocking fabric takes up ink particles and ink clusters which accumulate at the rolling edges of the woven yarns. In wet crocking the water on the crocking fabric softens the binder, causing a more homogenous ink distribution though breaking up the dry ink rocks. The influence of crocking is used to determine colorfastness of printed or dyed fabric assemblies (Society of Plastics Engineers et al., 2015).
5.2 Temperature and Time

The fixation temperature for the ink according to the ink supplier, should be 176°C. To investigate the effect of different fixation times and temperatures on wet and dry crocking results, the temperature and time was changed as shown in Table 3. The max temperature of 210°C was chosen based on the DSC graph of the fabric done prior to designing the experiment. In the DSC two distinct peaks show the melting temperatures of the PA and PE content in the fabric. The onset temperature for PA is located around 210°C. This was chosen to be the highest fixation temperature, because otherwise the fabric would melt and stick to equipment used during fixation process.
The time in the heat press was defined by the ink supplier as 1.0 minute (1.8 rpm at the available heat press). It was changed to approximately 0.5min (2.8rpm), 0.75min (2.3rpm), 1.5min (1.4 rpm) and 1.75min (1.1 rpm). The heated steel drum in the heat press does not rotate slower than 1.1 rpm, so the resting time of a specimen in the heat press is limited to 1 minute and 45 seconds.

Table 3. Times and Temperatures used during fixation process

<table>
<thead>
<tr>
<th>#</th>
<th>Time</th>
<th>#</th>
<th>Temperature in °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.75 min / 105 sec</td>
<td>1</td>
<td>176°C/350°F</td>
</tr>
<tr>
<td>2</td>
<td>1.5 min / 90 sec</td>
<td>2</td>
<td>190°C/375°F</td>
</tr>
<tr>
<td>3</td>
<td>1.0 min / 60 sec</td>
<td>3</td>
<td>200°C/392°F</td>
</tr>
<tr>
<td>4</td>
<td>0.75 min / 45 sec</td>
<td>4</td>
<td>210°C/419°F</td>
</tr>
<tr>
<td>5</td>
<td>0.5 min / 30 sec</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Samples were also fixed “upside down”, which means instead of the common way to insert the fabric with printed side away from the heated steel roll, it was facing the steel roll with a sheet of paper in between to investigate if this had any influence on the wet or dry crocking properties. Further one sample of each heat setting was fixed 2 times 60seconds (1.8rpm) to remove as much moisture in the binder as possible.
5.3 Results

5.3.1 SEM

SEM pictures of the crocking fabric, provided by Testfabrics Inc. shows residues of finish or other applicants as seen in Figure 11. The strings are only found on the crocking fabric, which is a white woven cotton fabric. Not such residues could be found on the nonwoven fabric crocked and un-crocked.

![SEM image of crocking fabric](image.png)

*Figure 11. Crocking fabric 10000x shows residue strings that breaks during crocking process*

On the SEM images taken from fixed an unfixed specimens showed that the binder in the pigment ink distributes on the fibers and forms a layer through fixation.
Increasing heat during fixation has not impact on the binder, as also determined through crocking tests. Increasing the heat to the melting onset of PA, as determined in a DSC, melt damage is caused to the fibers, without influence on the pigments or binder.

Figure 12. (1) Ink on fiber on sample dried 24h on air; (2) Ink on fiber after fixing 1.0min at 176°C

Figure 13. (1) Ink on fiber after fixing sample for 1.0min at 210°C; (2) Damaged fiber due to high heat on sample fixed 1.0min at 210°C
5.3.2 Crocking

In inkjet printing the ink is placed in drops on the substrate. Depending on the drop size ink clusters of different sizes are formed on and in between fibers. During dry and wet crocking of the nonwoven the fibers on the surface of the fabric are partly getting disconnected or ripped apart and reoriented forming ribbon like clusters on the surface as seen in Figure 9. The braking and dislocating of fibers also causes the ink clusters as seen in Figure 14 to break, too. Through this single particle and particles agglomerations get caught in the ribbon-like entanglement of fibers on the surface leaving visible colored stripes. Fibers and particles not caught up in the entanglements are transferred to the crocking fabric (Figure 10) or stay loose on the surface.

*Figure 14. Ink cluster on nonwoven fabric surface*
5.3.3 Influence of ink temperature during printing as well as fixation time and temperature on wet and dry crocking

After the first set of samples were printed with ink at the temperature of 32°C and 37°C the samples were fixed with different resting time in the heat press as well as different temperatures as listed in Table 3. After fixing and conditioning for 24h in lab conditions all samples where dry and wet crocked. The woven crocking fabric and the nonwoven samples where dried and scanned at 600 dpi on a HP Deskjet scanner. Wet crocking results showed not difference in amount of color transfer during rubbing. However, as shown in Figure 15 the dry crocking results differed between samples printed with 32°C and 37°C ink temperature, respectively. This indicates that with a change in ink temperature the crocking results of digital inkjet printed nonwoven can be influenced.

Samples printed with ink at 37°C and fixed at 176°C did not show significant differences in crocking results depending on the resting time in the heat press. However samples printed with ink that had 32°C during printing showed differences in crocking results depending on the time remaining in the heat press. Fixing the samples for 30 or 45 seconds showed to have a negative impact on the amount of color transferred during the crocking process. Also fixing the samples for 90 or 105 seconds had a negative impact on the result. The best result was gained with samples fixed for 60 seconds at 176°C as seen in Figure 15.
At 190°C fixation time no significant differences could be determined in the crocking results depending on the resting time in the heat press or the ink temperature during printing.

At 200°C the overall crocking results were mostly the same. No significant difference depending on resting time or ink temperature during print could be determined. However samples fixated at 200°C on the contrary showed to have overall better results than those

Figure 15. Dry crocking results based on different fixation times and temperatures in samples printed with different ink temperature during printing
fixated at 190°C. Here also the 32°C crocking results are slightly better than those from samples printed with 37°C.

At 210° the PA material starts to melt as suggested by the DSC. The material starts to shrink and sticks to the paper used to protect the fabric from the steel roll. Due to the shrinkage and destruction of the samples no crocking was conducted for those samples.

Figure 16. Wet crocking results based on different fixation times and temperatures in samples printed with different ink temperature during printing
In Figure 16 the wet crocking results are displayed. It clearly can be seen that with increasing fixation temperature the results become better. However the ink temperature during printing has no influence on the crocking results.

5.4 Conclusion

Changes in fixation time and temperature from the suggested settings, has no positive influence on wet and dry crocking. The suggested timed and temperature by the ink producer is 60 seconds at 176°C. This was determined the best time and temperature to fix the ink on substrate where the least ink abrasion could be found during wet and dry crocking. Other fixation times and temperature, as well as facing the printed side towards the heated steel drum had not positive effect on the crocking results.

Increase in ink temperature during printing also has no positive impact crocking results. The suggested temperature for the ink during printing is 32°C. Increasing the temperature to 37°C – which is the highest temperature available at the used printer – results in no improved crocking results.
METHODOLOGY

6 Material

Evolon by Freudenberg was selected as testing material for the scope of this research. Evolon is a hydroentangled Polyester and Polyamide microfiber nonwoven without any additional treatment. It was essential for this research to investigate how only the printed material without additional substances behave. The ratio of Polyester and Polyamide is approximately 70% to 30% and fabrics with different weights (gram per square meter (gsm)), thicknesses or approximate solid volume fractions SVF, respectively where used for the research as listed in Table 4.

