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Fuzzing mechanism and fibre fatigue of wool knit

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The fibre fatigue fibrillation and even fracture of knitted wool fabric under the rubbing force have been studied using scanning electron microscopy. The fatigue fracture sections, involved in the process of abrasion, show that loop hairs predominantly participate in fuzzing and the free ends exist in either pills formation or wearing-off. The major form of failure consists of the bend fatigue which is about 70 - 80% of the total failure and cracks. Fibrils occur in torsional fatigue (10 - 18%) and fibrillation head-ends comprise both bending and twisting.

Keywords: Fibre fatigue, Fibrillation, Fuzzing mechanism, Loop hairiness, Rubbing force, Wool knit

1 Introduction

The initial effect of abrasion on the surface of a fabric is the formation of fuzz as a result of two processes, namely the brushing up of free fibre ends which are not enclosed within the yarn structure, and the conversion of fibre loops[1]. The mechanism of fuzzing and pilling of fabric is generally illustrated by the three distinct stages in the life span of a pill, namely fuzz formation → pill growth → pill pulled away from the fabric[2,3]. However, this is the descriptive process of fuzzing and pilling rather than the mechanism. Other researches included study on the mathematic and kinetic model of pilling mechanism[4-6] or the initial phase of fibre entanglement of pilling using time-lapse microphotography through a slot in a rotating abradant[2]. Gintis and Mead[2] have described the fuzz-formation mechanism in terms of loop generation and pull-out but failed to give details of the actual entanglement mechanism.

In fact, there is an ambiguity and no explanation about ‘how to express the fuzz formation’ in the first step of fabric pilling. Firstly, fuzz was considered as the protruding fibre end, which was connate, like nature hair. Secondly, the end hairiness was considered to be grown as the result of end hair protruding to the fabric surface or one ‘leg’ of loop hair pulled out.

Although the sequence of events has been described qualitatively and quantitatively, there has been no distinct clarification of the mechanism of fuzz formation. In this study, fuzzing mechanism and the fibre fatigue of wool knit have been proposed, and the evidence of the process is validated with scanning electron microscopy (SEM) observations, along with the description of the fuzzing mechanism of polyester fabric[1].

2 Drag Forces and Model

One of the necessary conditions for pilling is inter-entanglement of hairs. It has been taken into granted that more hairs are responsible for more pills, which means that the fabric has the pill growth when hairiness is sufficiently high. However, the corduroy and smooth filament pile fabrics have little propensity for pilling. According to one opinion, the attention has been paid to the length of staple fibre and the reduction or removal of hairiness in textile processing[7]. Though these methods are practical and effective, the fabric pilling has been inhibited in the initial process. According to another opinion, pilling is followed by fuzzing having a definite boundary. The separation of fuzzing and pilling process leads people to neglect pilling, as it is a gradual process, which is similar to the ‘snowball’ rolling. The pill formation enhances the inter-fibre cohesion, and the speed of the fibre withdrawal, and shows more opportunities for the entanglement and holding the fibre pulling out.

At the base of the two conceptual biases, a fundamental truth has been overlooked, that is ‘loop hair plays the role of fuzz formation’. Figure 1(a)

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demonstrates the loaded force of an anchor-fibre, which can only lead to swing, resulting in the hairs oriented on the surface. However, the hairs as shown in Figs 1(b) and (c) may be beaten down firstly, and then dragged, while hairiness lodging appears in different direction.

The anchor-fibre in Fig. 1 (b) can be fallen left. It is difficult for the drag force P ($P = F\sin\theta$) provided by the force F to overcome the sum of three effects, that is (i) the bending effect (*BE*) of high bending curvature of the anchor-fibre, (ii) the friction f ($f = \mu F\cos\theta$) caused by the positive pressure N ($N = F\cos\theta$) and (iii) the cohesion force H due to the original anchor point. Thus, the fibre cannot be drawn to pull out but can be bent. Three parameters determine the direction in which fuzzing will proceed on a particular fibre-yarn-fabric combination, namely (i) the external force, F; (ii) the angle between the external force and vertical direction, θ; and (iii) the friction coefficient of internal fibres of the corresponding yarn and fabric.

