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On the Mechanical Analysis and Control for the Tension System of the Cylindrical Filament Winding

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Abstract
The constant winding tension can make the filament arranged in order. The stress distribution between the filament balance fully gives play to the enhancement of filament, and increases the intensive workload of the composite winding material. This paper conducts the mechanical analysis for the unwinding roller and tension measuring roller of the cylindrical winding machine so that gets the mechanical model, gives error compensation formula caused by the radius change of the yarn group in the unwinding side, designs the closed-loop control system and utilizes the dynamical-integral PID control strategy to achieve the tension control during the process of the cylindrical winding.

Keywords
Filament Winding, Cylindrical Winding, Winding Tension, Dynamical-Integral PID, Closed-Loop Control

1. Introduction
The winding process consists of the production of mandrel and lining, the disposition of the glue solution, the filament drying, heat treatment, winding, solidification, testing, and reconditioning [1]. Among these processes, the tension control is a difficult significant process, which has a relatively huge impact on the performance of the winding product. The constant winding tension can make the filament arranged in order and the stress distribution between filament uniform, therefore it is beneficial for implementing the enhancement of the filament and increasing the workload of the composite winding product, otherwise it will result in more than 20 percent of the damage for the strength action of the filament. In terms of wet winding process, the control of tension can

unify the results of the filament infiltration, reduce the thickness of the yarn sheet, and make the track of doffing accurate. Thus, the proper winding tension system and tension control is a significant element for achieving the quality winding product [2].

Many domestic scholars conduct the theoretical analysis and experimental research for the filament winding tension. Ding Baogeng, Yang Fujian et al. deduced the winding tension formula with full consideration for the prerequisite of the relaxation effect of the circle of winding glass fiber on the various layers. Xu Pingan established a new precise tension control system in his master’s thesis, controlling the tension of the yarns accurately during the filament winding process. Ren Qile designed and set up the tension control system in his doctoral dissertation, regarding the winding roller and swing rod as the object of study respectively. He employed the closed-loop control system of which the integral separation PID is the control strategy. Zhang Zongyi, Deng Guide, Shou Binan, and Li Xiaoyang et al. came up with an equivalent cooling method which made the pre-stress caused by the winding tension equivalent to the pre-stress caused by the cooling of the composite layer. They deduced the computational formula between the winding pre-stress and the cooling temperature of composite layer and utilized the general finite element software to study the influence of the winding tension on the stress of the round winding composite gas bottle based on the equivalent cooling method. Zhu Guohui et al. analyzed the winding vessel of the low stress inner shell designing and deduced the winding original stress formula of the steel band winding. Jia Xiaoning et al. came up with a static friction microcomputer control system of application of power and tension, which uses the torque motor directly connected with the yarn group axis to exert the original tension and control the original tension in the microcomputer. T Ueki, S Suzuki, R Morikawa and, H Hashimoto describe optimization method of winding tension for preventing the wound roll defects under unstable environmental temperature based on the optimum design technique by Hashimoto [3].

This paper conducts mechanical analysis for the unwinding roller during the cylindrical filament winding process. Based on the analyzed mechanical model, the control strategy of unwinding roller and winding process is deduced with the unwinding roller as the control target. This paper utilizes the dynamical-integral PID control strategy to achieve the control for the winding tension.

2. The Operating Principles of the Winding Tension Control System

The winding tension control system includes unwinding, tension acquisition, auxiliary facilities, and control, as is shown in Figure 1. Unwinding indicates the roller rotates to put lines under the tension of the winding filament. The filament moves with the rotating mandrel. Between the unwinding roller and the mandrel, many guiding roller control the direction of the winding filament to make it move steadily. The tension acquisition tests the tension in real time and transmits the results to the control part. In the open-loop control system, the winding roller radius is taken to test the tension with a relatively simple structure. While in the closed-loop control system, the force sensor is used to get the real-time tension and feed back the signal so as to achieve the closed-loop control. The auxiliary facility is based on the sensor’s features of fast response speed, high precision, and small displacement. The control indicates to calculate with the transmitted information in the testing part, have various control judgment, transmit the adjustment signal to the correspondent resistance production device, and finally achieve the goal to adjust the winding tension. The control part includes the controller and the executor of the tension control.
2.1. The Mechanical Analysis of the Winding Tension System

The winding tension control needs to ensure the effective performance of the winding products’ enhancement of the various layers of filament. However, the features of the winding filament, the winding radius change, the friction, the resin content will influence the stability of the tension during the winding process [4].

The proper control of the filament winding tension can enhance the quality of the winding products effectively. The designed tension control system utilizes the closed-loop control method in this paper. The tension sensor feeds back the real-time tension and the system gives the control signal after calculation to drive the executive component to operate the AC servo motor to control the unwinding speed of the unwinding roller and finally the goal to control the tension is achieved. Utilize the operation of the motor to impose the torque resistance on the winding roller to control the feeding speed of the winding roller so as to achieve the goal of controlling the winding tension.

2.2. The Tension Analysis of the Unwinding Side

As is shown in Figure 1, the filament winding tension control system mainly achieves the tension control by controlling the unwinding speed of the unwinding roller. Therefore this paper firstly analyzes the force situation of the unwinding roller during the winding process. As is shown in Figure 2, the unwinding roller should meet the dynamic balance requirement during the winding process as is shown in formula (1).

The balance equation of the dynamic torque of the stressed unwinding roller is:

\[ TR(t) = M(t) + M_{fr} + J(t)\omega(t) + M_0 \]  

In the equation,
- \( T \): filament tension (N);
- \( R(t) \): real-time radius of the yarn group (m);
- \( M(t) \): resistance torque of the motor (N·m);
- \( M_{fr} \): friction torque of viscidity (N·m);
- \( \omega \): the speed of the yarn group (rad/s);
- \( J \): the rotational inertia of the winding roller (kg·m²);
- \( M_0 \): the friction torque of the dryness (N·m).

From Equation (1), it can be known that the control target of the tension control system is a complex real-time system, including the radius of yarn group, the angular speed of the winding roller, and the rotational inertia of the unwinding roller, which change along with the time.

Therefore the above equation needs to be simplified, ignoring the elements which has less influence and has smaller change along with time. The detailed simplifying elements are analyzed as follows:

![Figure 2. The force analysis of the winding roller.](image)
1) The dryness and viscosity friction have little change along with time and have little influence on the system, thus they can be ignored;

2) The instant change has little influence on tension thus it can be ignored, such as the \( J(t)\omega(t) \), which is the rotational inertia of the unwinding roller and the rotational inertia of filament.

3) Because the rotational inertia of the yarn group is a steady state value which does not change along with time, the rotational inertia of yarn group can be ignored.

According to the above principles, the Equation (1) can be simplified into:

\[
TR(t) - M(t) = J(t)\omega(t)
\]

When the executive motor of the tension control system works normally, it usually is in a condition of dynamic braking. Its torque relationship is shown as Equation (3):

\[
M(t) = M_c + M_0 + J\frac{d\omega}{dt} = M_c + M_0 + M_d
\]

In the equation, \( M \) represents motor, the subscript \( c \) electromagnetic torque, \( 0 \) the no-load torque, \( d \) the dynamic torque; \( \omega \) the angular speed.

Because there are few no-load motors during the winding process, the no-load torque \( M_0 \) can be ignored; besides, when the motor is in a condition of steady rotation, its dynamic torque \( M_d \) is 0. Therefore the Equation (3) can be simplified into Equation (4):

\[
M_c = M_c
\]

Because,

\[
M_c = K\Phi I_d
\]

In the above equation, \( K \) is the electric constant of the motor; \( \Phi \) is the main flux and \( I_d \) is the torque current.

And because:

\[
M_c = FR
\]

In the above equation, \( R \) is the radius of the yarn group; \( F \) is the tension.

Deduced from the above:

\[
F = \frac{K\Phi I_d}{R}
\]

Converse the Equation (7):

\[
I_d = \frac{FR}{K\Phi}
\]

From the equation, it shows that the tension is related to the radius of the yarn group and the current component. To make the tension remain constant, the current \( I_d \) should be controlled linearly according to the radius change of the yarn group. In other words, the control of the braking torque of the motor is achieved through the control of the motor current, and then the tension control is achieved also. From the Equation (8), it is shown that the torque component \( I_d \) can be confirmed and the closed-loop control of tension can be achieved through testing and feeding back the radius of yarn group and the tension.

2.3. The Mechanical Analysis of the Tension Measuring Mechanism

The real-time tension acquisition is a significant feedback part in the tension control system. The proper periodical data acquisition for the real-time data of tension can enhance the control precision effectively. The popular tension acquisition method is shown as Figure 3. The three guide rollers are used to have tension measurement in the way of force transmission. The three guide rollers are arranged as the structure indicated in Figure 3. The tension sensor is set below the guide roller 2. When the mandrel rotates, the yarn will be wound and rotated around the mandrel. When the winding speed exceeds the unwinding speed, the yarn will have tension action. This tension will be transformed into the pressure action for the guide roller 2, be tested by the tension sensor and be fed back to the controller after getting the correspondent signal, thus constituting the feedback input of the closed-loop control. Such kind of means has simple structure, good application effect and it is easy to
Figure 3. The tension test of the three guide rollers.

The force analysis of the measuring device is indicated as Figure 4. When the middle guide roller 2 reaches a balance, its dynamic equilibrium is shown in Equation (9).

\[ J \omega + T_1 \cos \alpha_1 + M_0 = T_2 l_2 \cos \alpha_2 \]  

In the equation, \( J \) is the rotational inertia and \( \omega \) is the angular speed of guide roller 2 respectively. \( M_0 \) is the static friction torque of guide roller 2, \( l_1 \) the filament length from guide roller 1 to guide roller 2, and \( l_2 \) the filament length from guide roller 2 to guide roller 3. The static friction is ignored and the above equation can be simplified into:

\[ J \omega + T_1 \cos \alpha_1 = T_2 l_2 \cos \alpha_2 \]  

When the two sides of guide roller 2 have tension change resulting from the speed change, the positive pressure of guide roller 2 is calculated as Equation (11).

\[ F = T_1 \sin \alpha_1 + T_2 \sin \alpha_2 - F_0 = (T_1 + T_2) \sin \alpha_1 - F_0 \]  

In this equation, \( F_0 \) is the original pressure in the condition of balance, which is decided by the original winding tension.

