Introduction

Shrinkage in textile products is neither unique to cotton nor to knitgoods. However, the potential that cotton knitgoods often have to shrink by large amounts during laundering and wear has been a consistent cause of complaint by consumers and, consequently, is a constant cause of concern for the manufacturing community.

To understand why cotton knits shrink it is useful to think about shrinkage in terms of the Shape of the knitted loop. The concept of the Reference State implies that there is a Reference Shape to the loops, i.e. a shape that will be arrived at when the fabric has been completely relaxed. Therefore, shrinkage is simply a reflection of the difference in loop shape before and after relaxation, and the study of shrinkage boils down to the study of those processes that cause the loop shape gradually to arrive at the reference shape.

These processes can be reduced to three basic types, namely:-

- Those that cause a permanent change in the shape of the loop.

  i.e. processes that determine the Reference Shape.

- Those that cause temporary deformations in the loops

  i.e. processes that determine the shape of the loop before relaxation.

- Those that tend to relax stresses so that the shape of the loop is moved closer to the Reference Shape

  i.e. relaxation processes.

Thus, for any given relaxation procedure, the amount of shrinkage that will be seen is the result of:-

- how far away the loop shape is from the Reference Shape, and
- how efficient the relaxation process is in taking the loop shape towards its Reference Shape.

Shrinkage in fabrics is the result of relaxation of strains that have earlier been imposed during the total manufacturing sequence but which have not been set during wet processing. Thus the extent to which shrinkage occurs during a given relaxation treatment depends firstly on the size of the previously imposed strains and secondly on the efficiency of the relaxation.

Ultimately, all strains are reflected in deformation of the fibres and it is therefore the mechanisms of deformation, setting, and stress release in cotton fibres that hold the key to explaining shrinkage in fabrics.

Fibre Considerations

Cotton is a fibre with a highly complex structure and correspondingly complex behaviour. However for the purposes of a discussion of shrinkage, it can be simplified as follows.

The fibre is composed of long bundles of crystalline cellulose that are held together largely by hydrogen bonding. The bundles are not exactly parallel to the fibre axis but spiral around it, first in one direction and then in the other. The overall shape of the fibre is not straight and cylindrical. It twists backwards and forwards in sympathy with the spiralling of the basic structural units.

When the fibre is placed under stress, the fibrillar spirals are placed under both longitudinal and torsional forces that will impart a certain amount of strain to the structure. This causes the structure to deform and some of this deformation is not recovered, or recovered only very slowly, after the stress is removed. This is because some of the hydrogen bonds, that hold the structure together, will actually break and then reform in new positions in order to relieve some of the stress internally.

If the deformation is maintained, for example, when fibres are twisted into a yarn and held there, then many new bonds will be formed and the stress will gradually decay to a relatively low level. Consequently when the deforming force is removed, there is much less internal stress available to recover the deformation and the new shape is partly set into the fibre.

If the fibre is wet when it is deformed, then the deformation will be greater, the rate of stress decay will be faster, and the new shape will be set much more permanently, particularly if the fibre is dried whilst it is held in the deformed state.

This is because wetting the fibre causes the structure to swell, i.e. water penetrates between the basic structural units causing a loosening of the hydrogen bond network and allowing the structure to move more easily. When the water is driven out during drying, new hydrogen bonds form in positions that minimise the internal stresses and this tends to stabilise the new shape.

Repeated wetting and drying of the fibre whilst it is held in the deformed state will gradually relax the residual stresses even further and make the new shape permanent. Thus swelling treatments of cotton are somewhat analogous in their effects to heat setting treatments on synthetic fibres, though usually they are less efficient in stabilising the deformed structure.

Some swelling treatments are more effective than others. Hot water is more effective in promoting stress decay than cold water; mercerising solutions are the most powerful of all. A deformation that has been set by a powerful swelling treatment cannot easily be removed by a less powerful one.

Deformations can also be set into a structure by replacing a part of the hydrogen bond network by covalent bonds, e.g. by resin finishing (Crosslinking). These bonds cannot be broken by water swelling and so resin finishing is a very powerful setting process.

