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MECHANISMS OF WOOL SHRINKAGE IN FABRIC, YARN AND LOOSE WOOL

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Felting shrinkage in wool assemblies proceeds initially at a rapid rate followed by an extremely slow rate arising from two diverse mechanisms which are attributable to a difference in the degrees of freedom associated with fibre movement. In the initial rate, fabric shrinkage varies with crimp ratio, twist and cover factor in the diminishing order of their significance. It is also correlated with yarntex and tenacity. The analyses further reveal that wool felting at various stages of processing is governed by the same fibre characteristics which are, however, subject to interactions with assembly geometry. Besides, tightness of fabric structure may not be a cause of Shorter's mechanism in felting, although it increases fabric relaxation shrinkage.

The term "wool shrinkage" may sometimes mean the converse of yield during valuation of clips as in the U.S.A.,[1] but generally it represents the outcome of a process variously called fulling, milling or felting, well-known to the textile industry since the 12th century.[2] In addition to the manufacturing difficulties of "cotted" or matted fleece, felting shrinkage creates the problems of dimensional changes during end-use of wool garment. A comprehensive solution to these problems obviously needs systematic study of the relevant factors in a wide range of variation.

The unusual manifestation of spontaneous felting[3–6] appears to emphasise fibre writhing due to the differential swelling of ortho and para cortices with moisture regain variations. The importance of fibre twisting during felting phenomenon has been recognised by several workers.[7–13] The fibre writhing produces localised compression of the contiguous fibres, thereby creating new frictional contacts. The scale structure of the cuticle then ensures resultant fibre migration by preferential stabilisation of the rootward movements. The key requirement appears to be that, regardless of whether the forces are internal or external, directed[14] or undirected,[15] they must produce a degree of compression, either of the entire wool assembly or at localised sites. Compressive forces would rupture some of the existing frictional contacts to thrust new ones more frequently. On releasing the force, the deformed fibres would tend to recover their initial positions. This tendency would be opposed by the new frictional contacts, particularly, those arising originally from fibre movement in a with-scale direction. The repeated compression and release would thus induce quantised rootward displacements of the fibres or their parts governed by a ratchet mechanism.[16]

The tendency of wool fabrics to shrink, when rubbed or squeezed repeatedly in aqueous media depends on both the unique morphological structure[17] and the restrictions imposed by the manufacturing conditions. In this study, the former has been maintained constant by using the same wool in order to ascertain the precise influences of the latter and a washing time far beyond the usual limits.

Experimental

A Merino wool of fibre diameter 20.4 μ, length 9.0 cm and crimp 4.6/cm was processed in the shortened Bradford system to produce single worsted yarns of nominal counts 90, 60 and 30 tex, each count being spun at 3 levels of nominal twist factors—1.7, 2.0 and 2.5. Only the coarser yarns were found to be suitable for knitting with the aid of a 2-bed universal knitting machine equipped with 7 gauge/inch. The stitch length was adjusted at 1.64 cm for plain fabrics of density 4 wales and 5 courses per cm^2.

Shrinkage Testing.—With a view to isolate the residual relaxation x from felting y of a relaxed fabric of area A during felting, the following definitions have been analysed binomially.

$$\text{Apparent felting shrinkage } \frac{x+y}{A}=\frac{x}{A}+\frac{y}{A} \quad (1)$$

True felting shrinkage

$$\frac{y}{A-x}=\frac{y}{A}+\frac{xy}{A^2}+\frac{x^2y}{A^3}+\frac{x^3y}{A^4}+ \textit{ ad infinitum}$$
$$=\frac{y}{A} \quad (2)$$

if x is too small to retain any multiplication term x/A or its higher power. Previous studies[18,19] suggest that the value of x depends on temperature and pH of the medium. In water, the relaxation attains a limiting value corresponding to each temperature within 5 min[18,20] so that it may be considered practically independent of time if the wet process is prolonged beyond 5 min. Alternatively, any further relaxation after the bursting of fabric structure by milling pressure is incompatible to the concept of consolidation due to irreversible entanglement during felting. It can, therefore, be inferred that fibre swelling, crimp recovery, probably associated with reformation of the deformed H-bonds accompanying their hydrolytic rupture and redistribution of yarn twist may complete the release of manufacturing strain in the indicated time. Because of these, a relaxation of fabric was carried out in the same pH as the felting solution (0.1N HCl incorporating a few drops of wetting agent) at 40±2°C for 1 hr before washing it in 21°C, with a view to reducing the term x/A whereupon the apparent felting shrinkage approximately equals its true value.