2.4. The Analysis of Dynamic Compensation

During the winding process, because the non-uniform speed of winding the yarn resulting from the acceleration and deceleration motions, the tension finally changes. Therefore the control system cannot follow up and adjust in time and finally the filament is broken or loose. Thus, during the winding process, when the acceleration or deceleration motion caused by certain elements occurs, to ensure the uniform speed of winding the yarn, the speed compensation is required for unwinding roller. Normally certain braking torque will be imposed on the executive motor of the unwinding roller so that the tension can be maintained as constant. The dynamic torque is:

\[ M_d = J \frac{d^2 \omega}{dt^2} = \left( J_p + J_m \right) \times \frac{d \omega}{dt} \]  

In the above equation, \( J \) represents rotational inertia, \( p \) filament, \( m \) the roller.

During the filament winding process, the rotational inertia of filament is changing dynamically. It is in direct proportion to the radius change of the yarn. Therefore it can be calculated through Equation (13).

\[ J_p = \int (2\pi \rho b) R^2 dR \]  

In the equation, \( \rho \) is the density of the yarn; \( b \) is the width of yarn; \( R \) is the radius of yarn group. Then,

\[ \frac{d \omega}{dt} = \frac{d}{d_t} \frac{1}{R} \]
The simultaneous equation is:

$$M_d = \frac{1}{R} \left( \frac{1}{2} \pi \rho b R^4 + J_{st} \right) \frac{d}{d_t}$$

As is shown in Equation (15), the dynamic torque $M_d$ which needs compensation can be calculated through tracking the radius of the unwinding and winding yarn group and the accelerated speed of the unwinding roller. So it shows that the unwinding roller needs to remain a constant linear speed for achieving the control of the winding filament’s constant tension.

3. The Tension Control of the Winding Filament

The filament winding tension takes the closed-loop control method [5]. The tension sensor feeds back the real-time tension and the system gives the control signal after calculation to drive the executive component to operate the AC servo motor to control the unwinding speed of the unwinding roller and finally the goal to control the tension is achieved. The control principle is shown as Figure 5.

The classic PID strategy is used broadly in various closed-loop control systems [6]. However, as for the non-linear complex system like filament winding tension control, the classic PID control has poor effects. The modified PID control strategy has high demand for calculation and controller, such as the PID control based on the neural network. Because this paper aims to have the tension control for the cylindrical winding product, the dynamic integral of PID can meet the demand for the calculation and non-linear change [7].

The input of the dynamic integral PID controller changes the contained integral and differential parts of PID controller through weighting coefficient $\beta$ and finally achieve the steady control of the system [8].

When $\beta = 0$, the deviation $e$ will exceeds the normal value. The PID controller uses the PD to control thus the system will have relatively fast responding speed and meanwhile it can be avoided to expand the overshoot.

When $\beta = 1$, the PID controller will use PI to control.

When $0 < \beta < 1$, PID controller is controlled by the universal PID to ensure the control precision of system.

If the deviation time function is $e(t)$, the deviation change rate time function is $r(t)$, and the time of sampling is $n$, $e(n)$ will disperse into $e(n)$, $r(t)$ will disperse into $r(n)$, and $r(n) = e(n) - e(n-1)$. The dynamic integral PID control equation is shown as Equation (16).

$$u(n) = K_p(n) + \beta K_i \sum_{k=0}^{n} e(k) T + K_d r(n)/T$$  (16)

From Equation (5) to Equation (8): $n$ is the number of sampling, $n = 0, 1, 2$; $T$ is the period of sampling; $u(n)$ is the output at the nth sampling; $e(n)$ is the deviation signal; $K_p$ is the proportion coefficient, $K_i$ is the integral coefficient, $K_d$ is the differential coefficient.

According to the adjustment principles for the various coefficients of PID during the filament winding process, when the deviation of system is great, the integral action should be weakened and when the deviation reduces, the integral action should be enhanced. The dynamic integral PID can weaken the system fluctuation occurs during the adjustment process to enhance the stability of system. The dynamic integral indicates that when the deviation is huge, the integral acceleration should slow down and the integral action should be weakened correspondingly; when the deviation is small, the integral accumulation should accelerate and the integral action
should be enhanced correspondingly.

Set the coefficient \( G(e(n)) \), which is the function of deviation \( e(n) \). When the deviation increases, \( G(e(n)) \) will decrease, otherwise, it will increase. If the variation range of the time deviation \( |e(n)| \) in steady state is \([a, b]\), the chosen coefficient \( G(e(n)) \) is shown as Equation (17).

\[
G(e(n)) = \begin{cases} 
1, & |e(n)| \leq b \\
\frac{a - |e(n)| + b}{a}, & b \leq |e(n)| \leq a + b \\
0, & |e(n)| > a + b
\end{cases}
\]  

(17)

The integral term of the dynamic integral PID is shown as Equation (18).

\[
K'_I(n) = TK_i \left( \sum_{k=0}^{n-1} e(k) + G(e(n)) e(n) \right)
\]  

(18)

As is shown in Equation (18), the interval of \( G(e(k)) \) is \([0, 1]\). When the deviation exceeds the expected value, make the coefficient \( G(e(n)) = 0 \) and do not accumulate the current deviation; when \( |e(n)| \leq b \), \( G(e(n)) = 1 \), and the system normally is controlled by PID. At that time, the current \( e(n) \) will be accumulated and the coefficient of integral is shown as Equation (19).

\[
K'_I(n) = K_i \sum_{k=0}^{n-1} e(k)
\]  

(19)

When \( b \leq |e(n)| \leq a + b \), the integral accumulates a part of the current value, the results vary in the interval of \([0, e(n)]\), and the speed of integral varies in the interval of

\[
\left[ K_i \sum_{k=0}^{n-1} e(k), K_i \sum_{k=0}^{n-1} e(k) \right].
\]

Substitute Equation (18) to Equation (17) and the equation of the dynamic integral PID is shown as Equation (20).

\[
u(n) = K_P e(n) + K_i \left( \sum_{k=0}^{n-1} e(k) + G(e(n)) e(n) \right) + K_D r(n)/T
\]  

(20)

To test the dynamic integral PID control strategy, this paper chooses MatLab to have the simulation experiment. The step signal of 1 is chosen in the simulation. Its corresponding results show that the response and overshoot of the normal PID is shown in Figure 6. The duration of the shock cycle is longer. After about 15 seconds, the signal tends to be stable. The overshoot has reached 1.6 during the first 5 second. Obviously the dynamic integral PID is better than the normal PID (as is shown in Figure 7). The shock lasts less than 10 seconds. And the overshoot has reached 1.3. It indicates that the dynamic integral PID has better adjustment function for the overshoot, better steady-state performance, better adjustment quality, and better system transition. Therefore the dynamic integral PID control strategy has faster respond to the step and higher control precision, thus it is proper to be the filament winding tension control strategy.
4. Conclusion

To make the filament of the cylindrical winding product has constant tension and give full play to the fiber reinforced function, this paper analyzes the force on the unwinding roller and the tension acquisition part during the winding process, utilizes the motor to impose resistance torque on the unwinding roller during the process, designs and implements the tension closed-loop control system of which the unwinding roller is the control target. That system chooses dynamic integral PID control strategy. The simulation experiment results show that the response and overshoot of the normal PID obviously exceed those of dynamic integral PID. It indicates that the dynamic integral PID has better adjustment function for the overshoot, better steady-state performance, better adjustment quality, and better system transition. Therefore, the control system has relatively good stability, the overshoot is decreased efficiently, and the response time of system is shortened.

References


Investigation on Effect of Acid Wash with Thermocol Ball on Physical Properties of Knitted Garments

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Abstract
Washing is considered as the final process of garments finishing. Acid washing is one kind of finishing treatment used for making sewn garments aesthetic, fashionable, soft, comfortable and also adding value to the final garments. This paper investigates the effect of the acid washing (with thermocol balls and potassium permanganate) on different physical properties of three knitted garments (Single Jersey 100% Cotton T-shirt, Single Jersey 95% Cotton 5% Spandex T-Shirt and 1 ∗ 1 Rib100% Cotton T-Shirt). Typical washing procedures and techniques were followed and then physical properties were analyzed under standard condition. It is observed that fabric weight, CPI, WPI, spirality and shrinkage increase while bursting strength, stitch length absorbency decrease after washing treatment. pH of all the samples is under controlled and lies between 7 to 8. There is no change in pilling, colorfastness to wash, water and dry rubbing while a little bit decrease in wet rubbing.

Keywords
Acid Wash, Potassium Permanganate, Thermocol Ball, Physical Properties, Knitted Garments

1. Introduction
Nowadays, faded textile products have become very popular among the young customers all over the world [1]. For this reason, textile manufacturers are trying to develop numerous techniques to improve the visual outlook...
of the sewn garments [2]-[5]. Different denim washing techniques have been developed and used on different materials to create a large variety of designs for trendy denim garments and jeans [6]-[11]. Nowadays along with denim washing knit garments such as T-shirt, Polo shirt, and trouser, are also washed by using different techniques such as enzymes wash, softener wash, Silicone wash, tie dye wash, pigment wash, caustic wash, etc. are used to create or enhance the physical and mechanical property changes [12] [13].

Acid washing in knitted garments is a new technique which is done by potassium permanganate and pumice stone or other substitutes [13] [14].

Potassium permanganate is an inorganic chemical compound with the chemical formula KMnO₄ [15]. It is a strong oxidizing agent and used to make color fading effect on sewn garments [16]-[18]. Sometimes it is used at the point of hand sand area or without hand sand area. As it is a great oxidizing agent, after applying, it is necessary to neutralize the garments by any good neutralizing agent [19].

