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Experimental Investigation of the Washing Relaxation of Knitted Fabrics from Polyester Yarn with Stainless Steel Fibres

Abstract

In order to mathematically describe the washing relaxation of knitted fabrics from man-made fibres, we performed different experiments with 50 - 100 washing cycles. While washing with detergent was shown to lead to a logarithmic increase in the fabric width, washing without detergent leads to an approximately linear increase in the fabric width, which can be transferred into logarithmic behaviour after a number of washing cycles by then adding washing detergent. Moreover, the qualitative and quantitative dimensional change was proven to depend strongly on the original dimensions of the fabric – while a knitted fabric with only a few courses shows logarithmic behaviour and significant dimensional change, an approximately square fabric broadens more linearly and less strongly. In all cases, no end value for the fabric width is reached, i.e. no fully relaxed state.

Key words: *washing relaxation, knitted fabric, stainless steel fibre yarn, detergent, fully relaxed state.*

Introduction

Understanding the relaxation of knitted fabrics is important for the optimisation of fabric quality since the dimensional change after a number of washing cycles or after a long time of dry relaxation has to be taken into account while tailoring a garment; otherwise shrinkage has to be prevented as far as possible by finishing. However, only a few articles report on investigations of the relaxation of knitted fabrics in order to find a mathematical description which could support understanding and, in a second step, simulate the processes. This paper shows a detailed analysis of up to 100 washing cycles for different washing and fabric parameters, leading to a mathematical description of the process, and presents a theoretical explanation of the experimental results.

During the knitting process, tension is implemented in the yarn. Since the yarn was straight before, it tends to return to the original state after the knitting process, which is prevented by the neighbouring stitches acting equally. Each relaxation process results from the whole system trying to reach a local energy minimum, with the absolute energy minimum – a fully relaxed state – being blocked by energy barriers (i.e. friction and the influence of the neighbouring stitches) which can only be overcome by supplying energy from outside.

Directly after being taken out of the machine, a knitted fabric starts to relax. While the dimensional change of the knitted fabric is already significant during dry relaxation – especially during the first hours after knitting – a more relaxed state can be reached by wet relaxation, immersing the fabric in water for some time and letting it dry again afterwards. Even stronger relaxation is possible in the washing process, where mechanical energy and diminished friction due to the washing detergent influence the sample at the same time.

Although the washing relaxation of knitted fabrics strongly influences the parameters required for the production process, only selective examinations of a few washing cycles are reported in literature. The dimensional change and other parameters have been examined e. g. for a variety of structures of 80% lambs wool and 20% polyamide, for one washing cycle [1]. The shrinkage of cotton fabrics has been examined for 6 laundry cycles [2] and for 5 laundry cycles after enzymatic and alkaline scouring [3].The washing relaxation has been investigated especially for Milano rib and half Milano rib with respect to the take-down tension, tightness and yarn type for 1 washing cycle [4]. Plain knitted fabrics of silk, cotton and polyester with varying cover factors [5] have also been investigated, as well as single jersey, 1×1 rib silk and cotton fabrics [6] (10 laundry cycles each). The lyocell blend has been reported to enhance washing shrinkage during 5 washing cycles [7]. Cotton/spandex single jersey fabrics from a circular knitting machine have been examined for only one laundry cycle with dry and wet relaxation as pre-treatment and boil washing afterwards, showing a similarity between dry relaxation and the behaviour after dyeing [8]. Interlock structures of cotton and core spun cotton-spandex have been examined for 10 washing cycles [9], where an approximately linear increase in the course and wale densities was observed. Experiments with more than 10 washing cycles have not been found in literature. A geometrical model introduced by Kurbak theoretically describes the dry and wash relaxed states of rib knitted fabrics [10] but does not give any information about the course of the relaxation process.

The treatment necessary to reach a fully relaxed state differs, depending on the yarn material and experimental conditions: Silk knits are reported to reach a fully relaxed state after only one laundering cycle [6] or after 10 washing cycles [11], respectively. Wool knit fabrics have been found to be fully relaxed after 10 washing and tumble dry cycles if shrink-proofed adequately [12] or after 1 cycle of wetting-out at 40 °C, briefly hydro-extracting to remove excess water, and tumble-drying for 1 hour at 70 °C [13]. A combination of high temperature and wet treatment is reported to lead to full relaxation for a wide range of natural and synthetic fibres [14].