When cotton is swollen in water, its cross sectional area increases by 20 to 40% but its length changes very little. Thus, shrinkage of fibres has no role to play in the shrinkage of fabrics; it is the change in cross sectional area that has a definite effect on dimensional changes in fabrics. Resin finishing drastically reduces the swelling of the cotton fibres.

Yarn Considerations

Spinning a yarn and knitting a fabric imposes deformations on the fibres so that stress is built into the structure. If this stress were not relieved then a yarn would lie straight when taken from a fabric and it would spontaneously untwist when its ends were freed.

The fact that a yarn is attempting to straighten and untwist determines the shape of the loops in the Grey Fabric. In particular, the Twist Liveliness of the yarn has a very important influence by causing the loops to twist out of the plane of the fabric and generally distort the loop shape.

After a wet treatment some of the stresses have been relieved so the forces within the yarn, that are attempting to restore the straight, untwisted configuration, are considerably reduced. Therefore, the loop assumes a different shape.

Wet processing treatments do not only relieve the stresses built into fibres, they also impose new ones. The new stresses cause different loop shapes according to the amount of stress that has been imposed during the wet treatment. These new Loop Shapes will be partially set when the fabric is dried.

Thus it will be found that a process which imposes very high length tensions, such as continuous bleaching, will give fabrics whose loops are relatively longer and narrower than those of a fabric that has had a much gentler treatment, such as low tension jet dyeing. Wet processes will generally reduce the twist liveliness of the yarn.

The effect of wet treatments on yarn setting can easily be seen by removing yarns from knitted fabrics. If a yarn is removed from a grey fabric that has never been wet, then it will be found to have a wavy shape that suggests the knitted loops but does not faithfully represent them. If this yarn is wet out in hot water and held straight while it dries, the waviness will practically disappear.

If a yarn is removed from a fabric that has been dyed and finished, then its shape will be a much closer reflection of the knitted loops. Some twisting of the loops will be observed showing that not all of the twist liveliness has been removed. Wetting and drying of this yarn will not remove the loop shapes, although they may become somewhat less pronounced.

If yarn is removed from a Mercerised, dyed and finished (or Resin Finished) fabric, then the loop shapes will be almost perfect, and will be rather faithfully preserved after wetting and drying. Loop twisting will probably still be present, though much less pronounced.

Swelling affects the length and the diameter of a yarn. In water, cotton yarns will increase in diameter by about 20% and this swelling will cause the yarn to try to untwist (whether or not twist liveliness is present in the unswollen yarn). If the yarn is constrained by being in a fabric, then it cannot untwist so it is forced to shrink.

The amount of shrinkage depends on the Fibre Quality, the yarn structure, and the level of Twist. A large part of this shrinkage will be reversible and will be recovered when the water is removed, but a part will be more or less permanent due to fibre movement and stress decay. The permanent shrinkage seldom amounts to more than about 2% for normal wet processing treatments but it can be much higher as a result of mercerising, maybe 8%.

Yarn shrinkage is not the primary cause of fabric shrinkage but yarn swelling is a very important process of the type that causes temporary changes in the loop shape and usually has the effect of helping to move the loop shape towards its reference shape. The setting of the yarn structure, especially the decrease of twist liveliness, is an important component in fixing the Reference Loop Shape.

Fabric Considerations

The same processes that operate on fibres and yarns are also important for fabrics. The main difference with fabrics is that they are very susceptible to large temporary deformations with consequent drastic changes in the Shape. It is these temporary fabric deformations that are the main source of shrinkage.

Wetting a fabric causes the fibres and yarns to swell. The yarn attempts to untwist and shrink. The increased yarn diameter can only be accommodated by increasing the curvature of the loops out of the plane of the fabric. The yarns move closer together, the loops twist, the fabric becomes thicker, and the structure becomes locked into a shape and size that is more or less reproducible, depending on the fabric construction.

Usually the fabric shrinks in both directions. Agitation of the wet fabric, as in a washing machine helps the "wet reference" dimensions to be achieved more reproducibly. In general looser constructions will shrink more than tighter ones when wet fabrics are agitated without tension because there is more room in the fabrics for the yarns to swell and bend.