Thermocol is a commercial name. In 1951, the researchers of a German company named BASF successfully restructured chemical bonding of polystyrene (a synthetic petroleum product) molecules and developed a substance named stretch polystyrene. This substance was named Thermocol, which nowadays is manufactured through a simple process. Thermoplastic granules are expanded through application of steam and air. Expanded granules become much larger in size but remain very light, formable, & rigid [20]-[23].

Small thermocol balls (0.75 - 1 cm diameter) are being used as a substitute of pumice stone in garments finishing process [24] [25].

Elias et al. (2015) studied the effect of change in concentration of KMnO₄ and processing time on physico-mechanical properties of denim jeans during acid washing. It was found that the tensile strength, seam strength, stiffness and fabric weight were decreased after application of potassium permanganate with increasing processing time during washing treatment while yarn count (Ne), EPI, PPI and dimensional change were increased [26]-[28].

Solaiman et al. (2015) investigated the effect of three types of washing (enzyme, softener, Silicone) on Physical and Mechanical Properties on five types of following knitted garments: 100% cotton Single Jersey T-shirt, Slub Single Jersey T-shirt, Double Lacoste (5% Lycra) Polo shirt, Single jersey CVC (T-shirt) and PC single Jersey (T-shirt). The results showed that when enzyme wash was applied on the knit garments, it improved all the tested properties of knit garments, and it also reduced the hairy fibers from the fabric surface. Similar results were found in case of Silicone and softener wash as well [29].

However, the effect of acid wash with thermocol balls and potassium permanganate on physico mechanical properties on knitted garments was not studied in the past research. In this present study, three knitted garments (Single Jersey 100% Cotton T-shirt, Single Jersey 95% Cotton 5% Spandex and 1 × 1 Rib100% Cotton T-Shirt) were washed with H₃PO₄, KMnO₄ along with thermocol balls and various properties were analyzed according to standard methods.

2. Materials and Methods

2.1. Garments Samples

Following three types of reactive dyed knitted garments were used for this research:-

1) Single Jersey (S/J) T-Shirt (100% cotton), GSM 140;
2) Single Jersey (S/J) T-Shirt (95% Cotton 5% Spandex), GSM 159;
3) 1 × 1 Rib T-Shirt (100% Cotton), GSM 138.

2.2. Chemicals

Phosphoric acid (H₃PO₄, Yalong, China) and potassium permanganate (KMnO₄, GC, China), Jet (an anionic detergent, Bangladesh).

2.3. Washing Machine

- Before Brand Name—Ngai Shing Development Limited;
- M/C capacity-20 kg;
- RPM (Revolution per minute)—30 - 33 rpm;
- Origin—Hong Kong.
2.4. Acid Washing

At first make a solution (5% phosphoric acid and 15 g/L potassium permanganate)

↓
Thermocol balls are taken into the washing machine
(Thermocol balls 0.1% on the weight of garment)

↓
Sprinkle the solution into the machine

↓
Run the machine for 5 min
(For ensuring all the balls get wetted completely)

↓
Load the garments into the machine and washing process carried out for 15 min at normal temperature

↓
Unload the garments from the machine

↓
Cold wash by automatic washing machine (Front loading)
Detergent 1 gm/L (For 10 min at 30˚C temperature)

↓
Drain the bath

↓
Neutralization with Sodium metabisulfite (3 gm/L for 5 min at 45˚C)

↓
Drain the bath

↓
Unload the garments on trolley

↓
Hydro extracting

↓
Drying the garments (By tumble dryer for 15 min at 70˚C temperature)

↓
Washed goods

2.5. Testing and Analysis

Fabric weight was measured according to ASTM D 3776 method [30] and according to BS EN 14970-2006, stitch length was measured [31]. According to AATCC 8 standard both the dry and wet rub tests were done [32]. For absorbency testing, AATCC 79 method was followed [33]. CPI and WPI of the fabric was calculated by counting the number of the Coarses and wales contents in 1 inch of the fabric. IS 1963 method was used for this measurement [34]. According to ASTM D 2259, shrinkage of these sample garments were tested [35]. Bursting strength of samples was measured by an automatic bursting strength tester. Samples are gradually set on the diaphragm, the automatic bursting strength tester, measures time, distortion, pressure & the flow rate to burst the fabric. It was done according to ASTM D3786 [36]. AATCC 81-2006 method was used for measuring pH of the fabric [37]. Spirality (Dimensional change) was measured according to AATCC Test Method 187-2013 [38]. Pilling test of Single Jersey and Rib fabric was done according to ISO 12945-1:2001 [39]. Color fastness to washing and water were determined respectively according to ISO 105-C10 and ISO 105-E01 [40] [41].

3. Results and Discussions

In this article, the change of physical and mechanical properties due to the washing treatment has been investigated. The overall results are shown in Table 1. From this table, it is seen that the weight of the fabric increases for each garments. This increase is high in case of 1 × 1 Rib garments (13.76%). Actually when the knitted garments are faced with frictional action due to the thermocol balls and rotating cylinder of the washing machine, a trace of solution of KMnO₄ and H₃PO₄ also get penetrated into the fiber structure causing change in internal
Table 1. Effect of acid wash on physical properties of different cotton knitted garments.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Single Jersey 100% Cotton T-Shirt</th>
<th>Single Jersey 95% Cotton 5% Spandex T-Shirt</th>
<th>1 × 1 Rib 100% Cotton T-Shirt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before Wash</td>
<td>After Wash</td>
<td>Before Wash</td>
</tr>
<tr>
<td>Fabric Weight (GSM)</td>
<td>140</td>
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<td>159</td>
</tr>
<tr>
<td>Bursting Strength (KPa)</td>
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<td>332.1</td>
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</tr>
<tr>
<td>Coarse Per Inch (CPI)</td>
<td>50</td>
<td>52</td>
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<tr>
<td>Wale Per Inch (WPI)</td>
<td>34</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>pH</td>
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<td>7</td>
<td>8</td>
</tr>
<tr>
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<td>4.5</td>
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<tr>
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<td>4</td>
<td>4.5</td>
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<tr>
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<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Colorfastness to Water</td>
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<td>44</td>
<td>39</td>
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<td>Water Absorbency (Sec)</td>
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<td>4.5</td>
<td>4.5</td>
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<tr>
<td>Colorfastness to Washing</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
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<tr>
<td>Stitch Length (mm)</td>
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<td>2.95</td>
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<tr>
<td>Shrinkage (%) Lengthwise</td>
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<td>2</td>
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<tr>
<td>Shrinkage (%) Widthwise</td>
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<td>2</td>
<td>2</td>
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<tr>
<td>Pilling Resistance Warp</td>
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<td>4.5</td>
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</tr>
<tr>
<td>Pilling Resistance Weft</td>
<td>4.5</td>
<td>4.5</td>
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</table>

tension in the constituted molecules. The garments then tended to revert its more dimensions that results in the contraction of the yarns. This effect causes the reduction of the stitch length also increase stitch density for higher value of CPI and WPI. Thus weight of the garments, spirality and shrinkage increase after washing.

It is also found that the acid washing treatment of the knitted garments causes significant decrease in tensile strength (bursting strength). Maximum strength loss (6.31%) occurred in case of 100% cotton single jersey T shirt. At first thermocol balls with solution breaks the chemical bond of the primary wall of the cellulose molecules and after that it attacked slightly on secondary wall. The result of this reaction is that the primary wall of the cotton fiber is loosened and broken down quicker with the mechanical forces of washing machine and rough surface of thermocol balls. As a result, internal bonding force among the molecules of the cellulose gets reduced which causes lower tensile strength. No significant change was occurred in fabric pH as mild concentration of acid was used.

It is also found from the table that color fastness properties against washing, water and dry rubbing were unchanged while wet rubbing property is deteriorated a bit. After washing, absorbency reduced as the treatment changes the interfacial tension of the fiber molecules. The washed garments showed better pilling resistance.

4. Conclusion

Acid washing treatment with thermocol balls has greater effect on the physical and mechanical properties of knitted garments. In every case, it was found that the weight of the garments increased but bursting strength decreased after washing. This experiment will help the personnel related with the industrial washing process as well as researcher in this field. Although we conducted this experiment on single jersey and rib fabric only, similar results might be found for other knitted structure.

References


Investigation into the Effect of Extended Laundering on the KES-F Mechanical Properties of an Easy Care Treated Cotton Fabric

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Abstract

The effect of extended laundering on cotton fabric treated with Dimethylol dihydroxyethyleneurea (DMDHEU) easy care finish was investigated and the fabric characterised by crease recovery performance and the Kawabata Evaluation System for Fabrics (KES-F). The KES-F results indicated that the mechanical handle properties of the DMDHEU treated cotton fabrics were affected by both the levels of application of the DMDHEU easy care finishes and the stress relaxation of the fabrics in aqueous conditions.

Keywords

DMDHEU, Extended Laundering, KES-F, Cotton Fabrics, Easy Care

1. Introduction

Dimethylol dihydroxyethyleneurea (DMDHEU) is applied to cotton fabrics in order to impart easy care properties such as crease resistance/recovery and dimensional stability. However generally the crease recovery performance is improved at the expense of strength loss and increased shear and bending rigidity [1]-[7]. Some of the detrimental effects of the easy care finish on the mechanical properties of the cotton fabrics can be reduced by incorporating softeners in the easy care formulation [8] [9]. In order to overcome the disadvantages of the DMDHEU easy care finishes, extensive research has focused on the polycarboxylic acids based easy care finishes and improved strength recovery has been reported [10]-[20]. However, DMDHEU still dominates the textile finishing due to its outstanding durability and low cost which attracts more attention.