Table 4. Labeling and properties of Evolon fabrics

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Average Gram Per Square Meter (GSM)</th>
<th>Thickness in mm</th>
<th>SVF</th>
</tr>
</thead>
<tbody>
<tr>
<td>40PK*</td>
<td>0.49</td>
<td>0.175</td>
<td>0.1865</td>
</tr>
<tr>
<td>60PK*</td>
<td>0.63</td>
<td>0.292</td>
<td>0.1647</td>
</tr>
<tr>
<td>80PK*</td>
<td>0.86</td>
<td>0.342</td>
<td>0.1931</td>
</tr>
<tr>
<td>100PK*</td>
<td>1.02</td>
<td>0.377</td>
<td>0.2110</td>
</tr>
<tr>
<td>100B*</td>
<td>1.03</td>
<td>0.371</td>
<td>0.2169</td>
</tr>
<tr>
<td>130PK*</td>
<td>1.36</td>
<td>0.472</td>
<td>0.2177</td>
</tr>
<tr>
<td>130B*</td>
<td>1.36</td>
<td>0.463</td>
<td>0.2095</td>
</tr>
</tbody>
</table>

*PK and B label the method of proprietary production method by Freudenberg.
7 Ink

The pigment ink used in this research was provided by a company A. The ink contains pigment ink particles varying by color from 30nm to 150nm. It has an Ethylene glycol content of 10-20% and 1-5% Glycerin. The suggested temperature for printing was 32°C as recommended by the ink supplier. This temperature was temporarily altered to 26°C and 37°C for parts of this research.

During the project, the ink used in the printer changed. Preliminary tests and experiments were done with a different set of pigment ink, than the final tests. The set of pigment ink available for the final sample production for the testing for RO I, II and III was an experimental set of ink, provided by company A. It is not known how the two different sets of inks vary or differ from each other. One trial was conducted at Springs Creative and the ink used at Springs Creative was the same composition as used for the preliminary tests and experiments.

8 Machinery equipment

For printing the samples the EVO JP5\textsuperscript{evo} form MS-Italy was used. The printer can hold 8 different colors and has 4 print heads. In each print head two color channels are available. The ink temperature in each print head can be adjusted separately. The ink ejection is controlled and defined in the print modes A to F. A to D have sub print modes (2, 2HQ, 3, 4 and 4HQ) in which the speed of ink ejection (standard, high and maximum velocity) and the amount of ink per droplet (ranging from 4 to 72 Pl per drop) defined. However each drop of ink is formed by the accumulation of 4, 7, 12 or 18 Pl drops which are ejected simultaneously to form the final drop size.
The print settings as shown in Table 5 were set to print the samples used to evaluate the quality of the printed fabric. The drop sizes in print mode “A2” are 4, 7 and 12 Pl and the “2” means that ink is ejected in 2 passes at high velocity. For print mode “C2” the drop sizes are 4, 7, 11, 14, 16, 21 and 24 Pl and ink is ejected in 4 passes at maximum velocity. In print mode “F” the drop sizes range from 4 to 48 Pl and ejected in 6 passes at high velocity. For each setting 5 samples were printed.

Table 5. Print settings for each material and overall number of prints per samples

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Print Mode</th>
<th>Ink Temperature In °C</th>
<th>Number Of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>40PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>60PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>80PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>100PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>100B*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>130PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>130B*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>= 63</td>
</tr>
</tbody>
</table>

*PK and B label the fabrics classified production method

For curing/fixeding the ink on the substrate a rotary heat press from Practix M.F.G. was used and the pigment ink printed samples were cured for 60 seconds at 190°C.
9 Research Objectives

9.1 RO I – Standardized evaluation method for digital inkjet printing on nonwoven

For ROI a test print based on ASTM F1944-98 and suggestions from Dr. Pawlak (Pawlak, 2001) was developed as shown in Figure 20. The test print was printed on various substrates with changes in print mode and ink temperature to have wide range of data available. Three methods where used to evaluate the test prints and find the best method for formulating a standardized evaluation technique. First method was to digitalize the samples and then evaluate the pictures with an image processing program, called ImageJ. Second method was to remove all color from the test print file and only keep the outlines from the shapes and figures. The colorless test picture then was printed onto a transparency and its size and dimension trueness to the digital file confirmed. The transparency was used to lay onto the test print and evaluate how much the actual print differs from the transparency. Last method was to use a ruler and whaling glass to measure and evaluate the test print. A grading system was designed in which the difference from what it is supposed to be, is noted and graded.

All three methods where used to meaning full evaluate the test prints and formulate a standardized evaluation technique.

9.1.1 Method I: Computerized evaluation

For determining the print quality with a computer program the samples were cut and digitalized. The digitalizing was done with a flatbed scanner from Canon. The scan settings are shown in Figure 17. Important here is that the color format is set to “color” and not to “grey scale”. Images scanned in greyscale have less contrast. Through this further processing
programs are not able to fully capture all color differences and depth. The scanned images have to be transformed into 8- or 16-bit greyscale after scanning.

For determining the clearness and quality of the images ImageJ was further used to evaluate the samples. ImageJ is a public domain software for image processing. It is Java-based and was developed by the National Institution of Health (NIH) (ImageJ, 2017). It can be used to analyze pictures in 8-bit, 16-it and 31-bit and in several formats, such as TIFF or JPEG. ImageJ was used to stack, aligned and calculate differences in the samples.

Figure 17. Scan settings
To enhance the difference from each scan to the original test print, the scan pictures were stacked, aligned at the black solid square, unstacked and then the differences were calculated with the image process function.

In the stacking and un-stacking process two pictures are layered over each other or the layers are separated, respectively (also see Figure 18 “Image to Stack” and “Stack to Image”). With the aligning tool the stacked pictures are positioned exactly above each other. Alignment is important to minimize errors that can occur through misplacement during sample scanning. Alignment is only possible in a stack. After aligning the stack has to be unstacked therefore the image calculating option only works for separate pictures.
As a result of the Process “Image Calculator” where the differences between a sample picture and the template is highlighted are shown in Figure 19.
Figure 19. Different results gained by enhancing differences in sample picture and template. Samples are labeled Fabric-Printmode-Inktemperature: upper row, left to right: 100PK-C2-26°C, 40PK-F-32°C, bottom row, left to right: 130B-F-32°C and 130B-F-37°C
9.1.2 Method II: Optical evaluation I

For second method tested for evaluating the print quality, the color was removed from the print. All outline lines were narrowed to 0.02mm. The outline width for the squares and circles was changed into double line with 0.05mm. 3pt in double line equals a line distance of ca. 1mm. The colorless picture was then printed on a transparency film. The transparency was used to lay over the printed fabric to determine changes in clearness and form. In addition a whaling glass was used to closer investigate how much wicking was reaching over the lines of the transparency.

9.1.3 Method III: Optical evaluation II

For the third evaluation method tested in first, the shrinkage of the substrate due to heat treatment during curing was determined. The printed shapes, such as squares, circles, stripes and bars then were also measured and the measurements noted. The text was not further evaluated than looking at it from a distance of approximately 1.0 meter and noting how many lines of text were clearly visible. Still the wicking and clearness of the contrast colors helps to predict the overall clearness of the final print.

9.2 ROI – Influence of processing parameter on print quality of DIP nonwoven

To investigate and determine changes in processing processes such as ink temperature during printing, print mode as well as substrate properties, the samples produced for ROI were used. Based on the defined print quality and evaluation technique from ROI the samples were evaluated and categorized. Parameters and their effects investigated in this research where GSM and thickness or SVF of the fabric, respectively as well as print mode and ink temperature
during printing. All prints where produced on one day, so the humidity and air pressure where the same. The latter two aspects where not investigated due to the lack of time and amount of substrate available. Based on the result of ROI the samples were evaluated for ROII. As result a summary on how ink temperature during printing, print mode and substrate weight influence the print quality. Further, it will be discussed as to how this data can help to adjust print settings to achieve higher quality pigment printing of nonwovens.