In order to explain these different findings for the fully relaxed state and to provide a quantitative and qualitative description of the washing relaxation process, we performed dimension measurements

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after a large number of laundry cycles for different washing and fabric parameters. When such a mathematical description of the relaxation process was published previously, the dimensional change was reported to behave exponentially [15, 16]; the relation between the wet relaxed and fully relaxed state is claimed to be given by the *k* values introduced by Munden [17, 18]. Contrary to this finding, we show that for a large number of washing cycles, the relaxation behaviour can be clearly identified as logarithmic, leading to completely different extrapolations from a few washing cycles to a larger number, as well as qualitatively and quantitatively dependent on washing conditions and fabric geometry.

Experimental

The double face fabrics used in this study were produced on a flat bed knitting machine CMS-302 TC by Stoll (machine gauge E8, middle stitch length [stitch cam setting NP = 10.5], carriage speed 70 cm/s, one system). All the fabrics consisted of three fibre yarns 'S-Shield' (Nm 50/2), made by Schoeller, Bregenz (Austria), which contain 20% thin stainless steel fibres and 80% polyester fibres. The twist is for single yarn - 600 Z t/m, for the folded yarn - 425 S t/m, the tenacity is (673 ± 37) cN, and the elongation - (15.1 ± 0.8)% (yarn specifications according to Schoeller data sheet). These yarn and machine parameters resulted in knitted fabrics with initial values of (4.38 ± 0.10) wales/cm and (5.98 ± 0.17) courses/cm, a specific weight of (5.06 ± 0.10) g/dm^2 and a loop length of (0.81 ± 0.01) cm.

The special yarn used for the fabrics under examination is often used in sensory textiles, e.g. as tension or pressure sensors, but can also be used as a conductive path. Our investigation is – to the best of our knowledge – the first to deal with this special yarn and thus can be useful for any textile engineer working with this material. Moreover, the dimensional change and change in the electrical resistance of the fabrics during washing were compared. For washing, the resistance was shown to result mainly from abrasion effects, thus being unintentionally enhanced by this side effect [19]. However, despite the addition of the stainless steel fibres, the fibre yarn 'S-Shield' behaved similarly to pure polyester fibre yarns, which was verified for up to 20 washing cycles. The basic findings presented in this paper can be adopted for a variety of fabrics knitted from man-made fibre yarns.

For each series of measurements, a small ensemble of 5 nominally identical samples was examined in order to reduce uncertainty. Measurements of the width of the fabric were conducted in the middle of the fabric height in order to avoid edge effects.

Washing cycles were performed in a household washing machine with heavy-duty detergent without softener (except as noted otherwise) at 40 °C, with a subsequent spin cycle at 1200 min^{-1} (duration of washing cycle ~ 110 min). For drying, the samples were spread on a flat, smooth surface for (20 ± 2) hours at room temperature. Measurements were commenced after 1 day of dry relaxation.

Results

The first ensemble consisted of 5 samples with a width of 200 wales and height of 60 courses. ***Figure 1*** shows the average width depending on the number of washing cycles (height and thickness are not shown due to the larger relative error). While after the first washing cycle the width has changed by about 10%, it broadens by more than 50% after 100 washing cycles. A comparison with the results of the first ten washing cycles clearly proves that the relaxation process for fabrics from the special yarn under examination or similar man-made fibres cannot be ignored after ten (or even less) washing cycles.

Obviously the graph cannot be fitted with an exponential function or another function which would approach the upper limit of the fabric width, but it is described optimally by a logarithmic curve (grey line in ***Figure 1***)

$$W = W_0 + w\ln(n)$$

with the original fabric width W_0, relaxation parameter w and the number of washing cycles n.

Contrary to previously published articles claiming a 'fully relaxed state' to be reached after a number of washing cycles, such a curve does not approach any limit but grows to infinity – in the case of a real knitted fabric, it can be assumed that the end of this process is determined by the lifetime of the yarn, and that no fully relaxed state is ever reached by the normal washing process. Thus the simple approach using the constant *k* values is not viable here.