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Previous studies on the wash durability of the DMDHEU treated cotton fabrics as assessed by the crease recovery angle (CRA) performance and surface and bulk analysis indicated that the DMDHEU easy care finish applied to cotton garment is durable almost for the entire life of the garment [21]. An investigation on the wash durability of the DMDHEU on domestic laundering machines and wet cleaning conditions indicated that the easy care finish is less durable on domestic laundering machine than wet cleaning conditions due to the aggressiveness of the former. During the study, the hand (tactile) properties of the fabrics were only evaluated based on the coefficient of friction and geometrical roughness using the KES-F system. The surface friction of the investigated fabrics was found to be higher for the domestic laundering than wet cleaning conditions due to fibrillation tendency of the substrates in former. The effects of DMDHEU concentrations on the hand properties were not considered [22].

In current study, the effects of extended laundering of DMDHEU treated cotton fabric on the fabric’s mechanical properties as determined by the Kawabata Evaluation System for Fabrics (KES-F) were investigated.

The KES-F system was developed in Japan by a group led by Professor S. Kawabata in 1968 and came into operation 10 years later [23]-[26]. Originally the system was developed for objective evaluation of fabric “handle”, and was also commonly used for product/process development, process control and optimisation. The KES-F technique measures the fabric mechanical and surface properties, Table 1, at load levels typical of normal human handling and end-user applications and the objective measurements are correlated to subjective handle properties of the material. The acquired handle properties such as fullness, smoothness and stiffness can objectively be compared and adjusted for quality and performance control purposes. Fabric making up performance can be controlled by predicting problems such as seam pucker from the KES-F fabric “fingerprint” and fabric drape and other end-use characteristics can also be predicted from the objective measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tensile linearity</td>
<td>LT</td>
<td>-</td>
</tr>
<tr>
<td>Tensile energy per unit area</td>
<td>WT</td>
<td>gf.cm/cm²</td>
</tr>
<tr>
<td>Resilience</td>
<td>RT</td>
<td>%</td>
</tr>
<tr>
<td>Extension at specific load</td>
<td>EMT</td>
<td>%</td>
</tr>
<tr>
<td><strong>Shear</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear stiffness</td>
<td>G</td>
<td>gf/cm.deg</td>
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<tr>
<td>Hysteresis at 0.5°</td>
<td>2HG</td>
<td>gf/cm</td>
</tr>
<tr>
<td>Hysteresis at 5°</td>
<td>2HG5</td>
<td>gf/cm</td>
</tr>
<tr>
<td><strong>Bending</strong></td>
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<td></td>
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<tr>
<td>Bending stiffness</td>
<td>B</td>
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<tr>
<td>Hysteresis width</td>
<td>2HB</td>
<td>gf.cm</td>
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<tr>
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<tr>
<td>Energy of compression</td>
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<td>Resilience</td>
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<td>Compressibility</td>
<td>C</td>
<td>%</td>
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<tr>
<td><strong>Thickness and weight</strong></td>
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<td></td>
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<tr>
<td>Thickness under a force of 0.5 gf/cm²</td>
<td>To</td>
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<tr>
<td>Weight</td>
<td>W</td>
<td>mg/cm²</td>
</tr>
<tr>
<td>Thickness under a force of 50 gf/cm²</td>
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<td><strong>Surface</strong></td>
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<tr>
<td>Coefficient of friction</td>
<td>MIU</td>
<td>-</td>
</tr>
<tr>
<td>Mean deviation of MIU</td>
<td>MMD</td>
<td>-</td>
</tr>
<tr>
<td>Geometrical roughness</td>
<td>SMD</td>
<td>µm</td>
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</tbody>
</table>
Previous work suggested that the KES-F tests may be used for investigating the mechanical changes of fabrics during wet processing and it was reported that fabric laundering reduces stiffness and increase smoothness, softness and fullness of processed cotton fabrics [26]. The KES-F test was used to assess the effects of fabric raisings on comfort, hand and mechanical properties of artificial suede. The increased number of raisings caused the suede to have a soft and smooth surface and improved perception of luxuriousness [27]. The hand properties of woven and knitted fabrics were investigated using the KES-F and frictional analyser tests and the KES-F results indicate that there is a good correlation between friction and tactile properties for knitted fabrics but not for woven fabrics [28]. Furthermore the Kawabata system was applied on investigation on the effects of fabric movements in front-loading washers on hand properties. The study established a relationship between fabric movements and hand properties and the relationship could be used by the washing machine manufacturers on design of washing programmes of various types of garments [29]. The Kawabata system has also been tested and recommended for the paper industry for the determination of objective mechanical properties which can be used to translate the subjective handle properties such as softness/smoothness [30]. KES-F was used for investigating the performance of the TiO2 as an easy care finishes for cotton material [31].

In this paper the effects of extended laundering, with perborate and a non-perborate detergent, on the KES-F handle properties of the DMDHEU treated cotton fabrics was investigated.

2. Methodology

2.1. Materials

Scoured, bleached, 100% plain woven cotton fabric, 152 g/m² was supplied by Phoenix Calico, UK. Fixapret CP New (dimethylol dihydroxyethyleneurea, DMDHEU) was supplied by Dystar, UK. Magnesium chloride was supplied by Fisher Scientific, UK. The ECE non-phosphate detergent, ECE phosphate detergent and Tetra Acetylethylene Diamine (TAED, 92% active) were purchased from the Society of Dyers and Colourists (SDC), Bradford, UK. Sodium Perborate Tetrahydrate (97%) active was purchased from Aldrich Chemicals Ltd., UK.

2.2. Treatment Conditions

Aqueous solutions of DMDHEU, 60, 100 and 140 g/L, and magnesium chloride, 12 g/L, 20 g/L and 28 g/L, respectively, were padded onto the cotton fabric at 80% wet pick up. The magnesium chloride was included in the padding solution as a catalyst during curing. The padded fabrics were oven dried for 2.5 minutes at 100°C with subsequent curing for 4 minutes at 150°C. The cured fabrics were rinsed in warm water to remove any finish residue and then air dried for further tests.

Untreated and DMDHEU treated cotton fabrics were repeatedly laundered, up to 10 cycles, in a Wascator FOM 71 MP washing machine using the 5A wash cycle programme. The machine complies with British Standards for domestic washing and drying testing procedures, BS EN ISO 6330:2001 + A1:2009. The washing was performed with 12.5 g of ECE non phosphate detergent in the presence and absence of 30 g sodium perborate and 4 g of TAED per wash.

2.3. Crease Recovery Angle (CRA) Analysis

The crease recovery of the fabrics was determined using the British Standard test method, BS EN 22313:1992 [32], with at least ten replicates performed in both and the mean for both warp and weft (W+F) reported.

2.4. Kawabata System Evaluation for Fabrics (KES-F) Analysis

The samples, 20 cm × 20 cm, were conditioned at 65% R.H. and 20°C for 24 hrs prior to testing. In this work only the tensile, shear, bending and compressional properties were analysed. The results presented were the average of three measurements taken along the warp and weft directions of the tested fabrics.

3. Results and Discussion

Examination of the CRA performance of the cotton fabrics treated with DMDHEU easy care finish indicates the CRA performance increased with an increase in application of DMDHEU, Figure 1. When the DMDHEU treated cotton fabric was laundered both with/without perborate there were marginal decreases in the CRA
performance in the concentration range of 60 - 100 g/L DMDHEU, but the decrease did not reach the level of the control cotton fabric (0 g/L DMDHEU). This observation agrees with the previously reported information that the DMDHEU is durable even after extended laundering [21]. While the decrease in CRA performance with the number of washes was relatively small in the 0 - 100 g/L range, the decrease was more obvious at the 140 g/L DMDHEU application level, Figure 1. The nature of this phenomenon was discussed in detail in a previous study where the type of cellulosic crosslink introduced at varying levels of DMDHEU treatment was investigated.

Figure 2 presents the effect of extended washing on the extensibility (EMT) of the untreated and DMDHEU treated cotton fabric, as measured by the KES-F system. Treatment of the cotton fabric with increasing concentration (60 - 100 g/L) DMDHEU produced an increase in the fabric extensibility. In contrast application of DMDHEU at 140 g/L decreased the fabric extensibility below that of the untreated cotton. Fabric extensibility depends on the flexibility of the cellulose chain molecules to move. Application of DMDHEU crosslinks the cellulose chain molecules and thus restricts the mobility of the chains, while the aqueous padding of the fabric results in fabric relaxation and increased the fabric extensibility at 60 - 100 g/L levels. At 140 g/L DMDHEU the fabric relaxation effect cannot overcome the crosslinking effect, thus a measurable decrease in extensibility was observed. Subsequent Wascator washing relaxes the fabric, breaks bonds and increased EMT. Perborate washing caused greater oxidative damage and hence reduced EMT marginally less relative to the non-perborate washing.

The effect of repeated laundering on untreated fabric was to increase the fabric thickness and compressibility, Figure 3 and Figure 4. This increase was probably due to the fibrillation of the fibres and the formation of hairier and bulkier fabrics and stress relaxation of the fabric during washing. The effect of initial washing with perborate on the thickness of the fabrics treated with DMDHEU concentration was to reduce the fabric thickness $T_m$ and $T_w$, Figure 3 and Figure 4. This reduction in fabric thickness with the perborate wash treatment was probably due to its oxidative degradative effect preferentially removing embrittled surface fibres. Subsequently further fibres are able to become disengaged with the yarn structure, create a surface layer of protruding fibres and fabric thickness increased.

The effect of increasing DMDHEU application level was overall to increase the fabric rigidity above that of the untreated fabric, Figure 5. However with the 60 - 100 g/L applications the bending rigidity actually decreased due to the fabric relaxation effect outweighing the crosslinking effect of the formaldehyde-based
crosslinker. Application of DMDHEU at the 140 g/L level increased the bending rigidity above the untreated cotton value due to the crosslinking. In general subsequent laundering relaxed the fabric, broke internal bonds and decreased the bending rigidity. Little difference between the perborate wash and non-perborate washings was observed.
Figure 4. Effect of repeated washes, A—unwashed, B—one wash with perborate, C—ten washes with perborate, D—one wash without perborate, E—ten washes without perborate, on the thickness (T₀).