The grades given and displayed in the graphs represent the amount of change in comparison to the template. A value of “0” means that the print has not visible difference to the template and is considered very good quality. The higher the difference between the print and the template the higher the grad given. A grade of 5 means that it is a very low quality print as described and shown on examples in following chapter (Table 8, Table 9 and Table 10). The red line in each graph is marking the grade 2 level. All data above the line represents data that are not acceptable in terms of print quality as defined in ROI.

9.3 ROIII – Crocking of nonwoven

For testing, if the current crocking standard the samples that proved to have the best print quality during ROII where selected for the crock tests. Further, in the same print settings the test picture was printed onto a woven 100% Polyester fabric for comparison and, in addition, a print created at Springs Creative was used for further comparison as listed in Table 6.
Table 6. Sample IDs and Material description

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>130PK-C2-32°C</td>
<td>Evolon 130PK Nonwoven 70%/30% PES/PA</td>
</tr>
<tr>
<td>130PK-C2-37°C</td>
<td>Evolon 130PK Nonwoven 70%/30% PES/PA</td>
</tr>
<tr>
<td>130PK-F-32°C</td>
<td>Evolon 130PK Nonwoven 70%/30% PES/PA</td>
</tr>
<tr>
<td>130PK-F-37°C</td>
<td>Evolon 130PK Nonwoven 70%/30% PES/PA</td>
</tr>
<tr>
<td>SC – F</td>
<td>Springs Creative Cotton/Jute Woven material</td>
</tr>
<tr>
<td>SC – C2</td>
<td>Springs Creative Cotton/Jute Woven material</td>
</tr>
<tr>
<td>100PES-C2-32°C</td>
<td>100%PES Woven material</td>
</tr>
<tr>
<td>100PES-C2-37°C</td>
<td>100%PES Woven material</td>
</tr>
<tr>
<td>100PES-F-32°C</td>
<td>100%PES Woven material</td>
</tr>
<tr>
<td>100PES-F-37°C</td>
<td>100%PES Woven material</td>
</tr>
</tbody>
</table>

The print produced at Springs Creative was printed on a fabric designed and developed by Springs Creative. The fabric composition and pre-treatment as well as their print settings and printing profiles is profiled onto that fabric to achieve best possible print results. The exact composition as well as pre-treatment is not available for inclusion in this dissertation.

The results were not evaluated in terms of the quality of the ink adhesion on the fabric. It was solely investigated if the current crocking method is applicable for crocking nonwoven material. This was done by comparing the resulting amount of color abrasion.
9.3.1 Crocking squares

For testing the influence of different crocking fabrics on the crocking results, crocking squares of all nonwoven sample material were cut. The dimension was the same as the crocking squares produced by Testfabrics, Inc. for the woven cotton crocking squares which are 50mmx50mm.

9.3.2 Squared crocking peg

To test a different crocking square the 3D design program SolidWorks was used to design a cube with the measurements of 26x26x30mm. In the center of the square of 26x26mm a hole with 17mm diameter and a depth of 20mm was implemented. The cube then was printed in black Acrylonitrile butadiene styrene (ABS) polymer. The cube was designed to fit over the round crocking peg. The crock fabric was adjusted with a rubber band around the squared peg.
RESULTS

10  RO I

Based on ASTM F1944-98 a test print was developed and tested. For evaluating the test print different methods were investigated.

In the first method, the printed samples were scanned and digitally processed with the help of ImageJ program. The program enables the alignment of the scan and template files to highlight differences.

In second method, the developed test print was altered, as shown in Figure 24 and printed onto a transparency. The transparency then was used as a stencil to investigate color wicking and print clarity of the samples.

In a third method, the test print was evaluated based on measurements and simple optical evaluation.

10.1 Test print

For evaluating the print clarity of Digital Inkjet Printed (DIP) Nonwoven material a test print was developed. There are no known standards or standardized methods or print test patterns in existence for evaluation and testing DIP fabrics. In general a test print, inspired by ASTM F1944-98 and suggestions from Dr. Pawlak (Pawlak, 2001) was developed as shown in Figure 20. Colored Test Print (colors may not display as printed).

The test print designed contains following elements to test and investigate print clearness and wicking of each color of DIP nonwoven.
10.1.1 Skew

To enable measurement and determination of skew of the printer two bars along the edges of the test print are drawn. Each bar has the width of 1.0 cm. The length of the vertical beam is 25.0 cm. The horizontal has a length of 21.0 cm. The filling was in changing rainbow colors. After printing and curing the length and width of each bar can be measured by using a scale, a picture processing program or a transparency as described in 10.3.1.2.

Further, a solid black lined frame is drawn around the print along the edges of the format. The line width is 0.5mm. The frame enables to determine size changes, such as shrinkage of the substrate and print shifting in planar directions.

10.1.2 Squares and circles

For testing and evaluating wicking of each ink on the substrate, for each color a square and a circle is printed. The squares have a dimension of 2.0x2.0cm and the circles a diameter of 2.0cm for the colors. The black square has the side lengths of 2.5cm and the circle a diameter of also 2.5cm. With these shapes and forms the printing clearness along edges as well as the different wicking behavior of each color can be tested and evaluated. On the edges of the circles it also can be investigated how clear and accurate round edges are printed.

10.1.3 Text

A text in different font sizes and color is printed on various backgrounds.

- Yellow text on solid black background or text in the brightest color on the darkest color as background
Black text on yellow background or text in the darkest color on the brightest color as background

- Black text on substrate without additional background color or color in biggest contrast to substrate color

The text font size are one line 14pt, 12pt, 10pt, 9pt, 8pt, 7pt, 6pt, 5pt and 4pt, respectively.

Based on the results of printing this test pattern, the interaction of high contrast colors for fine line interaction can be tested and evaluated.

10.1.4 Stripes in vertical and horizontal direction with decreasing line width and spacing

For each color a set of horizontal and vertical lines is printed. The lines have decreasing line width and decreasing distance between each other. The biggest line for a letter sized print has a width of 5.0mm. This is the same distance as to its next line. The next line is half the width of the first and the distance to the next line is the same as the width of second stripe. The next line again is half the width of the previous as well as the distance to the next one. This is repeated until the limit of fines of line width is reached.

After printing it can be investigated how clear each color can be printed and how close lines can be next to each other and how thin they can be. Further, the wicking behavior in both the machine direction (MD) and cross direction (CD) can be determined.

10.1.5 Free Space

In the designed test print for this research the free area was filled with a calendar for 2018. Here numbers, fine lines and wicking of different color mixtures where tested.
Figure 20. Colored Test Print as designed by the author
10.2 Printing the test pattern

Each material sample was printed with different print modes and ink temperatures during printing. In the print mode the size and amount of ink drops is defined. The print modes vary in the printer used from A to H and from drop sizes between 4Pl and 72Pl per drop. Print mode A is used for paper and very fine material and it has the smallest amount of ink per drop and the lowest number of drops per run. H mode on the other hand, is used for heavy material with high absorbency. The amount of ink in each drop can reach up to 72PL per drop and more drops per run are possible. Print modes in this research where A2, C2 and F.

The ink temperature recommended by ink producer, the ink supplier, is 32°C. Other temperatures tested where 26°C and 37°C. In Table 7 the overall number and settings for sample production are listed. Scanned samples for each print setting and sample material can be found in the Appendix.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Print Mode</th>
<th>Ink temperature in °C</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>40PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>60PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>80PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>100PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>100B*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>130PK*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
<tr>
<td>130B*</td>
<td>A2, C2, F</td>
<td>26°C, 32°C, 37°C</td>
<td>9</td>
</tr>
</tbody>
</table>
10.3 Evaluation

After printing and heat curing the samples were evaluated. Three methods were tested to evaluate the print quality.