The drag force P could flatten the anchor-fibre [Fig. 1 (c)] to the right, which overcomes not only the cohesion force H due to the original anchor point, but also the bending effect (*BE*) and the friction f_1 between the surface of fibre A and B and the friction force f_2 ($f_2 = \mu F\cos\theta$) between the lower surface of L_b of the anchor-fibre and the surface of the wool knit. Compared to Fig. 1 (b), the bending effect *BE* and L_b tend to decrease, but it is difficult to be pulled out since the only drag force P generated by force F cannot overcome the sum effect of *BE*, f_1, f_2 and H ($P = BE + f_1 + f_2 + H$).

When the prostrate hair and the fibre in the yarn body lie in the same direction as shown in Fig. 1(d),

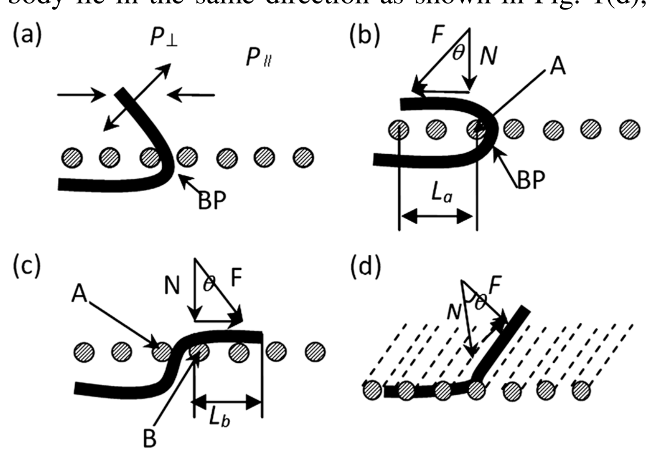

Fig. 1—Motion analysis of single free-end hair

the hair could be embedded into the gap of the fibers and the force F ceases to be effective. While if the hair is not implanted into the surface of wool knit, the friction increases with the contact area between the lower face of the anchor-fibre and the surface of the fabric. Thus, the anchor fibre has little propensity to be pull out.

Obviously, the end hair is not likely to grow longer but to swing, be flattened and embedded. Swinging leads to the bending fatigue of holding point BP and hairiness fracture and then directly fall-off from the surface of fabric (the fibres such as cotton, hemp and carbon can be processed faster due to low anti-bending fatigue). These fibres are otherwise beaten down, if not erecting from the surface again. The anchor fibres completely disappear, like most plastic fibres, such as rayon, linen, and cotton in wet state. Or they remain embedded and not ejected again; the anchor fibres vanish permanently (like straight and rigid fibres, such as silk, linen, and viscose). Hence, the protruding fibres ends, originally clung to the surface of the fabric, can naturally die as the result of abrasion, as long as the inter-fibres have little probability of occurrence of the entanglement.

It is exactly the loop hair (even just a small arch) that can attribute to the hairiness growth[2]. As illustrated in Fig. 2(a), both swinging force $P_{\perp}$ and deforming force $P_{//}$ of the loop hair will prompt hairiness dragging and growing. Under the action of $P_{\perp}$ [Figure 2 (b)], both ends of the loop hair may be drawn to pull out as long as $P_{\perp}$ is larger than the cohesion force at either end. This can not only improve the loop length but can increase the probability of re-withdrawal. Without withdrawal, the bending fatigue starts to occur on the point BP of bending formation. The loop arc moves to one side respectively under the action of $P_{//}$ [Figs 2 (c)

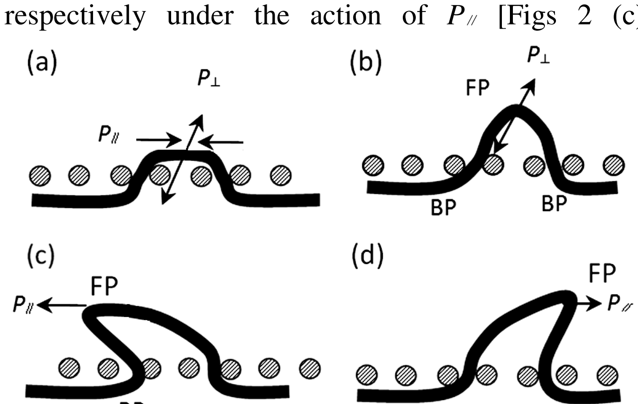

Fig. 2—Motion analysis of loop hair

and (d)]. The end will be dragged if the hold force is lower, thus increasing the length of loop arc. The loop hair is only mobile when the point BP suffers bending fatigue. Hence, BP is a variable value.