Because the wet, swollen structure is jammed, external forces are transmitted rather efficiently through to the fibres so that, in high tension wet processes, the fibres can become significantly strained and the strain may become partially set, particularly if the fabric is subsequently dried under similar high tension.

Mercerising solutions not only give a higher degree of fibre swelling, they also reduce the tensile modulus of the fibres and so a given stress will produce a greater strain. The tighter the fabric construction the more jammed it becomes on swelling and the less fabric deformation can be produced for a given level of stress but the more efficiently is the stress transferred through to the fibres.

It is important to realise that the dimensions achieved by a fabric that is fully swollen and well agitated without tension are practically independent of both the starting dry dimensions and the final (tumble-dried) Reference Dimensions. The wet dimensions are governed only by the yarn and fabric construction and the degree of swelling of the fibres. Fibres that have been mercerised will swell more than those that have not; fibres that have been Resin Finished will swell less.

In other words, for every fabric / process combination there is a "wet reference" state that ought to be highly predictable in the same way as the STARFISH Reference State is predictable and this phenomenon might well repay detailed study, from the theoretical point of view. However, for practical purposes this "wet reference" state would not be so easy to use to make predictions about shrinkage or final dry dimensions, because the further change in dimensions, that occurs during drying complicates the issue.

During drying, the fibres collapse again to their original shape and the swelling forces disappear. The loop then reverts to a shape that depends on the balance of forces present in the yarns during the drying process.

If the fabric is simply laid flat to dry, so that no external forces are present, then the balance is between the internal restoring forces on the one hand and frictional restraints on the other. The internal restoring forces are those that are attempting to bring the loop shape to its natural, Reference Shape in which the internal stresses are at a minimum.

In a well-set fabric, these restoring forces will be very small and so it will be difficult for them to achieve any change in the loop shape against the inter-fibre and inter-yarn frictional restraints. Thus the dimensions of the fabric will remain close to those of the wet state during flat, tensionless drying. Usually there will be some further shrinkage in both length and width but sometimes there will be growth, particularly in the width direction.

If the drying is accompanied by tensionless agitation, as in a Tumble Dryer, then additional energy is available to overcome the frictional restraints and much greater changes in dimensions will be seen during drying.

In this case the further changes in length and width are governed by the difference between the "wet reference" and the "minimum energy" loop shapes. For some fabric / process combinations, (e.g. Plain Jersey, - resin finish) this difference may be quite small but in others (e.g. tubular Mercerised) it may be very large. Usually the length gets shorter after tumble-drying but often the width becomes larger.

If drying is carried out under tension, then the restoring forces will be completely overcome and the dimensions after drying will depend on the level of tension and whether there is some kind of framing involved, such as a stenter. If there is no frame, then the effect of a given tension will be much greater on a loosely knitted fabric, which will extend considerably, than on a tightly knitted fabric, which will resist the extension better.

The shape of the loop will then tend to be at least partially set in the extended configuration. However, as soon as the tension is removed, the restoring forces will come back into action and will tend to change the loop shape back towards its Reference Shape so that the fabric will gradually relax.

The amount of this relaxation will depend on how far away the loop shape is from the Reference Shape (the bigger the discrepancy the higher the restoring forces) and the fabric construction (the tighter the fabric the higher the frictional restraints).

The frictional restraints can be modified by adding softeners (lubricants) to the washing or rinsing water, which may slightly accentuate the difference between the wet and the dry dimensions. For clean cotton fibres, frictional forces are also affected by the Moisture Content. The coefficient of friction of cotton fibres is at its lowest when the fibres are fully dry (less than about 3% water).

Fibre swelling begins to reduce when the fibre moisture content is reduced below about 40% and it is only below this level that space begins to become available in the fabric to accommodate further shrinkage. Thus the combination of declining frictional forces and increasing space allows the dimensions to change under the driving force of the energy supplied by agitation.

Multiple Relaxation Cycles

The restoring forces that attempt to develop the fully relaxed Loop Shape are rather small. Therefore, it may not be possible to achieve complete relaxation within a single wash and dry cycle even when tumble-drying is used. In practice it is observed that a truly stable state is not achieved until after several (sometimes more than ten) cycles of laundering.