10.3.1.1 Method I: Computerized evaluation

The prints where cut into letter-size samples and scanned. The samples were scanned in color mode. They could not be scanned in grey scale therefore the color contrast would fade. Afterwards the scanned images were transferred into 8-bit grey scale. This was done for each image separately. The image evaluation process in ImageJ, as described in 2 Digital Image evaluation also was done for each picture separately. This Method is time consuming due to the scanning and conversion processes.

Figure 19 and below in Figure 21 clearly show the differences between the scanned images and the template. The white or brighter lines in the images are the areas where the scanned sample and template files do not match. When more white area is visible the less the images match. A perfectly aligned and matching result would be mostly in black and dark gray shades for the different areas with different colors. Even the resulting pictures from the ImageJ analysis show differences between the template and the scanned samples due to fabric shrinkage and by misalignment of the shapes and forms in the sample image. The stacking, aligning and un-stacking process would have to be done for each shape in the picture to be able to get truthful and comparable results. Due to the lack of information that can be gained from the image processing and the amount of time necessary to create results as shown in Figure 21
this evaluation method was found to be more applicable as a research tool rather than as a standard evaluation technique.
Figure 21. Difference from sample to template due to fabric shrinkage 60PK-F-37°C
10.3.1.2 Method II: Optical evaluation I

For second method tested to evaluate the print quality, the color was removed from the print and the colorless print was printed onto a transparency as shown in Figure 24. Even when the outlines were narrowed to 0.02mm and a double line of width 0.05mm added, it was difficult to always determine how much wicking actually occurs therefore the lines of the transparency covered most of the wicking area. This made it difficult to obtain an accurate evaluation for comparable low wicking areas. Further, in cases where wicking was visible beyond the lines it was hard to actually determine how much wicking it was in general, therefore often just a few fibers showed wicking. In such cases the overall print quality was difficult to determine therefore some areas showed no wicking whereas others showed more. If the wicking reached clearly over all lines surrounding a shape the overall print quality was usually unsatisfactory but an accurate quantitative determination was still not possible.

For evaluating the text, the transparency showed to be helpful for identifying the clarity of the letters and numbers by laying it onto the sample. It also helped to evaluate how many lines are actually really readable by comparing the texts next to each other.

To determine the skew and shrinkage of the samples due to heat influence during curing the transparency showed to be most useful.

Overall, using the transparency approach had advantages and disadvantages during the evaluation process. Nevertheless, it is not solely suitable as a single evaluation technique for evaluating and determining the print quality of digital inkjet printed nonwovens.
10.3.1.3 Method III: Optical evaluation II

For the third evaluation method tested in first Research Objective, the samples were measured and the shrinkage of the substrate due to heat treatment during curing was determined. The average shrinkage in percent was calculated and showed to be between 0.18% and 1.25% in the Machine Direction (MD) and 0.46% and 1.39% in Cross Direction (CD) as displayed in Figure 22. Whereas some data might be altered during heat setting because the fabric tends to get stuck on the heated roll and get pulled into the machine. To prevent printed samples from getting caught the fabric sample was held and slightly pulled during the curing process.

Figure 22 Average Fabric Shrinkage in MD and CD in %
The printed shapes, such as squares, circles, stripes and bars then were also measured and the measurements noted. The text was not further evaluated other than looking at it from a distance of approximately 1.0 meter and noting how many lines of text were clearly visible. The wicking and clearness of the contrast colors helped to predict the overall clearness of the final print.

10.4 Discussion

During printing with different ink temperatures it became clear that printing with a very low ink temperature, in this case 26°C, there is frequent occurrence of striping. Even in print mode F, which ejects the biggest amount of ink during print head movement, the striping was visible especially for the red inks. With increasing fabric weight and thickness the color saturated decreased. The color saturation decrease mostly occurred in print mode A. In print mode C and F the saturation did not decrease as much, but remained visible. The color saturation does not only depend on the print mode and fabric weight and thickness, but also on the ink temperature during printing.

In the fabrics labeled as “B” it became clear that the production method has an impact on the final print quality of the fabric in terms of color saturation and print clearness. “B”-labeled fabrics absorbed more ink into the depth, leading to lower color saturation but also to more wicking in planar directions, in comparison to fabrics labeled as “PK”.

The manual evaluation technique proved to be more efficient and data as well as evaluation was clearer and made more sense. While the computerized evaluation was a convenient way to enhance especially distortion of the fabric and the print, it was very time consuming and
only allowed evaluation one area at a time. For each area that needed to be investigated the scanned image had to be aligned anew around that specific area with the template. Then the evaluation had to be done again. For this reason the defined evaluation technique only mentions the manual evaluation technique.

For the computerized evaluation method all samples were cut and scanned. After scanning the pictures were stacked, aligned and the differences to the template amplified, as described in Method I: Computerized evaluation. The resulting pictures amplified the differences between the template and the scanned picture.

Images were aligned at one point (in this case the black square) and the aligned part of the image showed the most true result regarding wicking or wetting. The surrounding shapes and figures do not represent the real wicking or wetting because the samples shrunk during heat fixation. To get true results for each object of the test print the image alignment would have to be done for each object separately which is not efficient and does not guarantee valuable results. Further, the overall process is very time consuming and needs beside the ImageJ program also a Photoshop program or other program to transfer the colored TIFFs gained through scanning into 8- or 16-bit grey scale pictures. By adding a scale to the scans it would be possible to use ImageJ to measure the objects in the scan and the template and determine differences mathematically. This approach would be even more time consuming and practically inefficient and was not done for this research.

The evaluation by the first manual evaluation technique – using a transparency – showed to be more suitable than the computerized method. In this technique, as described earlier the color is removed from the test print and the outlines are modified. The picture is then printed and
checked on its trueness to the original. By laying the transparency onto the sample, it can be readily seen if the size and placement of the objects fit the original design. Further, the skew of the sample can be determined by how the bars are aligned to each other and how well the frame lines are concisely defined. By using a whaling glass / pick glass or other magnifying device the wicking of the squares, circles and stripes can be determined. Here the transparency is laid upon the square, circle or stripe of one color and how much the color spread over the lines or the transparency was recorded. Based on the amount of deviation to the transparency the quality is determined. During the evaluation, several squares and circles that were smaller than the transparency were observed. Those prints in general had very little wicking and clear color separation but also mostly bad color saturation. The reduced size is attributed to the fabric shrinkage during heat treatment. Further, it was noticed that especially in fabrics with 40, 60, and 80 gsm, some areas wicked more than others as displayed in Figure 23. Even blue was the color with a visible lower wicking behavior than for example red, due to the un-uniformity of the fabric wicking occurred on one side of the shape whereas on the other side had a clear printed edge. This resulted not only in different measurements for same colored shapes, but due to un-uniformity in the fabric the wicking in one area of a shape was much higher than on the other side of the shape.
The text areas on the other hand were difficult to evaluate with the transparency. First the transparency was laid on the print and it was looked and tried to measure how much, if any ink was spread around the letters. The measuring showed to be extremely difficult and not very accurate. An evaluation then was tried to be done by just looking at the amount of ink wicking and spreading around the letters under a whaling glass. Still the grading was not accurate or satisfying. This led then to an evaluation which was done without the transparency. Important with text was, that it is clearly visible and readable. Especially with the yellow text on the black background. Here it was primarily looked for how visible is it and how clear can it be read from a distance of approximately 1.0 meter. Further it was checked on a closer look if all lines are printed clearly and visible. For the text on no background or on yellow background it was important that the letters are clear and the puncheons free of ink.