There are two findings during these changes. One is that two fibre end hairs are generated due to the loop hair fracture since $P_{\perp}$ or $P_{/\!/}$ is too large. However, the occurrence probability is extremely low because the impact force or cutting action play the fatal role and the new hair is difficult to be drawn out due to its short length. The other finding is that the loop hair constantly grows and gradually self-entangles or entangles with other hairs, which leads to entangle tightly to form 'ball'. It is found that the fibre bulging is the most fundamental and important factor in loop hair formation. It is well known that the crimp of the fibre is the natural bulging and that only natural fibre causes pilling. Therefore, it is proposed that the crimp is the main mechanism of the fibre fuzzing and pilling. Unfortunately, only a few studies have been conducted which suggest that the yarn hairiness and the pilling tendency descend with an increase in the fibre crimp[3,8]. Otherwise, the amount of the innate hairs on the surface of fabric have been considered in the industries for urgent attention and the process of singeing[9] is the prevalence in the finishing treatment for the commercial fabrics which removes the intrinsic fibre ends on the surface of the fabric; or the compact model decreases the end hair[10]; or the twist factor is enhanced to increase the cohesion force[11]. In fact, hairiness and pill formation are the two different properties and higher level of hairiness may not always reflect a greater pilling tendency[3].

What can contribute to the growth of the protruding end hairs on the end? In general, when it is hinged, most buried parts of anchoring fibres migrate outside of the fabric surface by the external forces of bending or pulling during abrasion action. The anchoring effect occurred is determined by the entanglement between hairy fibres, subsequently leading to pre-loop hair, as shown in Fig. 3 (a).

Succedent discussion and results are found consistent with the mechanism of the loop hairs. Force $P_{\perp}$ causes symmetrical pull-out and $P_{/\!/}$ leads to asymmetric one, which results in the gradual development of the protruding fibre ends and then the emergence of twisted or entangled fibre ends [Figs 3 (b), (c) and (d)], which (named vice crimp) are also composed of the main mechanism of pill formation and growth.

The diagram of the crimp of the fibre at different frequencies and curvatures is illustrated in Fig. 4. As compared to the standard crimp shown in Fig. 4 (a), the fibre with the high frequency and curvature is wound onto the yarn body more tightly [Fig. 4 (b)] than the other two and has lower hairiness in accordance with the Wang's study[8]. The high frequency and curvature could prevent the fibre from pulling out when it is lower than the frequency and curvature by twisting of the yarn.

3 Materials and Methods

3.1 Materials

The average diameter of the wool is about 19.45μm and the coefficient of variation in fibre diameter (CVD) is about 20%. The pure wool single jersey fabric specifications are: 48/1-Nm and 650T/m ring yarn, hank dyed with red color, 56 courses per 5cm, 44 wales per 5cm, 158g/m^2 specific weight, and a needle gauge of 16, 6.2 mm stitch length.