Due to the well-known curling tendency of knitted fabrics, the whole cloth, manufactured for each sample, was tested without cutting it for washing shrinkage. Six samples, each of the relaxed area about 50×30 cm^2 estimated in dry state under a pressure of 2 g/cm^2 and suitably demarcated by sewing with coloured thread, were all washed together in an impeller-type Hoover electric washing machine (model 0307, No. 86880) operated at the normal speed, using 1:400 (w/w) wool: liquor. After 0.5-hr washing, the marked cloth areas were estimated in the wet state under the said pressure and the procedure repeated for the succeeding washing periods of 2.5, 6.5, 14.5 and 24.0 hr. The mean of 6 measurements on each sample gave satisfactory reproducibility of the results.

Yarn Felting.—The yarn of 60 tex and 2.5 twist factor was laid into 3-ply with 7.8 turns per inch (t.p.i). It was refolded to make 3/2-ply yarn of 4.6 t.p.i. The ply was relaxed as before and sampled into thirty 6″-lengths identified by simple knots. Individual specimen was enclosed fully in a 10″ Terylene tube of 45-filament 225-denier yarn knitted at 0.5 cm stitch length with a circular machine of diameter 2 cm fitted with 32 needles. All specimens were felted together in the indicated medium by hand-squeezing. After 100 squeezes 5 specimens were taken out to measure felted length under a tension of 50 g but their enclosures were replaced to maintain original washing load. The procedure continued to obtain the mean felting of 5 specimens after 200, 400, 800, 1600 and 3200 squeezes.

Loose Wool Felting.—The Merino top was felted by Aachener Filztest[21] using the above liquor at 1:33 (w/w) wool: liquor in a 100-ml bottle to obtain the mean of six 1-g samples. The volume V_f of each felt ball was estimated from a geometric mean of 3 orthogonal diameter measurements on a dry ball which was successively tested for 10, 20, 60, 90, 120, 200 and 300 min washing. If V_i becomes initial volume of the sample noted after compressing and immediately releasing it twice with a piston traverse at 2 cm/min to a fixed volume of 10 ml inside a close-fitted cylinder in order to reduce packing variations,[22] the felting F is then obtained as follows:

$$F = \frac{V_i - V_f}{V_i} \times 100 \qquad (3)$$

Twist and Cover Factor.—Yarn t.p.i. for each sample was obtained by a Goodbrand twist tester from fifty 1″-test lengths.[23] The sample tex was estimated from ten 120-yd hanks conditioned and weighed in the standard atmosphere (65% r.h. and 21±1°C). The twist factor T was calculated as below:

$$T = \text{t.p.i.} \sqrt{\frac{\text{tex}}{886}} \qquad (4)$$

The cover factor C of each fabric was obtained from its stitch length L as follows:[24]

$$C = \sqrt{\frac{\text{tex}}{L}} \qquad (5)$$

Crimp Ratio.—Each yarn was sampled by at least twenty 4-cm test length which were unravelled before combing its one end by gripping fast the other end alternately to remove the intermediate fibres. About 100 fibres were then randomly drawn for measuring their straight lengths (S cm) by a millimetre rule engraved on a black surface to calculate crimp ratio (Cr) as follows:[25]

$$\text{Cr} = \frac{S-4}{S} \times 100 \qquad (6)$$

Yarn Strength Testing.—The sample tenacity and extension% were obtained in the standard atmosphere from forty 50-cm test lengths by means of an Uster automatic strength tester (range 200–2000 g). The ratio of these two parameters was "initial modulus", an index of yarn pliability and softness. Any bias in the estimation of the modulus due to nonlinearity of yarn load–extension curve is quite negligible[26] for statistical analyses.

Results and Discussion

The relaxation shrinkage (Table 1) varies with both yarn twist factor and fabric cover factor, thereby suggesting that relatively higher strain of knitting occurs in the weaker yarns of lower twist and in tighter fabrics. On the other hand, the high values of the present felting shrinkage compared to the previous results[27]—72.3% for worsted and 65.8% for woollen fabrics—may arise from the low cover factor and worsted processing employed here. Because of the processing difference, worsted fabrics exhibited higher shrinkage than did their woollen counterparts.