No transparency was used to evaluate the calendar. Here it was only checked and investigated how clear the numbers on the different colors are visible and readable. In another
test print with flowers instead of a calendar the color separation on the edges where briefly investigated. Due to limited amount of substrate the flower print was only available for 130PK fabric, which in general had good print quality.

A last evaluation method was used in which in first step the overall shrinkage of the substrate was determined and the percent of shrinkage calculated. Then all shapes were measured with a ruler. Here again the problem of the un-uniformity of the fabric, which lead to wicking on one side of a shape, but not on the other, occurred. Based on the expansion of the shapes in the print and the clearness of the texts it can be estimated how good or bad a print will be. The gained knowledge, however does not enable an accurate and meaning full evaluation and determination of a test print. The aspect of shrinkage was not considered for the evaluation with the transparency.

Due to limited time the color trueness to the prints were not tested.

10.5 Definition of Evaluation Technique and Evaluating

Based on the data and knowledge gained during the different evaluation processes an evaluation technique was developed. This technique and method is believed to be able to help determine and evaluate previous defined test print to be able to compare and control different prints on nonwoven.

10.5.1 Purpose

The purpose of a standardized testing and evaluation method is to be able to compare, predict and control the print quality of DIP printed nonwoven (as well as woven or knitted fabrics) based on the accuracy of defined shapes and print elements. By measuring,
categorizing and comparing those elements the print quality of a print can be measured and evaluated.

10.5.2 Test print

For testing and evaluating the print quality in terms of cleanness and ink placement accuracy a test print is designed. The test print is done on a US letter sized area. Skew, wicking, color interaction and ink placement accuracy can be evaluated, compared and extrapolated on bigger sized prints. This test print design can be adjusted depending on the companies’ or printer’s needs and expectations. However it shall contain following aspects and designs for testing and evaluating standardized objects.

10.5.3 Transparency

The designed test print is also printed onto a transparency. For this all color is removed and only the outlines of the shapes, pattern and pictures lines are left. The outlines for the stripes, bars and frame are narrowed to 0.02mm. The outline width for the squares and circles is changed into double line with 0.05mm. The distance between the double lines should be approximately 1.0mm. The colorless picture is then printed on a transparency film. The transparency is used to lay over the printed fabric to determine changes or distortion in placement or skew.

10.5.3.1 Skew

To enable measurement and determination of skew of the printer two bars along the edges of the test print are drawn. Each bar has the width of 1.0cm. The length of the vertical beam is
25.0 cm. The horizontal has a length of 21.0 cm. The filling can either be a solid color, pattern or, as chosen for this research, in changing colors. After printing and curing the length and width of each bar is measured by using a ruler or the transparency. Based on the filling the bars can be used for testing and evaluating color change over a distance as well as print sharpness and color saturation of a pattern.

A solid lined frame is drawn around the print along the edges of the format. The line width is 0.5mm and the color is optional. The frame enables to determine size changes, such as shrinkage of the substrate and print shifting in planar directions.

10.5.3.2 Squares and circles

For testing and evaluating wicking stability of each ink on the substrate, for each color a square and a circle is printed. The squares have a dimension of 2.0x2.0 cm and the circles a diameter of 2.0 cm for color and 2.5cm and 2.5cm for black. The number and color of squares and circles depend on the numbers of colors in the System. For each color one pure colored circle and square is printed. With these shapes and forms the printing clearness along edges as well as the different wicking behavior of each color can be tested and evaluated. Further can this shapes be used to evaluate how a pure color area looks like on the substrate.

10.5.3.3 Text

Text lines in different font sizes and colors are printed on various backgrounds. For each of the following one text block should be designed.

- Yellow text on solid black background or text in the brightest color on the darkest color as background
- Black text on yellow background or text in the darkest color on the brightest color as background
- Black text on substrate without additional background color or color in biggest contrast to substrate color

The text font size is chosen based on the average font size for a US letter sized paper. The text font size are one line 14pt, 12pt, 10pt, 9pt, 8pt, 7pt, 6pt, 5pt and 4pt, respectively.

10.5.3.4 Small stripes in vertical and horizontal direction with decreasing line width

For each color a set of horizontal and vertical lines is printed. The lines have decreasing line width and decreasing distance between each other. The biggest line for a letter sized print has a width of 0.5cm. This is the same distance as to its next line. The next line is half the width of the first and the distance to the next line is the same as its width. The next line again is half the width of the previous as well as the distance to the next one. This is repeated until the limit of fines of line width is reached.

10.5.3.5 Free Space

Depending on the final print or common designs printed on used fabric, the free area can be filled with pictures in various colors and contrast, graphs, patterns or symbols.

10.5.4 Printing

The test print is printed in at least 3 different print modes. One print mode which is most commonly used, one for a comparable lighter substrate and one for a comparable heavier substrate than the used one.
10.5.5 First sample selection

After printing and curing/fixation a first selection based on the overall print quality is done. Here samples are sorted out that do clearly not meet the expectations, such as extreme faded color or extraordinarily wicking and color bleeding.

10.5.6 Evaluation

For evaluating the print a ruler, whaling glass and the transparency printed as described in 10.5.3 are used to evaluate the samples.

10.5.6.1 Text:

Aspects for a first evaluation in the areas of printed text in different color and contrast background colors.

1. Is the text just visible or is the text clearly visible?

2. Is the text readable? Is each letter clearly defined? Are the puncheons empty and clear of color?

3. Is wicking or misplaced ink casting “shadows” of the letters?

The evaluation is done from a viewing distance of approximately 1.0 meter.

In Table 4 examples of each possible image are shown and marked with corresponding grade. The grading expresses the amount of change to what it is supposed to look like. “0” means no change or deviation to the original file is visible. Whereas “5” marks the worst amount of change or deviation from what the text areas should look like.
Table 8. Grades and examples for text evaluation

<table>
<thead>
<tr>
<th>Grade</th>
<th>Text visibility</th>
<th>Readability</th>
<th>“Shadows”</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>All lines of text are clearly visible and readable</td>
<td>All lines of text are clearly visible and readable</td>
<td>No shadows or wicking around the letters is visible</td>
</tr>
<tr>
<td>1</td>
<td>6 lines of text are visible and readable</td>
<td>7 lines of text are visible and readable</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5 lines of text are visible and readable</td>
<td>6 lines of text are visible and readable</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4 lines of text are visible and readable</td>
<td>5 lines of text are visible and readable</td>
<td></td>
</tr>
</tbody>
</table>
Table 8. Continued

<table>
<thead>
<tr>
<th>4</th>
<th>3 lines of text are visible and readable</th>
<th>4 lines of text are visible and readable</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2 or less lines are visible and readable</td>
<td>3 or less lines are visible and readable</td>
</tr>
</tbody>
</table>

After the grading, the grades are accumulated and divided by 3. The result then gives the grade for the print quality of the text areas. The closer to 0 the better the less difference to what it is supposed to be and the better the result.