3.2 Pilling Properties

The wool knitted fabric was cut into 150mm×150mm pieces and kept 24h in standard

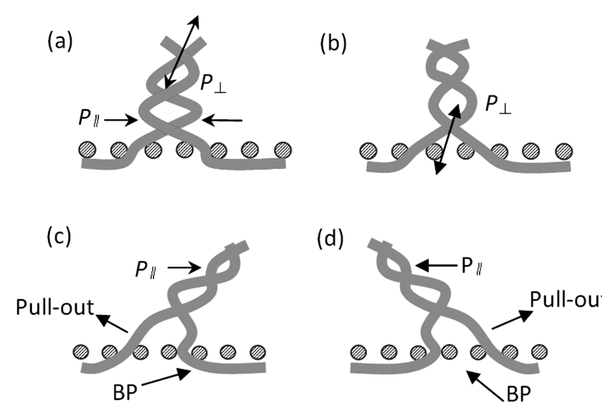

Fig. 3—Motion analysis of entangled end hair

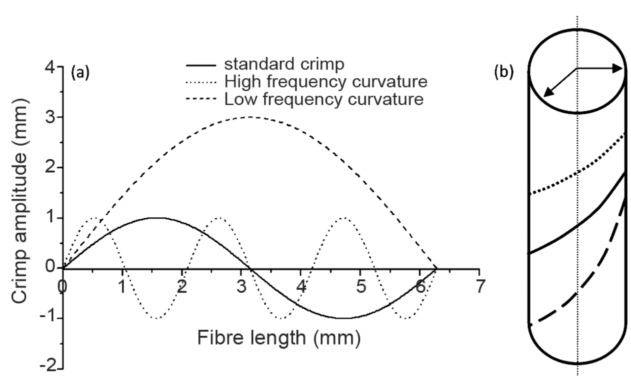

Fig. 4—Crimp diagrams of different frequencies and curvatures

atmosphere (20±2°C and 65±2% RH). The fabric samples were placed in the Martindale fuzzing-pilling and abrasion meter (YG401E, Ningbo Textile Instrument Factory). The right sides of two pairs of samples were abraded with 125, 500 and 5000 rubs under 260g loading weight according to the GB/T4802.2-2008.

3.3 SEM Study

SEM (model JSM-5600LV) images of fuzzy microfibrils protruding from the surface of wool knitted fabrics and the pills clinging to it were taken with an X-650 microscope, typically operating at an acceleration voltage of 10 kV. The samples were sputter-coated with gold prior to the observation.

4 Results and Discussion

4.1 Fibrillation of Bending Fatigue End

Cortical cells of wool fibre consist of multi-level fibrillation body (proto-fibril, microfibril, macrofibril and fibril bundles)[12].

We set Martindale abrasion experiment for 500 times, because the surface of the fabric is found to be fluffed with very little pilling in this condition. In the pilling experiment, numerous fibrillation ends were observed. This arouses suspicion as to the protruding fibre end mechanism on fuzzing and pilling of wool fabric. In fact, the view of original hairiness causing pilling should have been questioned earlier since the fabric after singeing still has pilling propensity.

Figure 5 (a) shows some bulging loop hairs in the initial pilling abrasion. The individual initial bending fibre segment is shown in Fig. 5 (b), whose scales on the bending point of the bugling fibre are almost stripped due to the rubbing and wearing. It is clear that the scales on the surface of fibre play an important role in protecting the wool from a variety of damages. Anchor fatigue of the fibre starts at this point where the anchor is forced to bend itself [Fig. 5 (c)] or around another fibre[13] [Fig. 5 (d)].

Results indicate that there are bend fatigue and some apparent fibrillation ends of the fibres suffering the considerable frequent abrasion action [Fig. 5 (d)]. The severity of the fibre breakdown ranges from the early stages of bending splitting [Fig. 5 (a)] to virtually complete fracture [Fig. 5 (d)].

Figure 5 (d) depicts the unbroken fibrillation loop ends, which does fatigue to the point where they are bended and fractured (bending point BP and force action point FP illustrated in Figs 1 and 2 respectively). It can be seen that loop fibre splits into finer fibril bundle along the longitudinal, and the friction contact gives rise first fracture, which is typical characteristics of fatigue failure. It is also seen that the outer edge of the BP of the loop hair splits first, and then the all fibril bundle starts breaking. The BP also exists in the end hair, which could provide bending fatigue. In the absence of pull-out fatigue for protruding fibre end, the fracture can only occur on the surface of the yarn and the fabric. It can therefore be concluded that the bending action of fibre ends at the most regions of fabric will lead to the bending fatigue characteristics.

4.2 Complex Fatigue for Loop Hair

In addition to bending fatigue and twisting fatigue, there exists the complex fatigue, including bending and twisting fatigue [arrow C in Fig. 6 (a)]. It can be seen from Fig. 6 (a) that there are different types of hairs.

The fibre tip [Fig. 6 (a), arrow A] of wool is similar to that shown in Fig. 6 (b), which proves the statement that tips of wool fibre in textile products are smooth and show un-fibrillation. Initial bending fatigue as shown in Fig. 6 (a) (Arrow B) corresponding to the Fig. 5 (c) suggests that the bending fatigue mechanism takes the dominant position. Figure 6 (b) illustrates the morphology of the complex fatigue. It tends to be fractured into the spiral fibrillation in the core of fibre.