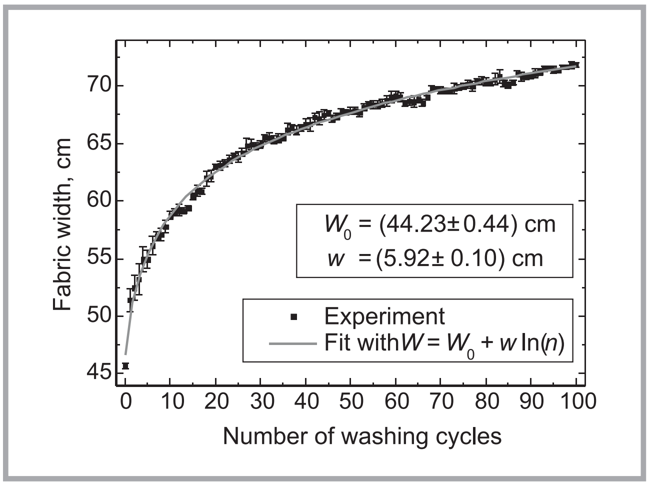

Figure 1. *Measured width of first sample series after up to 100 washing cycles, and the logarithmic fit to experimental data. The fitting equation and parameters are given in the graph.*

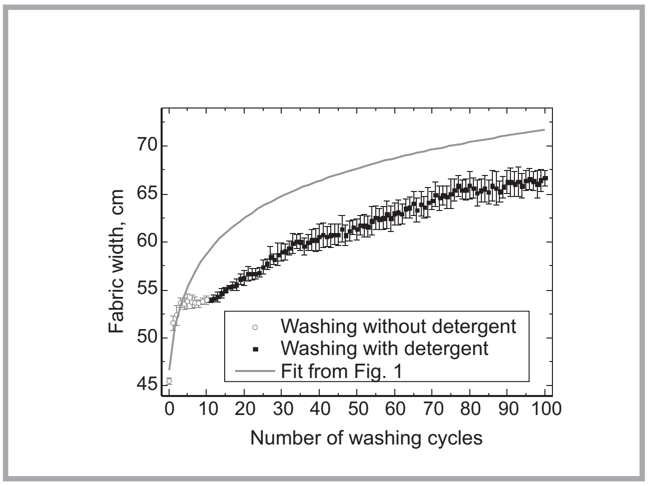

Figure 2. *Measured width of second sample series after up to 100 washing cycles, the first ten of which were performed without detergent (grey open circles), and logarithmic fit from Figure 1.*

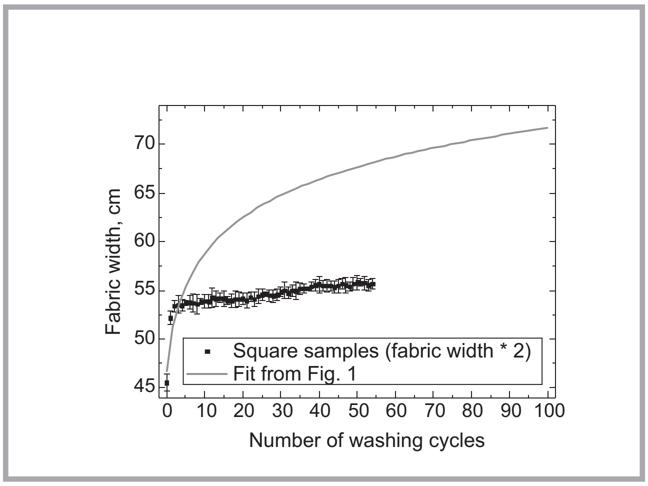

Figure 3. *Measured width of third sample series after up to 55 washing cycles and logarithmic fit from Figure 1.*

An explanation of this finding is given in the discussion below.

In order to examine the influence of the washing detergent, a second ensemble, nominally identical with the first one, was washed ten times without any washing detergent. As can be seen in ***Figure 2***, after the first few washing cycles, the experimental results were no longer consistent with those found for washing with detergent (for easier comparison, the fitting line from ***Figure 1*** is included in ***Figure 2***). Instead, the relaxation process practically stops.