10.5.6.2 Squares and Circles

For initial evaluation the samples can be evaluated and graded on examples shown in Table 9. After that the length, height and diameters of the squares and circles are measured. This can either be done for all colors or only for the two most wicking ones. Based on the shrinkage of the material and the measurements of the shapes, the wicking width and length can be calculated.
Table 9. Grades and examples for evaluating wicking in squares and circles

<table>
<thead>
<tr>
<th>Grade</th>
<th>Squares</th>
<th>Circles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td><img src="image" alt="Squares 0" /></td>
<td><img src="image" alt="Circles 0" /></td>
</tr>
<tr>
<td>1</td>
<td><img src="image" alt="Squares 1" /></td>
<td><img src="image" alt="Circles 1" /></td>
</tr>
<tr>
<td>2</td>
<td><img src="image" alt="Squares 2" /></td>
<td><img src="image" alt="Circles 2" /></td>
</tr>
<tr>
<td>3</td>
<td><img src="image" alt="Squares 3" /></td>
<td><img src="image" alt="Circles 3" /></td>
</tr>
</tbody>
</table>
10.5.6.3 Stripes

The stripes can be evaluated with the transparency. Here it is observed how many of the stripes are separately visible without any ink connections due to wicking. Further, the stripes can be measured in height and length. In Table 10 examples for various quality of stripes is displayed with grades, similar to the grading scale of the other shapes.
Table 10. Grades and examples for evaluating stripes

<table>
<thead>
<tr>
<th>Grade</th>
<th>Stripes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td><img src="image1.png" alt="Grade 0 Example" /></td>
</tr>
<tr>
<td>1</td>
<td><img src="image2.png" alt="Grade 1 Example" /></td>
</tr>
<tr>
<td>2</td>
<td><img src="image3.png" alt="Grade 2 Example" /></td>
</tr>
</tbody>
</table>
Table 10. Continued

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>4</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>5</td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
</tbody>
</table>
10.5.6.4 Skew and bars

The skew is measured with a ruler or other measuring device. The frame around the print should have the size of a US letter paper (11 x 8.5 inch / 27.95 x 21.6cm). Depending on the deviation the shrinkage of the fabric due to heat curing can be determined. This is necessary to adjust large sized prints to fit required dimensions.

The bars along the vertical and horizontal edges have to be straight in all dimensions. This can be first evaluated by measuring the length of the edges and then by laying the transparency on it. Even if there is significant substrate shrinkage the bars should be corresponding in terms of straightness.

10.5.6.5 Other errors

Ink head calibration: When using a new fabric with the test print, incorrect calibration or incorrect color allocation, etc. can be determined. While the calibration is usually done when a profile is set up for a new fabric, a similar fabric or supposedly the same fabric can be slightly different, resulting in uneven lines and edges. Incorrect calibration can occur for one or for all colors and this effect can be determined at the edges of the squares, circles and stripes.

10.5.7 Final Grading

After all samples are evaluated and graded the grades area accumulated and divided by the number of grades given. The result is the final grade which describes how much the print differs from the initial print file. The higher the value of the grade the lower the print quality. The highest grade a sample can have before it is considered as not acceptable for publication
is the grade “2”. The implication is that samples with a grade higher than a value of “2.1” should be reprinted with adjusted settings, such as print mode or ink temperature.

With the evaluation technique it also can be determined if a substrate is suitable for the given ink and print mode.
Three Rings for the Elven-kings under the sky,
Seven for the Dwarf-lords in their halls of stone,
Nine for Mortal Men doomed to die,
One for the Dark Lord on his dark throne
In the Land of Mordor where the Shadows lie.
One Ring to rule them all,
One Ring to find them,
one Ring to bring them all and in the darkness bind them
The Lord of Rings

Figure 24. Test Print (colors removed)
10.6 Summary

The developed test print enables an evaluation and determination of digital inkjet printed material. Even though tests were performed on nonwoven material, the test print and evaluation method can also be applied for other textile materials. With the texts on different colored backgrounds it can be estimated how much wicking of contrast colors has to be expected. The wicking of the single pure colored squares, circles and stripes helps to evaluate and predict edges, corners and rounding as well as how narrow stripes can be printed without loss of sharpness. Overall the test print and its evaluation enables a constant and uniform method to compare and predict the print quality in terms of print sharpness as well as color saturation and color trueness on different substrates.

11 ROII

11.1 Purpose

The purpose of Research Objective II was to investigate how changes in printing parameters and fabric properties influence the print quality of digital inkjet printed nonwoven fabrics as defined in RO I.

11.2 Results

In all graphs in following chapter the columns represent the grade of all samples in each specific sample set. The dots, squares and triangle mark the samples that have assumingly good color saturation. This means any sample which is only represented with a column, but does not have a representing dot, triangle or square – independent of its grade – has unacceptable color
saturation. The red line in each graph defines the acceptable print quality, i.e. above the red line value is unacceptable.

11.2.1 Print mode and GSM

At an ink temperature of 26°C only one sample of one print mode reaches a grade within an acceptable range. 130B-A2-26°C has an average grade of 2 as it can be seen in Figure 25. All other samples not only have a grade above 2 but most of them even above grade 3. The overall quality grading for samples printed in print mode F shows to be the worst followed by samples printed in print mode C2. The sample that reaches a grading of 2 is printed in print mode A2 which ejects ink droplets in the range of 4, 7 and 12 Pl at high velocity.

![Print Quality depending on Print Mode at 26°C](image)

*Figure 25. Print Quality depending on print mode at ink temperature of 26°C*
Removing all sample data of samples without acceptable color saturation only samples with 40, 60 and 80 GSM, respectively at print mode C2 are left. However, the print quality of those samples are all above grade 3. The sample initially reaching a grade 2 (130B-C2-26°C) does not have a good enough color saturation.

As shown in Figure 26 the print quality for samples printed at 32°C ink temperature and different print modes decreases with increasing amount of ink on the substrate, except for 130PK. Samples printed in print mode F is on average, graded 3 or 4, independent of the GSM. Samples printed in print mode C2, however, have on average a better grading overall but except for 130PK the grade is not above 2.0.

Again, there is no obvious trend depending on the change of GSM vs. PQ. Samples printed at 32°C and in print mode A, have overall the best print quality in terms of print clearness but not in terms of color saturation.
After removing sample date of samples with bad color saturation only one sample printed in print mode A is left. All samples printed in print mode C and F have good color saturation. Prints printed on samples labeled with 130PK show to have not only the best color saturation (except for print mode A) but also overall the best print quality. On the other hand the fabric with the same GSM but a different production method – 130B – does not fulfill the criteria for good print quality independent of the print mode.

Overall no clear linear trend depending on GSM and print mode at an ink temperature of 32°C to print quality can be found.

In Figure 27 the print quality of the samples printed with different print modes at an ink temperature of 37°C are shown. Similar to Figure 26, fabrics labeled with 130PK overall have
the best print quality and color saturation. All other samples printed with print mode F have the highest deviation to the initial print file and are mostly graded with 3 or 4, except 130PK. Samples printed in print mode C as well as A also do not meet the previously defined quality criteria. Overall, an exception are prints made on fabric labeled with 130PK. Here the print quality as well as the color saturation for print mode C and F is good and close to grade 0.

![Print Quality depending on Print Mode at 37°C](image)

*Figure 27. Print Quality depending on print mode at ink temperature of 37°C*

Removing the sample data of samples with low color saturation only one print done in mode A is left, which is 80PK-A2. All other prints done in print mode A do not reach an acceptable
color saturation. On the other hand all samples printed in print mode C or F do have good color saturation.

Keeping the temperature the same, as shown above at 37°C, it becomes visible that the print mode has a high influence on the print quality. The more ink on the substrate the lower the quality becomes independent of the GSM of the fabric, except for 130PK. In general, 130PK shows the best quality for all print modes A, C and F when ink temperatures are 32°C and 37°C but not for 26°C.

11.2.2 Ink temperature and GSM

Prints done in print mode A2 were found to have the most samples graded with 2 or below. The best quality in that print mode is reached at ink temperature 32°C and 37°C. No print that was printed with an ink temperature of 26°C reached a better average rating of 3 as displayed in Figure 28.
Figure 28. Print Quality depending on ink temperature at print mode A2

However, removing the data labels from samples without good color saturation only the sample printed with an ink temperature of 32°C on a fabric with 40 GSM fulfills both criteria of color saturation and print quality. Samples on 80PK fabric, print mode A at 32°C does fulfill the quality criteria but does not have good color saturation whereas the same fabric printed with ink temperature of 37°C does have good color saturation but not good print quality. There is no trend showing how the print quality is related to the fabric weight when the print mode is A2.