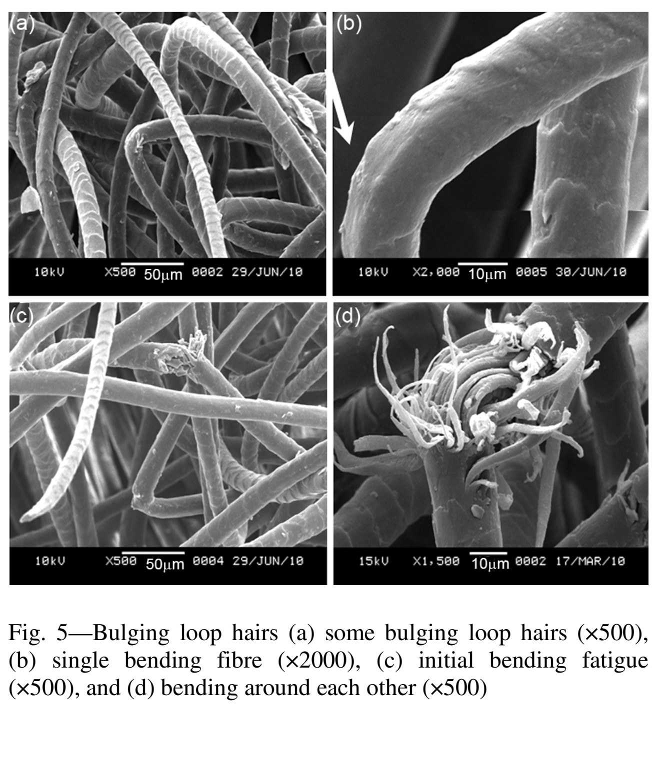

Fig. 5—Bulging loop hairs (a) some bulging loop hairs (×500), (b) single bending fibre (×2000), (c) initial bending fatigue (×500), and (d) bending around each other (×500)

4.3 Comparison of Fatigue Characteristics of Hairiness

By former analysis, fuzzing, pilling or wearing-off show the same characteristics compared to the anchor hair on the fabric. Withdrawal differs from fatigue failure in the holding or entangling form of upper part of hair. Withdrawal offers the potential for hairiness fuzzing, pill growth and wear-off (fibre withdrew), which is constrained to the holding form of two ends of fibre and influencing factor. A new concept about the hairiness on and outside the fabric surface is proposed while the one inside the fabric (fibre inside of the yarn body) has already been discussed and explained[6]. Fatigue failure is the base for hairiness die-away, pill wear-off and even hairiness entangled to pilling. Its major action form, however, is rare to be discussed or concluded.

This study shows the following viewpoints. Fuzzing mechanism during fabric abrasion is the action, not by free protruding fibre end (shortened as F mechanism), but by entangled loop hair and potential loop hair. However, the two forms exist in the bending point (BP) which affects the bending fatigue on the BP with high curvature, twisting fatigue and fibrillation characteristic of complex fatigue (bending + twisting fatigue). Bending fatigue is referred to B mechanism, twisting fatigue as T mechanism and complex fatigue as C mechanism.

Since the damages are occurred inside the fabric surface by B, T and C mechanisms, as free end hairs of F mechanism are less on the BP through projecting hairs observation without effecting on pilling, the F mechanism is just the original smooth end [Fig. 6 (a)]. Therefore, F mechanism is another word for the original smooth end. Damages due to B mechanism are more presented on the force point (FP) of loop hair whose damage characteristic is FP. This occurs on the loop hair. It can be extrapolated that this is the characteristic of fracture of loop hair.