Washing Time.—In order to demonstrate felting mechanism in a wide variety of practical situations, the percentage area shrinkage a has been presented (Fig. 1) as a function of the washing time t. For clarity, the diagram illustrates the typical (average) relationship (curve 2) together with the limiting ones (curves 1, 3). All these graphs manifest widely different slopes. A high initial slope up to 2.5 hr washing is followed by a very low steepness that could not possibly be attributed to any cumulation of a temperature effect[28] since the rate of cooling in this experiment is directly proportional to the rise of temperature (Newton's law). Such a phenomenon seems discernible in fabric,[24] yarn[29] and loose wool[28] felting rates, but is more prominently displayed in Figs. 2 and 3. The initial depression of steepness in Fig. 3 may result from a resistive influence of conspicuous fibre crimp that lessens progressively in the intermediate stage of slightly higher steepness. An obvious implication is that any valid comparison of felting rates exhibited by different manufacturing assemblies should be restricted to the domain of the same slope. Such a comparison is likely to clarify some dissimilar results[30–33] since in contrast to an early conclusion[33] the common pattern noted in Figs. 1–3 suggests that fibre characteristics governing loose wool felting rates are quite similar to those determining yarn and fabric felting rates.

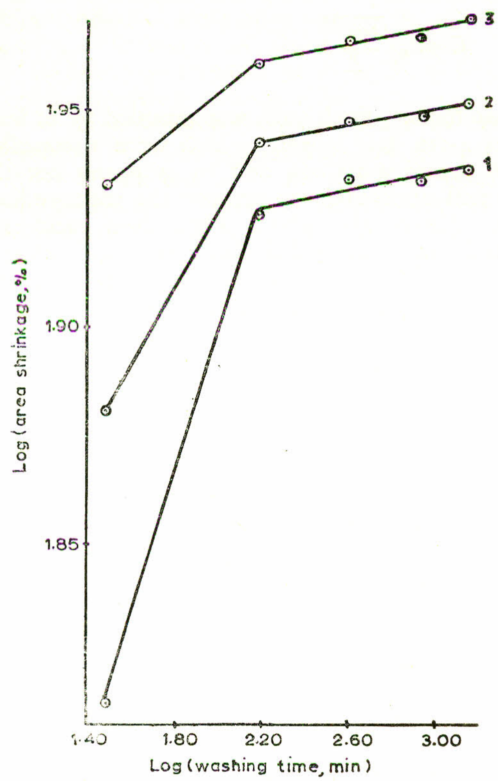

Fig. 1.—Relationship between fabric area shrinkage and washing time; curve 1 sample (w90/2.5), curve 2 all samples and curve 3 (w60/1.7).

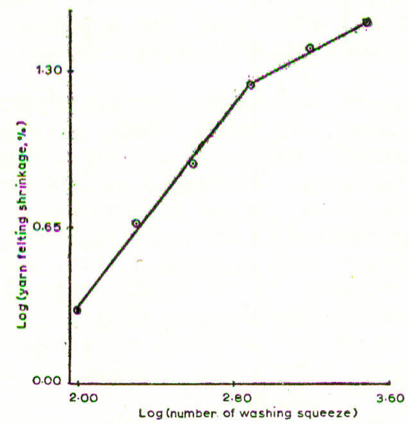

Fig. 2.—Relationship between number of washing squeeze and felting shrinkage in 3/2 ply worsted yarn.

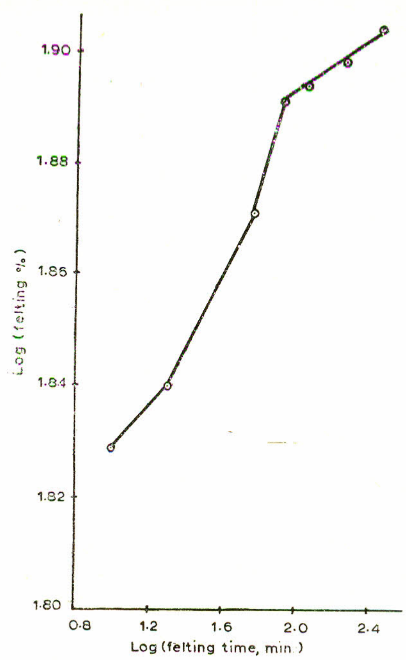

Fig. 3.—Loose Wool felting as a function of time.