Figure 5. Effect of repeated washes, A—unwashed, B—one wash with perborate, C—ten washes with perborate, D—one wash without perborate, E—ten washes without perborate, on the bending rigidity.

Figure 6 illustrates the effect of increasing DMDHEU treatment levels of cotton fabric and extended washing on the shear stiffness (G) of the cotton fabric as measured by the KES-F system. Application of DMDHEU at 140 g/L increased G due to crosslinking of the cellulose chain molecules within the fibre/yarn. Below this level the effect of aqueous padding relaxing the fabric predominated and decreased G. At 60 - 100 g/L the crosslinking was counteracted by this relaxation. Subsequent Wascator washing relaxed the fabric, broke bonds and de-
creased $G$ for the 140 g/L application and untreated cotton fabrics. For other application levels washing increased $G$ and again little difference between perborate wash and non-perborate washing was observed.

Figure 7 presents the effect of DMDHEU concentration and extended Wascator washing on the shear hysteresis (2HG5) of the cotton fabric as measured by the KES-F system. Application of DMDHEU at 140 g/L increased 2HG5 due to crosslinking of cellulose chains in the fibre. Below this level aqueous padding relaxed the fabric and decreased 2HG5. At 60 - 100 g/l the crosslinking/embrittling effect was counteracted by this relaxation. Subsequent Wascator washing relaxed the fabric, breaks bonds and decreased 2HG5 for the 140 g/L application and untreated fabric. For the other fabric treatments washing increased 2HG5 probably due to fibre surface modification increasing inter-fibre frictional interactions. Little difference between perborate wash and non-perborate washing was observed.

Figure 6. Effect of repeated washes, $A$—unwashed, $B$—one wash with perborate, $C$—ten washes with perborate, $D$—one wash without perborate, $E$—ten washes without perborate on the shear rigidity.

Figure 7. Effect of repeated washes, $A$—unwashed, $B$—one wash with perborate, $C$—ten washes with perborate, $D$—one wash without perborate, $E$—ten washes without perborate on the shear hysteresis at 5° shear angle.
Re-examination of the effect of repeated Wascator washing on the CRA performance, Figure 1, bending properties, Figure 5 and Figure 6 and shear properties Figure 7 indicated that the 140 g/L DMDHEU treated cotton has the relatively largest decrease in CRA performance, bending and shear rigidity properties when compared to 60 - 100 g/L DMDHEU after repeated washing. Previous research has demonstrated that crosslinking of cotton fabrics with DMDHEU concentrations at lower than 140 g/L favours tri- and tetra-functional crosslinks and the crosslinks are stable to extended laundering. However DMDHEU application at 140 g/L is dominated by unstable bi-functional crosslinks [21]. Hence the measurable decrease in CRA performance, bending and shear properties of the cotton 140 g/L DMDHEU treated, washed cotton fabric may be explained by the bi-functional crosslinks which are unstable to repeated Wascator washing and are prevalent at this higher application levels. Therefore the optimal application levels of DMDHEU easy care finish in cotton fabrics is anticipated to be in 60 - 100 g/L.

4. Conclusion

Cotton fabrics were treated with DMDHEU at increasing concentration and the effect of extended laundering on the cotton fabric treated with DMDHEU easy care finish was investigated. The presence and durability of the easy care finish on the cotton fabric was monitored using the CRA performance. The CRA performance test results indicated that DMDHEU treatment at (0 - 100 g/L) was stable to extended laundering conditions, however the 140 g/L treatment was significantly affected by the extended laundering conditions and can be explained by the nature of crosslinking between cellulose polymer and DMDHEU at varying concentrations. The KES-F results indicated that the handle properties of the DMDHEU treated cotton fabrics were affected by both the level of application of the DMDHEU easy care finish and the stress relaxation of the fabrics in aqueous conditions. It was evident that the presence of perborate in the wash formulation had relatively little effect on the fabric handle properties above that observed with laundering with the non-perborate formulation.

References


A New Approach for Machine Gauge & Production Calculation of Various Kinds of Rib and Interlock Knitted Fabric Structure

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Abstract

Various types of rib and interlock fabrics found in the market depend on their structure such as 1 × 1 rib, 2 × 1 rib, 2 × 2 rib, 3 × 1 rib, 3 × 2 rib, 4 × 1 rib, 4 × 4 rib and 1 × 1 interlock, 2 × 2 interlock etc. These all types of fabric can be possible to knit in circular knitting machine after machine setting. When these fabrics are knit on the machine, some needles are needed to drop or withdrawn from needle groove according to their design such as 1 × 1, 2 × 1, 2 × 2 etc. Due to needle dropping or withdrawing production per hour will changed as production per hour directly depends on the No. of active needle. No. of needle or active needle depends on machine gauge. This paper gives a new approach for machine gauge which is somewhat different from other thinking. This paper also shows the production calculation formula with their machine setting for various rib and interlock fabric with their derivation. By this paper, one can easily understood about machine gauge and calculated production of any type of rib and interlock knitted structure. Complexity of calculating production can be reduced by this paper.

Keywords

Machine Gauge, Production per Hour, Formula, Rib, Interlock, Fabric

1. Introduction

Knitting is the second most popular technique of fabric or garment formation by inter-looping one or one set of yarns. Continuous length of yarn is converted into vertically intermeshed loops either by hand or by machine in knitted fabric [1]. Knitted fabric can be classified into two main categories such as warp knitted fabric and weft knitted fabric. Due to higher production, lower cost and easy installment demand of weft knitted fabric increas-
ing day by day. For the weft knitted fabric production, two main knitting machines are used such as flat bed knitting machine and circular knitting machine. But in worldwide, circular knitting machines are widely used because higher production and higher quality of fabric can be achieved [2]. On the basis of knitted stitches per minute against the capital cost of the machine, circular garment-length machines are generally more productive than flat bed machines for cut and sew knitwear. Prior to computer controls, the price/performance ratio was 1:3 in favor of body-width circular machines [3]. The term circular covers all those weft knitted machines whose needle beds are arranged in circular cylinder and dials or only in cylinder including latch, spring bearded and very occasionally compound needle machinery, producing a wide range of fabric structures, garments, hosiery and other articles in a variety of diameters and machine gauges [2]. There are four weft knitted structure named single jersey, rib, interlock and purl. It is possible to produce all of these knit fabrics by circular machine after some changes. Circular machines are mainly single cylinder type for single jersey fabric, cylinder and dial type for rib and interlock fabrics and double cylinder types for purl fabrics [3]. Single jersey is the simplest structure among four basic wefts knitted structure. Due to machine complexity, higher cost and lower demand uses of purl structure decreases day by day. On the other hand, uses of rib and interlock structure increase day by day. Many types of rib structures can be produced according to the arrangement of needles in the cylinder and dial bed [2], such as $1 \times 1$, $2 \times 1$, $2 \times 2$ etc. Also interlock structures can be produced in many types such as $1 \times 1$, $2 \times 2$, $3 \times 3$ etc. Production of knitted structure is totally mathematical based depends on various factors. Machine gauge is one of the important factors among them. It is very important for the knitter to calculate the productivity of a machine in order to be able to schedule production and specify the delivery dates to the customer [4]. It is very easy to calculate the production of single jersey and $1 \times 1$ rib fabrics. There are some problems associated due to machine setting when knitters going to calculate the production of other rib and interlock structures. This paper is going to show the production calculation formula for various rib and interlock structure.

2. Related Term

**Machine gauge:** The machine gauge of knitting machines is a measure expressing the number of needles per a unit (normally 1 inch) of the needle bed width or circumference [2] [3]. Machine gauge is defined in various units (systems) in various countries. Definition of gauge also depends on the types of knitting machines. Most popularly, it is defined in English system as the number of needles per inch [1].

**Machine diameter:** The diameter of knitting machines is measured at the bottoms of the two opposite needle grooves in a cylinder or at the top of the two opposite needles in a circular bar and is usually expressed in inches [2].

**Number of feed system or feeder:** On the circumference of a circular knitting machine up to 120 knitting cam sets can be mounted, each cam set fed with a separate yarn. This results in obtaining 120 knitted loop courses in one machine revolution [2].

**Stitch length:** The length of yarn knitted into one stitch in a weft knitted fabric [2].

3. Materials & Method

**Rib circular latch needle machine:** There are two circular needle beds on this type knitting machine such as cylinder bed and dial bed. Latch needle cylinder dial revolve through the stationary cam system. In this machine, there is one set of needles on the circumference of a vertical cylinder and a second set of needles, arranged perpendicular to the first set and mounted on a horizontal dial [2]. In rib gating each cylinder needle is neighbored by a dial needle and they are offset with respect to each other such that when both sets move forward to catch yarn, each cylinder needle passes through the gap between two neighboring dial needles [5]. A 30 gauge circular knitting machine is consider suitable for the production of $1 \times 1$ rib fabric and approaching the machine gauge newly.

**Interlock circular latch needle machine:** In case of conventional interlock machine, both the needle bed contains one short butt and one long butt needles once after another. But in modern machine the needles are of the same length [2]. With an interlock gating the two interlocking ribs are knitted with a phase difference by two neighboring feeders [5]. In interlock gating, the needle in two beds must be exactly opposite to each other so only one of the two can knit at any feeder [3].

**Machine setting for $2 \times 1$ rib machine:** A $1 \times 1$ rib gating in which each cylinder needle is neighbored by a dial needle and they are offset with respect to each other such that when both sets move forward to catch yarn,
each cylinder needle passes through the gap between two neighboring dial needles. When this 1 × 1 rib machine is converted for 2 × 1 rib fabric, one needle is dropped after every two needles from both of the needle bed. Needle can be dropped by using miss cam or withdrawn of needle from the needle groove.

**Machine setting for 2 × 2 rib fabric:** When 1 × 1 rib machines is converted for 2 × 2 rib machine, two needles are dropped after every two needles from both of the needle bed.