However, the question arises as to whether this progressive shrinkage is simply further relaxation towards a predefined loop shape, or whether the laundering process itself is affecting the shape of the loop with every cycle so that, in effect, the target is a moving one.

There are at least two major mechanisms by which the shape of the loop could be affected by the laundering procedure.

There could be some setting effect, which is slowly removing some of the distortions imposed by previous wet processing steps or slowly reducing the residual Twist Liveliness of the yarn.

There could be some progressive change in the yarn structure due to fibre migration and yarn bulking, particularly in the case of tumble-drying.

In addition, one could imagine other, more subtle effects such as loss of fibres from the yarn or a gradual change in the stiffness and frictional characteristics of the fibres.

There is some experimental evidence for a progressive, irreversible change in the loop shape brought about by the laundering process. If there were no additional effects due to the laundering and drying process alone, then the "wet relaxed" and the "fully relaxed" states should be reversible.

In other words, if a fabric that has been given five cycles of washing and tumble-drying is subsequently given five cycles of washing and line drying, then its dimensions should be identical to one that has been given ten cycles of washing and line drying.

In fact, unambiguous conclusions from experiments of this nature are quite difficult to obtain, because of the large number of samples that would have to be examined to make the data both secure and representative. However, such experiments as have been performed have given the clear impression that the reversibility of the two states is not perfect.

If a smooth curve is drawn through the data for shrinkage as a function of the number of laundering cycles, it will be found that the curve can be decomposed into two exponential functions.

One of these has a relatively high "rate constant" so that the expression reaches its maximum value after only one or two cycles regardless of the fabric type or processing history.

The other has a rate constant that is usually relatively low so that its maximum value is reached only after many cycles. The first function has been taken to describe the more or less instantaneous "Relaxation" process whereas the second has been ascribed to the slow, incremental "Consolidation" process.

In the case of the length direction, the expression for Consolidation is positive indicating progressive shrinkage.

In the case of the width, however, the expression is often negative, indicating that the effect of Consolidation is to make the fabric grow in width over successive cycles of laundering.

These opposing tendencies (Relaxation shrinkage and Consolidation growth) for the width direction probably provide the explanation for the commonly observed phenomenon that the variability of test data is almost always higher for the width direction than for the length.

Summary

Shrinkage is an expression of the change in Loop Shape that is brought about by a relaxation process.

The shape of the loop before relaxation is determined by:-

- temporary distortions imposed on the fabric during processing.

The shape of the loop after relaxation is governed by:-

- yarn and fabric structure,
- the type of wet process, especially the amount of tension applied when the fibres are swollen and the amount of setting that is achieved by the total wet processing sequence,
- the type of relaxation process, especially the amount of agitation that is available during drying.

Shrinkage proceeds in two main steps:

Step 1

- The first step is driven by fibre swelling which causes the fabric to shrink to a sort of wet reference state that depends almost exclusively upon the yarn and fabric structure.
- The wet dimensions are quite independent of the original fabric dimensions and are probably substantially independent of the relaxed dimensions.

Step 2

- The second step is driven by the agitation available during drying and depends on the balance of restoring forces and restraining forces within and between the yarns and fibres.
- The restoring forces will be higher, the further away the wet dimensions are from the fully relaxed dimensions. As the loop shape approaches the fully relaxed shape, the restoring forces become very small.
- The restraining forces are mainly to do with inter yarn friction. They are highest when the fibres are wet and lowest when the fibres are bone dry.

- For low levels of agitation the dimensions of the dried fabrics will be quite close to the so - called "wet relaxed" state that was common in the early literature on knitted fabric geometry. For high levels of agitation, the fully relaxed loop shape will be approached.

Multiple Cycles of Relaxation

Multiple cycles of relaxation produce further increments of shrinkage. These further increments may be simply better and better approximations to the (constant) relaxed loop shape or, more likely, they may represent incremental changes in the shape of the loop due to setting and / or consolidation of the yarn structure.