The observed slopes are, however, directly proportional to the felting rates so that equation 7 of monomolecular rate process, fitted to limited data,[34,35] will assume two significant rate constants corresponding to the diverse steepness.

$$\frac{da}{dt} = k\,(x-a) \qquad (7)$$

where x=limiting percentage area shrinkage and k=a constant characteristic of the rate of felting.

The foregoing may imply two different felting mechanisms in accordance with Makinson's[12,13] views, i.e., the "release" of strain or untwisting mechanism producing a high felting rate in the woollen fabric knitted from single and Shorter's[36] mechanism bringing in a very slow rate in the worsted cloth of two-ply yarn. But its implication that relatively tight construction of the worsted fabric can favour Shorter's process seems to be at variance with the results in Fig. 1 where the tightest fabric (W90/2.5) exhibits the highest felting rate in the initial stage, thus implying a preponderance of the release mechanism therein. The former, however, needs simultaneous existence of both permanent constraints fully inhibiting fibre displacements through them and partial entanglement permitting unidirectional fibre movement towards the root end to consolidate the wool assemblies. Such a condition is more likely to prevail in the final than in the initial stage of felting. Furthermore, the large difference in felting rates of the two mechanisms can be explained in the light of the degrees of freedom associated with fibre migration. The release mechanism has 3 translational and 3 rotational degrees of freedom for each of the, say, N operating fibres, thus giving a total of $6N$ whereas each of, say, M fibres participating in the Shorter's mechanism possesses only the 3 translational degrees of freedom so that $6N{:}3M$ represents ratio of felting rates in the release and Shorter's processes. This interpretation is in conformity with an effect of the number of fibres in a yarn cross-section on the yarn felting rates.[18]

The final stage of slow felting, when attainable without a great deal of shrinkage in the initial stage, shows considerable implications for shrinkproofing. This may be possible in presence of conspicuous neps as visible in noil. Because of the negligible shrinkage at the final stage, the succeeding analyses are based on the data derived at 0.5 hr washing which was considered to be the midpoint of the initial stage of felting.

Twist and Cover Factor (C).—Graphical analyses of the area shrinkage a demonstrated a linear relation between log a and twist factor T. Subsequent regression analysis resulted in the following equation:

$$\text{Log}\ a = 2.092 - 0.0985T \qquad (8)$$

which, within the scope of this study, accounts for 75.7% of the variations in felting shrinkage so that yarn twist faetor is at least three times more important than any one or a combination of the other independent variables. Further analysis showed that, whilst the slope of the straight line described by equation 8 remained practically constant, its intercept on the shrinkage axis varied inversely with cover factors. Hence, the influence of C was incorporated into a general equation as follows:

$$\text{Log}\ a = \frac{K}{C} - 0.0985T$$

$$\text{or,}\ a = \exp^{2.303}\left(\frac{K}{C} - 0.0985T\right) \qquad (9)$$

where the value of K(12.379 in 90 tex and 10.297 in 60 tex samples) depends on yarn tex. The resulting higher felting rate of the coarser yarn containing more fibres in its cross-section conforms to a tex effect[24,37] manifested by knitted fabrics. This effect, in juxtaposition with a highly significant influence of fibre diameter[38–41] on wool shrinkage in all types of assemblies, confirms the foregoing concept of degree of freedom but contradicts an earlier generalisation[33] that factors influencing loose wool felting are quite different from those involved in yarn and fabric felting. This conclusion can, however, arise from linear comparisons involving the different mechanisms of felting since the significant influences of both cover factor[42–45] and yarn tex disappeared whilst the twist factor retained its paramount effect on fabric shrinkage at the final stage. Besides, an agreement of the predicted area shrinkage (given by equation 9 and the indicated values of K) with the observed values (Table 1) obviously confirms the present inference that agrees well with the highly significant effect of twist factor on crimp ratio,[46] since the latter accounts for the major bulk of variation in loose wool[18] and fabric felting.

Crimp Ratio.—By far the most important of all the variables examined here is the crimp ratio (Cr). The equation 10 of simple regression as given below,

$$\text{Log}\ a = 2.1955 - 0.0518\text{Cr} \qquad (10)$$

accounts for 82.1% variations within the present range (Table 2) and predicts the area shrinkage more accurately than equation 9. Both equations may provide broad guides to the manufacturers of

Merino wools. In general, the highly significant role of crimp ratio appears to be associated with fibre migration speed through modifications of the number and angle of frictional contact between wool fibre as well as affecting their resistance to bulk compression.