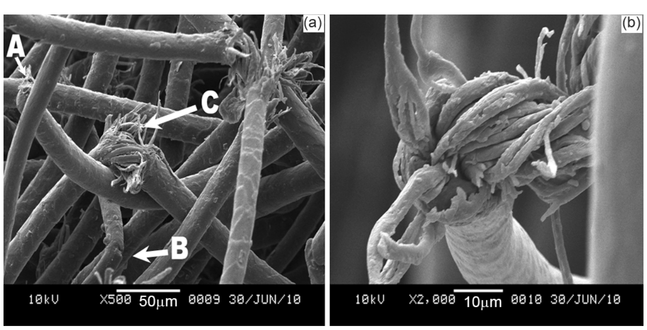

Fig. 6—Morphological characteristics of complex fatigue (a) smooth end and bending fatigue morphology of loop hairs, and (b) complex fatigue

The characteristic of B, T and C mechanisms is illustrated in Fig. 7.

The experimental results demonstrate that B mechanism with 70-80% gives first place to the fatigue, T mechanism with 10-18% and the left 2-20% is for C mechanism, according to the observation of the SEM images of 200 point of fatigue. It can be found during the experiments that B mechanism occurs and develops at a rapid rate; especially for the steady and tight wool fabric. The reason is that in the tight fabric the frequency and power of action are higher and thus bending can take place at the lower force and BP seldom moves which are also suitable for C mechanism. C and T mechanisms occur and develop slowly as the result of low frequency of twisting, appropriate acting force and direction.

It can be inferred that the pilling mechanism is not F mechanism but B, T and C mechanisms. The former characterized with "bald" is hard to grow up. The fibrillation ends of B, T and C mechanism easily tend to get entangled with each other, resulting in dragged and pulled out. This contributes to the fuzz growth or fracture occurrence, making more hairiness. B, T and C mechanisms should coexist while pill wearing-off though the main mechanism is still B. F

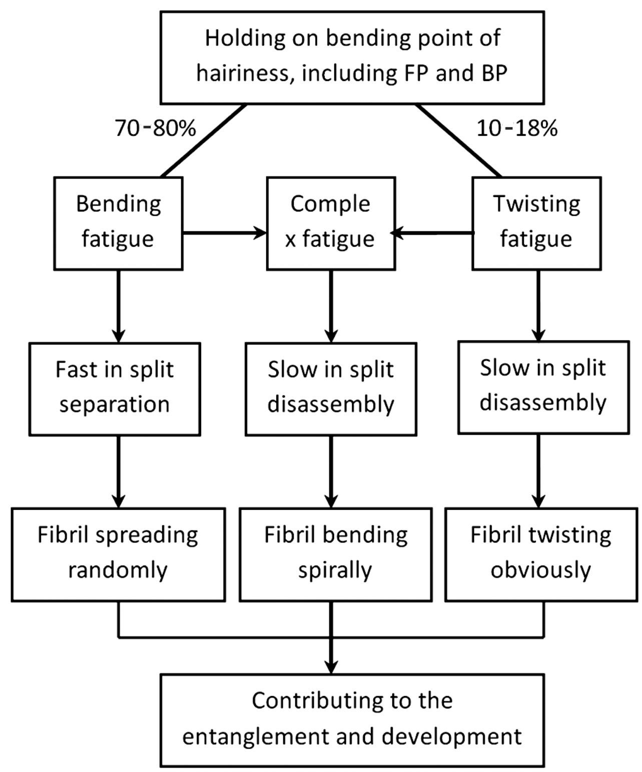

Fig. 7—Fuzzing mechanism and fatigue fracture of wool fabric hairiness

mechanism is a low priority in the fuzz picking-up but arises and strengthens with the pill pull-off. The reason is that friction holding between pill and hairiness causes the withdrawal or snaps of anchor fibre whose end is non-fibril and smooth. F mechanism leads to pill wear-off, thus taking a dominant position in theory. This needs to be observed and verified with pill detached.

5 Conclusion

The main mechanism of loop or potential loop hair formation is wool fibre crimps which bring about objective fibre bulging on the yarn surface as a result of the possibility of hooking or inter end hair holding to form potential loop hair. In short, innate hairiness is caused by textile processing, whereas acquired hairiness is the result of fibre crimp. Force point (FP) and bending point (BP) lead to the point of fatigue fracture, which tends to fibrillation crack for end damage. The majority of fatigue form is duo to bending damage (70-80%), where fibrils extend disorderly. Twisting fatigue causes torsion fibrils protruding. Furthermore, the fibrillating ends also exist by bending and twisting fatigue.

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