After 10 washing cycles without detergent (grey open circles), the washing of the *identical* samples was repeated with detergent, starting with the 11th cycle (black squares). The relaxation process started again, following a similar shape as in the first experiment. For a larger number of washing cycles, the values get slightly closer to the fitting values from the first experiment, suggesting that after several hundred washing cycles, both values – for the first 10 washing cycles with and without detergent – become identical.

Apparently the washing detergent significantly diminishes the yarn-yarn friction coefficient during the laundry process. Since the different forces acting on the stitches within the fabric during washing cannot easily be modelled in an experiment outside the washing machine, these friction coefficients were not measured.

The effect of the original dimensions of the knitted fabrics on the relaxation behaviour were examined by comparing the previous results (for a width of 200 wales and height of 60 courses) with an ensemble of 5 samples with a width of 100 wales and height of 240 courses, produced with identical parameters to the other ensembles. After the first washing cycle, the samples were approximately quadratic.

The sample height and width were chosen quite contrary in both of the sample sizes under examination in order to point out the different types of relaxation behaviour caused by these sizes. If only a sample of typical 60 cm × 60 cm dimensions had been examined, the differing effects of washing on smaller samples would not have been detected.

This finding should not only be communicated to textile engineers in companies but also to researchers who often do not explicitly announce their sample sizes. A more exact examination of the influence of sample sizes has been conducted during the last half year after the submission of the present manuscript and is planned to be presented in a new article.

Figure 3 shows the results for more than 50 washing cycles, again compared with the fit from ***Figure 1***. Obviously the fabric width has completely different behaviour than for the differently shaped samples examined before.

The absolute values for the first ten washing cycles are similar to those measured after washing without detergent (***Figure 2***). Apparently the relaxation process is similarly "blocked" in the square samples, as has been recognised for washing without detergent. The shape of the curve seems to be approximately linear. This finding has been proven true for ensembles with different stitch lengths (smaller and larger) and with less height, down to 140 courses.

Discussion

The logarithmic shape of the curve in ***Figure 1*** is typical for stochastic systems. In such a system, each single part (here: each stitch) tends to lower its energy; however, with a certain probability a state of higher energy is taken in the next process step (here: after the next washing cycle). In this way, energy barriers can be overcome with a certain probability in order to convert the system from a local energy minimum to one with lower energy, supporting the effort of the whole system to reach the absolute energy minimum.

As the comparison of the first two measurements – with and without washing detergent – shows, the relaxation process is strongly influenced by the washing detergent. Apparently the washing detergent diminishes the friction between the yarns and thus supports the relaxation process by decreasing the energy barriers between the local energy minima. This finding can be used practically to develop a washing detergent which either supports relaxation – in order to reach a strongly relaxed state as soon as possible, before a knitted garment leaves the production company – or to suppress the relaxation process when the customer washes it.

The qualitative and quantitative influence of the original dimensions of a sample on its relaxation behaviour – which is clearly evident from comparing ***Figure 1*** and ***Figure 3*** – is unexpected for an apparently macroscopic sample. Such a dimensional dependence is only known from small-scale systems e.g. micro-magnets in different shapes. However, on second glance, a knitted fabric does indeed show similarities to microscopic systems: The number of its "elementary units", i.e. its stitches, is only of the order of 1,000 - 10,000, which is more or less comparable with a micro-magnet consisting of about 100 - 1,000 magnetic moments or other small-scale systems [20 - 22]. For the first ensemble, the height of 60 courses is of the same order of magnitude as typical diameters of nano-magnets. In this way, an apparently macroscopic knitted fabric could be used as the model for a microscopic system, since the behaviour of the sample is influenced only by the number of elementary units in the sample, irrespective of their size.

Conclusion and outlook

The washing relaxation of double face knitted fabrics from polyester fibre yarn with 20% stainless steel fibres has been shown to follow a logarithmic curve for up to 100 washing cycles. A quantitative as well as qualitative change in this behaviour is recognised when washing without detergent. Moreover, the original dimensions of the knitted fabrics have been proven to strongly influence the relaxation process.

More detailed examinations of these unexpected findings will follow. In particular the idea of a macroscopic knitted fabric as a model for a microscopic system will be examined in further experiments and compared with respective simulations.

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