Samples printed in print mode C2 overall had a bad print quality independent of the ink temperature during printing, except for fabrics labeled with 130PK. No other sample fulfills
the quality criteria in terms of print clearness and wicking. However, most samples do fulfill the criteria of good color saturation. For prints with low ink temperature, however, with increasing GSM the color saturation decreases as shown in Figure 29.

![Print Quality depending on Ink Temperature in Print Mode C2](image)

*Figure 29. Print Quality depending on ink temperature at print mode C2*

Samples printed in print mode F show overall a bad print quality, independent of the ink temperature during printing. The high amount of wicking, which leads to bad print quality as defined in ROI comes from the high amount of ink ejected during the printing process in print mode F. There is no trend on how the print quality increases or decreases with increasing or decreasing ink temperature during printing. The color saturation in nearly all samples is good,
except for 100B, 100PK and 130B. However, again samples 130PK showed to have very good
print quality as well as good color saturation.

Overall, there is no trend in change of print quality in each print mode depending on the
GSM of the samples.

11.2.3 Fabric type

As it clearly can be seen in Figure 31 there is no trend depending on the weight of the fabric
as labeled by Freudenberg. Overall, most samples produced have poor print quality in all print
modes and at all ink temperatures, except 130PK. 130PK fulfills the criteria for a good print

Figure 30. Print Quality depending on Ink Temperature at print mode F

Figure 30. Print Quality depending on Ink Temperature at print mode F
as well as good color saturation for most print settings and ink temperatures for 32°C and 37°C. Other samples that have good print quality are 40PK-A2-32°C, 80PK-A2-32°C and 100B-A2-26°C. However only 40PK-A2-32°C has good color saturation.

Samples produced with a different production method and labeled with “B”, such as 100B and 130B, overall showed to have a higher wicking behavior in comparison to those labeled with PK or the same weight class. Also the color saturation differed greatly between the samples produced with different methods.

![Figure 31. Print quality in dependency of fabric weight and production method as labeled by Freudenberg](image)

Figure 31. Print quality in dependency of fabric weight and production method as labeled by Freudenberg
11.3 Springs Creative

Samples produced at Springs Creative in Rock Hill, South Carolina, were found to be highly different in terms of color saturation and print quality at the same print settings as shown on 40PK samples in Figure 32. The samples were printed at an ink temperature of about 29°C and in print mode C2. In comparison to samples at NC state with an ink temperature of 26°C in print mode C2 the samples had very good color saturation but also extreme wicking, especially in samples with low GSM. Samples with higher GSM, such as 130PK and 100PK had better print quality at good color saturation. Here, the difference between the production methods for 100 and 130 PK and B became more obvious.

Figure 32. Difference in print quality based on production facilities

However, due to lack of time and limited amount of sample substrates following parameter which could influence the print quality were not further investigated.
11.3.1 Software

The software used at NC State are RIP Master and Match Print. Therefore, the MS printer is an open software printer, every print software compatible can be used. The software used at Springs Creative are Neostampa, Ergosoft and Textprint. A possibility would be that each print software translates file data slightly different, which can lead to different results in print quality and color saturation.

11.3.2 Humidity

Samples produced at Springs Creative showed to have a much higher wicking rate than samples produced at NC State. One major difference between the production facilities is the humidity in the production room. Whereas, at Springs Creative the humidity is mostly tried to be kept constant at around 50%RH, the humidity at NC State varies depending on the weather and is neither controlled nor monitored. The overall humidity and the moisture content of the fabrics could lead to increased or reduced wicking on the fabric, as well as to reduced viscosity of the ink at the ink nozzles.

11.3.3 Air pressure

The constant pressure in the printer varies depending on the air pressure in the lab. This is also influenced by the weather. The constant pressure of the printer at NC State is not controlled or monitored. At Springs Creative the constant pressure values is checked regular and adjusted to stay mostly constant at -3.
11.3.4 Ink

At the beginning of 2017, the ink supplier for the pigment ink had developed a new generation of pigment ink. Samples printed at Springs Creative where printed with the old generation, whereas at NC State the new generation was implemented to test it. Due to confidentiality and trade secrets no information about the specific differences of the new and old generation are available.

11.4 Summary

As shown in Figure 25 to Figure 31 the print quality is mostly dependent on the amount of ink ejected onto the fabric (print mode) as well as the viscosity, which is controlled by the temperature during printing. No distinct trend depending on the weight of the fabrics, as labeled by Freudenberg, could be determined. However 130PK in most cases has the best print quality and good color saturation. The only exception is for prints done with an ink temperature of 26°C. In general, prints, printed with low ink temperature showed to have the highest amount of bad grading, except for 100B-A2-26°C. With increasing GSM and thickness the amount of ink absorbed into the depth increases, leading to less wicking in the planar directions. In samples with “-A-26°C” the least wicking occurs in the samples with approximately 100gsm. Whereas in samples with 130gsm the absorbency is so high that striping occurs due to the low amount of ink and the quick ink penetration. The stripes nearly disappear when more ink, such as in print mode “C” or “F” is ejected onto the substrate. However for samples with 100 and 130 gsm also the production method labeled as “B” and “PK”, respectively showed to have high impact on the print quality.
However, ink temperature has the most severe effect on color saturation. The lower the ink temperature during printing the higher the viscosity of the ink, which results in low color saturation at samples with higher GSM. Here the fabric weight has a big impact on the final print. This also means that the ink droplets ejected onto the fabric stay mostly separated and do now form a cohesive layer of ink. This means that in case of a clogged ink nozzle stripes are immediately visible. The production method “B” or “PK” had no significant influence on the color saturation.

Based on the gained knowledge in this research it can be said that for each fabric the print settings have to be determined periodically. By decreasing the ink temperature in a print mode the ink viscosity can be increased and the wicking be reduced. The exact temperature however has to be determined for each kind of ink and each color separately.

In a practical application, if the color saturation is sufficient but the wicking in the grading range of 1 or 2, in first step a print mode with less ink ejection should be used. To further reduce the wicking in the substrate the ink temperature can be reduced slightly to increase the viscosity of the ink. In case of a fabric change based on presented data and experience new print settings can be estimated and limited.
12 ROIII

12.1 Purpose

The purpose of this research was to investigate if the current crocking standard is applicable for crocking nonwoven material or if it has to be altered or renewed.

12.2 Problems

12.2.1 Fabric mounting

While testing how the fabrics are to mount onto the crocking pegs, it was found that it was relatively hard to mount the crocking fabric onto the crocking cube without wrinkles on the edges. Also, the fastening of the fabric onto the round peg is easier with a round clamp. A rubber band to fasten and fix the crock fabric on the squared crock peg is a possibility but is much harder to handle in the small space between the crocking peg on the arm and the sample holder. Being able to remove the squared crocking peg and turn it upside down to mount the crocking fabric on it, helped during the testing but still made it not easier getting the fabric onto the peg without wrinkles on the crocking surface. For this crocking test an easier solution has to be designed.

12.2.2 Wet crocking

In the AATCC 8 method, the amount of water to put onto the crocking square is defined as 65% of the weight of the material. The amount of water needed to get the same wetness of the fabric in the nonwoven crock squares is much more than in the woven ones. Still, the same amount was used and the water was placed in the middle or on the exact crocking area,
respectively in the nonwoven materials. This might have led to more moisture in the crocking area for the nonwoven materials than for the woven crocking squares.