Mechanical Properties.—The anomalous effect of fibre length on fabric shrinkage was ascribed to a direct influence of yarn strength[47] but the proposition needs verification. The significant negative correlation (Table 2) of log *a* with yarn tenacity confirms the viewpoint and parallels the higher felting rates of fibres exhibiting greater ease of extension.[38] Although stronger yarns are generally made by tougher fibres, the present yarns were all made from the same wool. Consequently, the tenacity effect may arise from variation in yarn geometry. Also, the correlation of yarn extension% with log *a* just failed to be significant (—0.80 vs ±0.81). On the other hand, the positive correlation (0.65) of log *a* with the "initial modulus" is far from being statistically significant but the sign of the relationship parallels a recognised association[38] of felting rate with the power of recovery from extension of individual fibres. Hence, the ability of recovery from strain manifested by an ordered assembly appears to be a complex function of both the recovery power of its constituent fibres and their interaction with the assembly geometry.

Conclusion

The observations on loose wool, yarn and fabric felting exhibit two widely varying rates, which suggests a similarity of the fibre characteristics involved therein. An initial rate of rapid felting is ascribable to a "release" mechanism and the slow final rate to Shorter's mechanism. These mechanisms can be explained by a difference in the degrees of freedom operative in the two processes but not by any variation in tightness of fabric construction as indicated in early studies.[12,13]

Table 1.—Distribution of Relaxation and Felting Shrinkage of Plain-Knitted Fabrics with Cover Factor and Yarn Twist Factor.

Sample	Relaxation shrinkage (% area)	Cover factor	Twist factor	Felting shrinkage (% area) Observed	Felting shrinkage (% area) Predicted by eq 9	Difference
*W90/2.5	16.3	6.05	2.7	65.1	60.3	4.8
W90/2.0	17.5	5.95	2.1	70.5	74.6	−4.1
W90/1.7	19.8	5.95	1.7	82.9	81.8	1.1
W60/2.5	14.1	4.90	2.6	72.4	70.0	2.4
W60/2.0	15.2	4.85	2.1	79.0	82.0	−3.0
W60/1.7	17.6	4.88	1.8	85.5	85.7	−0.2

* Worsted yarn of nominal tex and twist factor respectively designated by the succeeding numbers.

Coefficient of correlation between log (felting shrinkage) and twist factor = −0.87,* significant at the 5% level.

Table 2.—Relationship of Fabric Felting with Yarn Mechanical Properties and Crimp Ratio.

Sample	Tenacity (g/tex)	Extension (%)	"Initial modulus" (g/tex)	Crimp ratio %	Area shrinkage% (*a*) Observed	Area shrinkage% (*a*) Predicted by eq 10	Difference
W90/2.5	8.22	24.4	0.337	7.52	65.1	64.0	1.1
W90/2.0	7.31	19.4	0.377	6.62	70.5	71.3	−0.8
W90/1.7	6.96	18.6	0.374	5.46	82.9	81.8	1.1
W60/2.5	7.21	18.9	0.381	6.48	72.4	72.4	0
W60/2.0	6.61	16.6	0.398	5.46	79.0	81.8	−2.8
W60/1.7	6.07	15.6	0.390	5.20	85.5	84.3	1.2

Coefficient of correlation of log *a* with tenacity ($r = -0.81$*) and crimp ratio ($r = -0.91$**) being significant but not that with "initial modulus" ($r = -0.65$) and extenssion % ($r = -0.80$).

Furthermore, it is desirable to compare felting rates of the linear assemblies within the domain of either of the two rates.

At the initial rate, fabric felting varies significantly with fibre crimp ratio, yarn twist factor, fabric cover factor, yarn tex and tenacity whilst its variation with "initial modulus" and yarn extension are not significant. All these relationships imply that the fibre attributes affecting felting rates in the ordered assemblies are differentially modified by their interactions with assembly geometry. Eventually, an observed variation of fabric relaxation shrinkage with both yarn twist factor and fabric cover factor indicates a higher "crimp recovery"[48] of the loose yarns and tight fabrics.

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