**Machine setting for 3 × 2 rib fabric:** For 3 × 2 rib fabric machine setting, two needles are dropped after every three needle from both of the needle bed.

**Machine setting for 3 × 3 rib fabric:** When 1 × 1 rib machines is converted into 3 × 3 rib machines, three needles are dropped after three needle from both of the needle bed.

**Machine setting for 4 × 1 rib fabric:** For 4 × 1 rib fabric machines, one needle is dropped after every four needle from both of the needle bed.

**Machine setting for 4 × 4 rib fabric:** For 4 × 4 rib fabric machines, four needles are dropped after every four needle from both cylinder and dial bed.

**Machine setting for x × y rib fabric:** Here x denoted the no. of face loop and y denoted the no. of back loop. y no. of needles is needed to dropped or withdrawn after x no. of needles for this type of fabric.

**Machine setting for 1 × 1 interlock fabric:** In this case, needles of both beds operate consecutively and then after a certain delay on the passive needle bed. The active needle bed is that which receives the yarn for forming loops from the yarn carrier. That means the time of knitting operation fifty percent needles are active and rest fifty percent are inactive. In next knitting cycle previously inactive needles are active and previously actives are inactive.

**Machine setting for 2 × 2 interlock fabric:** When 1 × 1 interlock machines are converted for 2 × 2 interlock machines, two needles are dropped after every two needle. Needles can be dropped by using miss cam or withdrawn of needle from the needle groove. 2 × 2 interlock machine runs by maintaining same principle of 1 × 1 interlock machines.

**Machine setting for x × y interlock fabric:** Here x and y denoted no. of face and back loop respectively. When any interlock machine converted for this type of structure y no. of needles are needed to dropped or withdrawn after x No. of needle. Operating principle is same as any other interlock fabric.

### 4. Results & Discussion

**New Approach for Machine Gauge:** Appropriately machine gauge is the total number of needle grooves of tricks per unit length (normally 1 inch). It can be also defined as the capacity of carrying total no. of number of needles per inch. It is somewhat same to the old concept. For an example, A 30 gauge circular knitting machine is running with 1 × 1 rib fabric machine setting. That means the machine has 30 needles in 1 inch and also 30 needle grooves. When this machine is converted for 2 × 1 rib fabric, it has been needed to drop or withdrawn 1 needle after every 2 needle from both of the needle bed. In this case, no. of needle is 20 in 1 inch length where needle grooves remains 30. But the machine is 30 gauges for all time and for all of the structures.

**Production Calculation:** If all needle grooves are filled by needle,

\[
\text{Total number of needle} = \pi \times \text{Machine diameter} \times \text{Machine gauge}
\]

\[
\text{Total number of stitches produced per hour} = \text{No. of needle} \times \text{RPM} \times 60 \times \text{No. of feeder} \times \text{efficiency}
\]

\[
\text{Length of yarn converted into stitches per hour} = \text{Total no. of stitch produced per hour} \times \text{stitch length}
\]

\[
\text{Weight of yarn converted into fabric in lbs} = \frac{\text{Length of yarn converted into stitches per hour in yards}}{840 \times \text{Yarn count (Ne)}}
\]

So the formula of production will be,

\[
\text{Production per hour in lbs} = \frac{\pi \times \text{Machine dia} \times \text{Gauge} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency}}{840 \times \text{Yarn count (Ne)} \times 36}
\]
**For 2 × 1 rib fabric:** In 2 × 1 rib machines one needle is dropped after every two needles so that two third of total needles are active in the machine.

Production per hour in lbs

\[
\frac{\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{2}{3} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency}}{840 \times \text{Yarn count (Ne)} \times 36}
\]

**For 2 × 2 rib fabric:** During machine setting of 2 × 2 ribs gating two needles are dropped after every two needle. So, two fourth or half of total needles are active.

Production per hour in lbs

\[
\frac{\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{1}{2} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency}}{840 \times \text{Yarn count (Ne)} \times 36}
\]

**For 3 × 2 rib fabric:** In 3 × 2 rib gating two needles are dropped after every three needle so that three fifth of total needles are active and rest are inactive.

Production per hour in lbs

\[
\frac{\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{3}{5} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency}}{840 \times \text{Yarn count (Ne)} \times 36}
\]

**For 3 × 3 rib fabric:** Three needles are dropped after every three needle for 3 × 3 rib gating. So that three sixth or half of total needles are active in the machine.

Production per hour in lbs

\[
\frac{\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{1}{2} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency}}{840 \times \text{Yarn count (Ne)} \times 36}
\]

**For 4 × 1 rib fabric:** During the time of 4 × 1 rib machine setting one needle is dropped after every four needle. So that four fifth of total needles are active.

Production per hour in lbs

\[
\frac{\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{4}{5} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency}}{840 \times \text{Yarn count (Ne)} \times 36}
\]

**For 4 × 4 rib fabric:** For 4 × 4 rib fabric machine setting, four needles are dropped after every four needles. So, half of total needles are active in the machine.

Production per hour in lbs

\[
\frac{\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{1}{2} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency}}{840 \times \text{Yarn count (Ne)} \times 36}
\]

**For x × y rib fabric:** For x × y rib fabric machine setting, y no. of needles is dropped after every x no. of needles. So, x off 1/x + y No. needles is active and rest is inactive.

Production per hour in lbs

\[
\frac{\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{x}{x + y} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency}}{840 \times \text{Yarn count (Ne)} \times 36}
\]

**For 1 × 1 interlock machine:** During interlock fabric production at a time fifty percent needles are active and rest fifty percent are inactive. There is no need to drop any needle for 1 × 1 interlock fabric.
Production per hour in lbs
\[
\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{1}{2} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency} \\
= \frac{840 \times \text{Yarn count (Ne)} \times 36}{4 \times \text{No. of feeder}}
\]

For 2 × 2 interlock fabric: For the machine setting of 2 × 2 interlock fabric 2 needles are needed to drop after every two needle from both of the bed. For this reason half of total needles are present in the machine and acting as working needle. Again fifty percent or half of total present needles are working at a time.

Production per hour in lbs
\[
\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{1}{2} \times \frac{1}{2} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency} \\
= \frac{840 \times \text{Yarn count (Ne)} \times 36}{4 \times \text{No. of feeder}}
\]

For x × y interlock fabric: For x × y interlock fabric machine setting, y no. of needles is dropped after every x No. of needles from both of the needle bed. So, x off 1/x + y No. needles is active and rest is inactive. In one knitting cycle fifty percent of total active needles are working. In second knitting cycle rest fifty percent needles are working. So, in every knitting cycle fifty percent of total active needles are working.

Production per hour in lb
\[
\pi \times \text{Machine dia} \times \text{Gauge} \times \frac{x}{x + y} \times \frac{1}{2} \times \text{RPM} \times \text{No. of feeder} \times \text{Stitch length (inch)} \times \text{Efficiency} \\
= \frac{840 \times \text{Yarn count (Ne)} \times 36}{4 \times \text{No. of feeder}}
\]

No. of active needles present in the machine directly influence the production per hour of knitting machine. Increasing the No. of active needle in the machine increases the production of this machine. According to this and also according to the formula 1 × 1 interlock fabric production is half of 1 × 1 rib production. But in practically 1 × 1 interlock fabric productions are slightly decreases than 1 × 1 rib fabric. Because in case of interlock fabric production higher machine speed (RPM) than rib fabric can be achieve. Machine speed (RPM) depend on various factors such as type of fabric, fabric quality, yarn quality, machine condition etc. If RPM are constant for all types of fabric than production are decreases with the design variability of fabric.

5. Conclusion

Machine gauge is an important factor for any particular structure and also for calculation of production. Appropriate approach of machine gauge may need to be use for calculation of production mathematically. The values which are used in the production calculation have influences on the production of knit fabric. On the other hand, yarn quality and fabric quality also influenced the knit fabric production. All the values can be constant without total No. of active needle present in the machine. If design of fabric needed to be changed, No. of needles must be dropped and production fabric decreases. Production of fabric has directly influenced the cost of fabric. Higher the fabric production means lower of cost and vice versa. In those cases, cost of fabric will be changed with the design variability of fabric such as 2 × 1, 2 × 2, 3 × 1 etc. Knitting price per kg also changed as production per hour decreases. However, it is important for the knitter to calculate the production per hour in weight to deliver the products according to buyers lead time. Knitting charge also depends on the production of fabric. Lower the production means per kg production takes higher time. So, knitting charge will be changed as the changing of production per hour. This paper helps to give a new thinking about machine gauge of a knitting machine. By this paper, knitted fabric production in weight can be calculated easily. Although knitted fabric production can be calculated in length but knitted fabric is sold in market by means of weight. So calculation of knitted fabric production in weight is most important for the knitter and also for the person who are related to this sector.

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References


Iodine Sorption Value and Surface Chemical Analysis of Regenerated Cellulosic Fibres

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Abstract

The surface chemical analysis and bulk analysis were conducted for fibres regenerated from waste garments and treated with iodine solution. The aim was to assess the fibre accessibility by the iodine solution and ascertain the location of the reagent within the fibres. X-ray Photoelectron Spectroscopy (XPS) analysis indicated that the fibres regenerated from indigo dyed waste denim garments (ReCell-Denim) had a relatively high accessibility by the iodine solution compared to the standard lyocell, ReCell-1 and ReCell-2 fibres. With the exception of ReCell-Denim, the standard lyocell, ReCell-1 and ReCell-2 fibre’s iodine sorption values correlated well with the percentage crystallinity. The high accessibility of the ReCell-Denim fibres was attributed to the presence of the positively charged nitrogen from the indigo dyes that improved the substantivity of the fibres to the iodine solution. The iodine sorption of the fibres is relatively higher in the bulk compared to the fibre surface.