12.3 Result

During first testing rounds it was found that there is no visible difference between the different nonwoven crocking materials in terms of color abrasion. However, using 130PK as crocking material, it was hard to mount onto the crocking pegs. The same applies for 100PK, 130B and 100B where much softer and easier to handle as well as 80P; 60PK and 40PK. Due to limited amount of time the crocking squares made of 130B and 40PK were used for the tests as well as the woven crocking squares.

12.3.1 MD – CD

Crock testing done along machine direction (MD) and cross direction (CD) to the hydroentangling lines of the nonwoven samples did not show visible impact on the color abrasion of the sample material.

12.3.2 Crocking Nonwoven samples

The woven crocking fabric shows more color abrasion than the nonwoven material when using the squared crocking peg. Whereas, using the round peg more color abrasion is found on the nonwoven crocking material than on the woven. In general, the squared crocking peg – due to its higher surface areas with that wider distributed force area – has less surface destruction than the round peg on the crocking samples. However, crocking in CD of the fabric does not cause visible more color abrasion but more surface destruction of the samples regardless of the crocking peg shape.
The ink temperature during printing did not have an impact on the crocking results. However the amount of ink, defined by the print mode (C2 and F) showed to have an impact on the results as it can be seen in Figure 33. The more ink on the substrate the more color transfer took place during the testing. This was valid for dry as well as for wet crocking. However, the wet crocking results did not differ between woven and nonwoven crocking material (Figure 33).
Figure 33 Crocking results for 130PK. Left to right: Woven, 40PK, 130B crocking squares. Top to bottom: Squared-dry, Round-dry, Squared-wet, round-wet
12.3.3 Crocking 100PES woven

No significant difference could be determined between samples of 32°C and 37°C. Again, the amount of ink, determined by the print mode C2 and F was found to have impact on the amount of color transfer during crocking. Whereas, it is not as significant as in the nonwoven samples (see Figure 34).

The crocking squares made of nonwoven material showed high surface destruction in form of banding after crocking the woven material. This had no influence on the crocking result as it can be seen in Figure 34.

Samples crocked with the squared crocking peg showed, in general, less color abrasion than the round ones. In wet crocking the overall amount of color removed was more but still less than in the nonwoven. Whereas, the samples during nonwoven crocking did show surface destruction and banding, the nonwoven squares showed high surface banding. The color abrasion was the same with the round crocking beg for all crocking squared, but highly reduced for the squared crocking of the woven material.
Figure 34 Crocking results for 100PES. Left to right: Woven, 40PK, 130B crocking squares. Top to bottom: Squared-dry, Round-dry, Squared-wet, round-wet
12.3.4 Crocking Samples from Springs Creative

The best dry crocking results were gained from crocking the samples printed at Springs Creative. However, the wet crocking was similar to those gained from the nonwoven samples. This was valid for both round and squared pegs as it can be seen in Figure 35.

Figure 35 Crocking results for Springs Creative Samples. Left to right: Woven, 40PK, 130B crocking squares. Top to bottom: Squared-dry, Round-dry, Squared-wet, round-wet.
12.4 Discussion

During preliminary test it was found that the ink temperature during printing had an influence on the crocking results. However, during the project the set of ink in the used printer changed and final crocking tests were done with an experimental ink set provided by company A. This ink showed to behave different from the ink used in the preliminary tests and experiments. Preliminary results indicated that a change in ink temperature would influence the color abrasion during crocking. However, in final test this showed not to be applicable for a different set of ink. In the final tests the results were influenced by the print mode (amount of ink put onto the fabric surface) as shown in Figure 36.

Further, the preliminary research indicated that the current crocking method would show differences between crocking nonwoven fabrics and woven fabric of the same kind. With the new set of ink this could not be reproduced. This, however, clearly shows that the crocking behavior depends on various factors such as ink generation, temperature of ink during printing and maybe also fabric structure as well as crocking peg geometry.
The test results of the crocking test overall showed that crocking nonwoven material is different than crocking woven material. The differences may result from the different surface properties of the woven and nonwoven material. The surface fibers of the used nonwoven material may be more prone to abrasion and thus cause a higher degree of color transfer.

Figure 36. Color abrasion of dry crocked 130PK – C2 – 32°C (top) vs. 130Pk – C2 – 37°C (bottom)

12.5 Summary

The test results of the crocking test overall showed that crocking nonwoven material is different than crocking woven material. The differences may result from the different surface properties of the woven and nonwoven material. The surface fibers of the used nonwoven
material are less entangled and fastened into the material structures than the 100% Polyester woven material. Besides the crocking material and the crocking sample also the shape of the crocking peg has influence on the results. The wet crocking results, however did not show much differences when using different crocking material or a different crocking peg.

Even preliminary test indicated that the ink temperature would have impact on the test results, this could not be confirmed. The biggest influence on the crocking results disregarding the crocking peg and material has the amount of ink on the substrate. However due to limited time and sample material no extensive research could be conducted.

12.6 Conclusion

Based on the presented results it can be said that the current crocking standard is only in limited definition suitable for crock testing nonwoven. The weight and amount of strokes for the testing seem appropriate. But to gain data that are truthfully comparable for woven and nonwoven material the crocking fabric for crock testing a nonwoven material should be a nonwoven as well as woven material. To further exclude influences on a certain nonwoven material in comparison to the woven material, a squared crocking peg should be used. Only with results conducted with both material and pegs a real and valid comparison and evolution can be done for crocking nonwoven material.

Therefore it is suggested to add to the AATCC 8 test method that for testing a nonwoven material a nonwoven square and a squared crocking peg should be used. As mentioned in AATCC 8, for final evaluation the results of an in-house comparison fabric should be used.
This fabric should be crocked with round peg and both material as well as squared peg with woven and nonwoven crocking squares to ensure a true and representable result.

13 Suggestions for future work

Due to limited time and sample material not all aspects of each research objective could be investigated in depth. Further, even though it was tried to consider as many as possible influences and aspects for each research during the sample production, testing and evaluation new possible influences emerged.

13.1 ROI

In RO I a standard print and evaluation method to determine the print quality of digital inkjet printed nonwoven was established. The test method was applied on samples produced during the research and was found applicable. However, for an actual implementation into industries the standard should be further tested and a survey conducted on how it is practically applicable in industries. Further suggestions and proposals for changes should be tested and if applicable implemented.

13.2 ROII

As shown above, by changing the ink temperature during printing as well as the fabric weight the final print quality can be influenced. The most important factor that influences the print quality on a nonwoven material was shown to be the print mode. However, due to lack of time and limited amount of sample material other influencing parameter could not be tested.
Based on the observation of print results and processes at Spring Creative and NC State, following suggestions for future work evolved:

Investigating the influence of external aspects, such as

- Choice of Software
- Humidity in the printing laboratory
- Humidity of the substrate
- Weather (air pressure)

on the final print quality of digital inkjet printed fabrics. This research not solely can focus on nonwoven material, but also on woven and knitted material.

Beside external aspects, also material properties such as SVF, thickness or porosity can be further investigated on how they influence the final print quality.

13.3 ROIII

Differences in results during preliminary and final crocking test showed that the crocking behavior of nonwoven not necessarily can be compared to crocking of a woven material. Important factors, such as ink generation, ink temperature during printing as well as other factors can influence the test results. Due to limited time during this research following suggestions for future work evolved.

- Influence of nonwoven production and bonding method on crocking results
- Extended research on the influence of crocking material on the crocking results
- Define a rule or guideline for wetting a nonwoven crocking fabric therefore nonwoven can have different wetting behavior than the woven cotton crocking square
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