Keywords

Iodine Sorption Value, XPS, Bulk Analysis, Cellulose, Waste Garments

1. Introduction

Traditionally man-made cellulose fibres are produced from regenerated cellulose II by treatment of native cellulose such as high purity wood pulp with strong sodium hydroxide or physical dissolution [1]. The fibres regenerated by treatment of the pulp with strong sodium hydroxide solution are generically known as viscose fibres whereas the fibres regenerated by the solvent dissolution are generically known as lyocell fibres [1]. Lyocell fibres are commercially regenerated by the dissolution of the high purity pulp in an N-methyl N-morpholine oxide (NMMO) solution and subsequent extrusion and regeneration of the fibres. The lyocell process is preferred due to less consumption of water, less toxicity and 100% potential recovery of the solvent during the fibre making process.
process.

Although all regenerate fibres exhibit the cellulose II unit cell, the properties of the fibres above molecular level depend other factors such as the spinning conditions, [2], with density, crystallite size, crystallite orientation and pore structure of the fibres varying. Accessibility by reagents was among the properties reported to vary with the treatment history of the feed stock for fibres regenerated from cotton waste garments using the NMMO solution [3].

The accessibility of the fibres is important because it provides information on how the fibres respond to the reagents during wet processing such as dyeing. Empirically the fibre accessibility by reagents is determined by the Iodine Sorption Value (ISV) test. According to Nelson, [4] [5], the ISV test was first developed for the determination of effectiveness of mercerization process. The test were later modified and considered as an empirical test for the investigation of the structure of both natural and regenerated fibres during fibre growth [6] and regeneration processes [7], respectively. The ISV test provides an empirical estimation of the accessibility of cellulose fibres by various reagents such as dyes [4] [5]. During wet processing of cellulose fibres, the chemical reagents modify the fibre’s structure by accessing the amorphous fraction of the substrates.

The ISV test results are affected by the test temperature, duration of equilibria, the degree of agitation, reagent concentration and the method for measuring the iodine adsorbed, [5] [8], thus the data reproducibility is always not acceptable [4] [5]. If the temperature is not well controlled during the test, the ISV results may vary by up to 5%, therefore it is important to ensure constant temperature and the ISV data should specify the temperature under which adsorption occurred [8]. Despite the existing weaknesses in terms of reproducibility of the results the ISV has widely been applied on the determination of accessibility of cellulosic fibres by number of researchers [4] [5] [9]-[11]. The ISV test results were used to determine the crystallinity index of the cellulose fibres as one way of monitoring of the changes of supermolecular structure of the fibres [4] [7] [9] [10]. The iodine sorption test was also used with other techniques to investigate the relationship between sorption and accessibility properties of lyocell, viscose and modal fibres. The results indicated that repetitive washing and drying affected the pore size and pore size distribution of the cellulose fibres and its accessibility/sorption properties [11]. Structural change of cellulose fibres is more sensitive to ISV than other accessibility tests such as water retention and water sorption tests [4] [11]. Further studies suggested that water sorption and retention power could only be used as a measure of swelling ability and the accessibility of fibres to aqueous baths during wet finishing processes whereas iodine sorption is a measure of the accessibility of the fibres and of crystallinity index [10]. However the use of cellulose accessibility through the use of various reagents as a method to estimate crystallinity of cellulose has been regarded as contentious [9]. This is due to the fact that the different reagents used to determine crystallinity of fibres brought different results for the same type of fibres [12]. For instance when the adsorbed iodine is above 11% on weight of cellulose, the iodine solution tends to penetrate the crystalline regions [4]. This suggests that under certain conditions the iodine solution would access both crystalline and non-crystalline components of the cellulose polymer.

The ISV test has also been used to observe accessibility of polyester fibres following heat setting, the results indicated that as the heat setting increases, the fibres will have less sites accessed by the iodine. However if the iodine sorption test is conducted at increasing temperatures the sorption increases, due to the temperature “opening” the fibre structure and increasing the iodine diffusion into the fibre structure [13].

While previous research has concentrated on the optimization of the sorption conditions, no study has focused on optimizing the determination of the iodine adsorbed by cellulose. It is the aim of this study to investigate the ISV of selected regenerate fibres and the location of the adsorbed iodine.

X-ray Photoelectron Spectroscopy (XPS) is an analytical technique which is used to study the surface chemical composition of solids. With XPS, the sample is bombarded by X-ray beam in an evacuated chamber. The X-ray beam interacts with the substrate’s atoms, causes excitation and escape of electrons from the surface of the specimen; the electrons are collected depending on the atomic binding energies. The electrons escape from those atoms which are within the outer 10 nm of the surface of the specimen and the binding energy of the ejected photoelectron is influenced by chemical environment and oxidation state. In addition to providing qualitative information from the photoelectron binding energy, quantitative information can be obtained from the spectral intensity which provides atomic composition of the solids.

XPS is commonly used in surface chemical analysis of textile substrates. For instance XPS was used to determine the location of the flame retardants, soil repellence and easy care finishes following application of the finishes on the cotton fabrics and the results indicated that in order to understand the effectiveness of the appli-
cation of the finishes, it is necessary to determine both surface and bulk analysis of the treated fabrics due to the fact that some of the finishes react in both the surface and bulk of the substrates [14].

XPS was used to probe surface changes of the cotton substrates which were plasma treated and chemically modified with flame retardants [15]. XPS was also used to investigate the wash durability of an easy care finished cotton fabrics whereby the stability of the methylol-based easy care finishes on different wash programmes was determined. By the use of XPS it was possible to determine the type of crosslinking between the easy care finish and the cotton fabrics in relation to the crease recovery angle performance [16]. Other applications of the XPS in textiles include assessment of the stripping of the easy care finishes from cotton fabrics in order to reclaim cotton fibres for regeneration of new fibres [3] [17]. In such treatments the effectiveness of removal of nitrogen containing easy care finish was assessed by monitoring of the N(1s) atoms on the surface of stripped cotton fabrics. The stripping of polycarboxylic acid easy care finish was monitored by the -C(1s) peak intensity assigned to the -CO2H or -CO2-Cell. XPS was also used to characterise the effectiveness of silane modification by silane in order to improve fibre compatibility with the matrix during composite making [18].

This paper investigated the surface chemical composition of the fibres regenerated from cotton waste garments and determines the accessibility of the fibres by reagent by the use of ISV. Furthermore the location of the reagent in the fibres is quantified by the XPS and bulk analysis of the Iodine treated fibres.

2. Experimental

2.1. Dissolution and Spinning of Fibres

The purification, dissolution of the pulp and spinning of fibres were done based on the previously reported work [3] where in order to spin fibres the required spinning dope was prepared by mixing 300 g of 50% NMMO solution with 27 g pulp and 0.2 g n-propyl gallate using a laboratory scale mixer. The dissolution process was made possible by mixing the pulp and NMMO solution at increasing temperature and vacuum at suitable steps until the final spinning dope was composed of 9% cellulose, 13% water and 78% NMMO. For every sample the dissolution dope was checked for fibre solubility using a light microscope. The fibres were then spun from a laboratory scale spinning machine at Lenzing AG, Austria. The spinneret used had 19 holes of 100 µm in size and the spinning temperature was 115°C. The dope throughput was 0.03 g/min per hole, the air gap conditions were set at 30 mm, 24°C and 53% relative humidity. The winding speed was 25.1 m/min. and water was used to precipitate the fibres. The fibres were then oven dried at 60°C overnight prior to further analysis. The source and properties of the feedstock use for fibre making is presented in Table 1.

2.2. Determination of the ISV

The ISV of the ReCell fibres and Lyocell fibres was determined in accordance to method described by Nelson [5]. A 0.3 g specimen was placed in tared 250 mL, glass stoppered Erlenmeyer flask and weight of flask and contents was recorded. A volume of 2 mL concentrated iodine solution (which was prepared from 5 g Iodine, 40 g potassium iodide and 50 mL water) was added on the sample. The mixture was then mixed with a glass rod and the weight of the flask plus fibres plus iodine solution was recorded. After mixing the specimen with iodine, the mixture was allowed to stand for 3 minutes in order to reach sorption equilibrium between the fibres and concentrated iodine solution.

At the end of sorption equilibrium, 100 mL of saturated sodium sulphate solution (200 g/L) was added into the flask containing the fibres and iodine solution. Part of the sodium sulphate solution was used to rinse the glass rod which was used to mix the fibres with concentrated iodine solution. Then the system was stirred using

<table>
<thead>
<tr>
<th>S/No.</th>
<th>Source</th>
<th>Purification approach</th>
<th>Fibre name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cotton fabric</td>
<td>Washed 50 times using detergent, Ground into pulp</td>
<td>ReCell-1</td>
</tr>
<tr>
<td>2</td>
<td>Cotton fabrics</td>
<td>Treated with easy care finish, washed 50 times stripped in acid-alkali solution blend with 80% high purity wood pulp</td>
<td>ReCell-2</td>
</tr>
<tr>
<td>3</td>
<td>Waste denim garments</td>
<td>Washed and ground into pulp</td>
<td>ReCell-Denim</td>
</tr>
<tr>
<td>4</td>
<td>Wood pulp</td>
<td>Chemical treated pulp</td>
<td>Lyocell</td>
</tr>
</tbody>
</table>
mechanical shaker for one hour at 23°C ± 1°C. The saturated solution of sodium sulphate was added in order to remove any excess iodine which was not bound to the specimen. After addition of the saturated solution of sodium sulphate the mixture was shaken on mechanical shaker for one hour to ensure complete desorption of the excess iodine. A blank solution was prepared by similar procedure omitting the sample. After one hour of the shaking of the mixture, the solution was filtered using tared coarse-frit glass crucible. The aliquot amount of sample and blank solution were titrated with 0.02N sodium thiosulphate solution. The sample was then washed on tared crucible thoroughly with deionised water, dried in crucible at 105°C for 4 hours and finally the crucible was allowed to cool under phosphorus pentoxide and weighed to obtain the final mass of the fibres. The ISV (mgI$_2$/g cellulose) was calculated according to the Equation (1)

$$ISV = 126.91 \times N \times F \times \frac{T_s}{W}.$$  

(1)

where $T_s = T_b \times I_s/I_b$ is the mL sodium thiosulphate solution equivalent to initial iodine in aliquot of sample solution; $I_s$ is the weight of concentrated iodine-potassium iodide solution in sample solution; $I_b$ is the weight of the concentrated iodine-potassium iodide solution in blank solution; $T_b$ is the mL sodium thiosulphate solution for aliquot blank; $t_s$ is mL sodium thiosulphate solution for aliquot of supernatant filtered from sample; $F$ is aliquot factor (total volume is 102 mL; W, oven dry weight of sample in grams. Three replicates were conducted for each type of fibre and the mean reported.

Samples for XPS and bulk analysis were treated parallel to the ISV test but after adsorption/desorption of the iodine the samples were cold rinsed and air dried.

2.3. XPS Analysis

XPS analysis was performed using a Kratos Axis system spectrometer. The fibre bundles sample were cut from the middle of the specimen and attached to the sample holder using double sided tape. Monochromatic AlK$_\alpha$ X-rays (1486.69 eV) with a power of 150 W were used to irradiate the samples. A wide scan spectrum was recorded with pass energy of 160 eV from which the surface composition (C, I, N and O) was determined. High resolution Carbon (1s) spectra were recorded with pass energy of 40 eV. The binding energy (BE) values were calculated relative to the Carbon (1s) photoelectron at 285.0 eV. Charge compensation for the samples was achieved using a 4 - 7 eV electron beam at a flood current of approximately 0.1 mA, and an electrically ground 90% transmission nickel mesh screen adjacent to the fibre samples. Data analysis was performed using the CASA XPS software [19].

2.4. Elemental Bulk Analysis

Elemental analyses were performed by using a Carlo Erba instrument EA1108 Elemental Analyser. The error associated to the measurement is ±0.04%.

2.5. Wide Angle X-Ray Diffraction (WAXD) Fibre Analysis

The crystallinity of the fibres were determined from the WAXD analysis as previously explained [20] and described here under;

The Xpert Phillips (Power 45 kV and current 40 mA) instrument with a copper anode with an X-ray wavelength of 1.54060 Å was used for WAXD analysis. Scans were recorded from 1° to 30° 2θ with a step size of 0.07 with both equatorial scans acquired for aligned fibres, taking the meridional axis as the orientation reference.

In order to account for the instrument broadening contribution to the experimental peak width, the same experiment geometry was applied to a powdered silicon standard with the (111) reflection at 28.40° (2θ). The crystallinity of the fibres regenerated from cotton based waste garments and lyocell fibres were determined from the wide-angle X-ray diffraction patterns recorded perpendicular to the fibres axis. The percentage of crystalline material was calculated by the first determination of the peak height of the diffractograms at the position of the (002) plane at 2θ = 21.7° ($I_{002}$) and the peak height of the amorphous background at 2θ = 16° ($I_{am}$) and crystallinity was calculated as Equation (2).
crystallinity = \frac{I_{002} - I_{am}}{I_{002}} \times 100 \tag{2}

The WAXD crystallinity were compared to both XP and bulk iodine sorption values.

3. Results and Discussion

Examination of the wide scan surface elemental analysis of the iodine free ReCell and Lyocell fibres indicated that the surface of the fibres is rich in C and O and the XPS analysis of the ReCell-Denim fibres indicated some surface nitrogen, Table 2, which can be assigned to residual indigo dye present in the fibres. The high resolution C1(s) spectra of the ReCell and Lyocell fibres indicated that the major spectral species occurred at 285.0 eV, which was due to C-C and C-H bonding species, indicating that the surface was not pure cellulose, Figure 1. The nature of these impurities was not ascertained but some of it may be due to the purification of the feed stock, dissolution and regeneration solvents.

The nature of chemical species occurring at 285.0 eV for natural cellulose has been previously investigated and reported somewhere else [14] [16] [21] [22]. Re-examination of Table 2 indicated that the C(1s) peak intensity ratio of 286.6 eV (C-O) to 288.0 eV (C=O, O-C-O) was highest for lyocell fibres (5:1 ratio) and lowest for ReCell-Denim fibres (2.4:1 ratio). The ReCell-1 fibres indicated a relative spectra intensity ratio which is within the minimum theoretical range. The relative spectral peak intensity for ReCell-2 was 28% below the theoretical minimum and the reason for such deviation may be due to the contaminations arising during the purification of the feedstock, dissolution and regeneration solvents. Theoretically the relative spectral intensity for the C1(s), BE 286.6 eV to BE 288 eV is supposed to be 5:1 (+10%). The lower peak intensity ratio for ReCell-Denim fibres was probably due to the residual indigo dye present in the fibres and this is further confirmed by the extraordinary ISV of the ReCell-Denim fibres. It was anticipated that the ReCell-Denim fibres could have exhibited the lowest 286.6 eV (C-O) to 288.0 eV (C=O, O-C-O) spectral peak intensity due to the residual indigo dye present in the fibres; but the ReCell-2 fibres exhibited the lowest relative spectral peak intensity and the reason for such deviation is uncertain.

Table 3 shows the surface and bulk iodine content of the ReCell fibres treated in concentrated iodine solution and the WAXD crystallinity of the untreated fibres. The crystallinity of the fibres increases in the order of lyocell, ReCell-2, ReCell-1 and ReCell-Denim. The ISV for the fibres was expected to decrease as the crystallinity of the fibres increases but the ReCell-Denim was anomalous.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Fibre & Wide Scan, atomic % & C1(s) high resolution component intensity \\
& C & O & N & C-O & C=O & C-O/C=O \\
\hline
Lyocell & 76.0 & 24.0 & 0.0 & 27.4 & 5.4 & 5.1 \\
ReCell-1 & 72.9 & 27.1 & 0.0 & 34.3 & 7.9 & 4.3 \\
ReCell-Denim & 71.5 & 28.0 & 0.5 & 32.7 & 13.6 & 2.4 \\
ReCell-2 & 76.0 & 24.0 & 0.0 & 32.5 & 9.0 & 3.6 \\
\hline
\end{tabular}
\caption{XP wide scan elemental atomic composition and C1(s) BE = 286.6/BE = 288.0 eV intensity ratio for lyocell and ReCell fibres.}
\end{table}

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Fibre type & WAXD Crystallinity % & Surface iodine content,% atomic & Bulk iodine content,% atomic \\
\hline
Lyocell & 79.6 & 1.0 & 13.0 \\
ReCell-1 & 86.6 & 0.5 & 8.6 \\
ReCell-Denim & 87.1 & 1.0 & 11.2 \\
ReCell-2 & 81.7 & 0.8 & 8.0 \\
\hline
\end{tabular}
\caption{XP I(3d) surface and iodine bulk atomic composition for ReCell fibres treated with iodine solution.}
\end{table}
The results indicated that the bulk of the fibres adsorb more iodine than the surface and this supports the argument that under certain conditions the iodine sorption penetrates into the crystalline component of the cellulose [4]. The ReCell-1 fibres have the lowest surface adsorption of iodine followed by ReCell-2, ReCell-Denim and lyocell fibres. The lower surface iodine adsorption by ReCell compared to standard lyocell fibres was related to the relatively higher crystalline fraction in the former and this agrees with the previously reported findings [20]. However, despite the highest crystallinity, the ReCell-Denim exhibited higher surface iodine content than the ReCell-1 and ReCell-2 fibres, and can be explained as follows. During treatment of the fibres with iodine solution, the iodine (I\textsubscript{2}) reacts with the iodide (I\textsuperscript{-}) to form a highly soluble tri-iodide ion. In order to maintain the concentration of the iodine in the solution there is always an excess of I\textsuperscript{-} ion which with the tri-iodide ion, was adsorbed by the cellulose. The adsorption of the iodide ion is via the partially positive hydrogen atoms of the cellulose polar hydroxyl groups. The ReCell-Denim fibres also contain indigo dye which possesses partially positive charges, thus enhancing the adsorption of the iodine by the fibres. This explains the relatively high ISV of ReCell-Denim fibres relative to ReCell-1 and ReCell-2 fibres.

Blending of wood and waste cotton pulp resulted in an enriched cellulose surface thus producing an increase in the adsorption of iodine at the surface and explains why the iodine content for the ReCell-2 fibres was higher.
than ReCell-1 but lower than lyocell fibres. The bulk iodine content of the lyocell, ReCell-1 and ReCell-Denim followed the same trend as for surface XP iodine. However the exception was observed for ReCell-2 fibres with the bulk iodine content below the ReCell-1 and lyocell fibres, the reason for this behaviour is uncertain at present.

Examination of the C1(s) spectra of the fibres treated in iodine solution indicated an increase in the spectral peak intensity at 289.0 eV, Figure 2. The formation of peak associated with carboxylic acid species may be due to degradation of the fibres in acidic treatment bath or oxidation.

4. Conclusions

The surface chemical analysis and bulk analysis was conducted for fibres regenerated from waste garments and treated with iodine solution. The aim was to assess the fibre accessibility by the ISV and ascertain the location of the reagent within the fibres. XPS and bulk elemental analyses indicated that the fibres regenerated from waste denim without stripping off the indigo dye (ReCell-Denim) had a relatively high accessibility to the iodine solution compared to Lyocell, ReCell-1 and ReCell-2 fibres. The iodine sorption values of the investigated

Figure 2. C(1s) XP spectra of (a) Lyocell, (b) ReCell-1, (c) ReCell-Denim and (d) ReCell-2 fibres after treatment in iodine solution.
fibres were generally increasing as the decrease in WAXD crystallinity. The high accessibility of the ReCell-Denim fibres was attributed by the presence of the positively nitrogen from the indigo dyes that improved the ability of the fibres to attract the negatively charged iodine.

Both XPS and iodine bulk analysis demonstrated that the iodine solution was mainly contained in the bulk of the fibres. The results suggest that more study may be conducted on the possible use of XPS or elemental analyses for the determination of the iodine sorption value of cellulose fibres instead of the titration technique.

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