In-situ observations of abrasion mechanisms of nonwoven fabric

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Abstract

Experiments were conducted to observe non-woven fabrics *in-situ* during abrasion, with a view to elucidating the mechanism of abrasive damage. The initial stage involves the generation of fuzziness, characterized primarily by unbroken fibers being pulled out of the fabric with or without detachment from a bond site. Use of higher bonding temperatures during manufacture reduces this form of damage, and leads to better abrasion resistance. The morphology of the pills that were formed has been correlated to the abrasion conditions. For example, long pills are formed preferentially upon abrasion with a smooth surface, while ball pills are generated upon abrasion with another fibrous material.

Keywords: non-woven fabric, abrasion mechanisms, bonding strength, pills

1. Introduction

Fabric abrasion, and the resultant pilling, is a significant problem in the textile industry [1, 2, 3]. Pills are balls of tangled fibers, often connected to the surface of a fabric by anchoring fibers, and resulting from damage to the garment [4]. They degrade the appearance of the fabric and, in some applications, can cause health concerns [5]. The formation of pills in knitted and woven fabrics has been studied, and categorized into four stages. First, the free ends of fibers are pulled out of the yarn to create areas of 'fuzz' [6]. Second, these free fibers form permanent entanglements as a result of back-and-forth motion, and then tighten into balls [7]. Third, the fibers that anchor these balls to the structure of the yarn are pulled out to form discrete pills [7]. Fourth, these pills can fall off the fabric if the anchoring fibers fail.

The last three stages of pill formation may be similar for woven, knitted or non-woven fabrics, once there are enough long, fuzzy fibers on the surface of the fabric [8, 9, 10, 11].

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However, the mechanisms by which the fibers form the initial fuzz are expected to be different between woven and non-woven fabrics. In a woven or knitted fabric made from a yarn, the fuzz can be formed if the free ends of the fibers are brushed out of the yarn, or if fiber loops pulled out of the yarn are broken [7]. Once a fiber is broken, it can be pulled out of the yarn if the frictional force between the fibers is overcome. In a thermo-bonded non-woven fabric, the individual fibers are not formed into a yarn, but are joined together at discrete bonding sites. Therefore, the length of a free fiber that might be formed when a fiber breaks is determined by the distance to the nearest bond site to which it is attached, which can be longer than the distance between neighboring bonds, particularly if the bond sites themselves can be broken. This fundamental difference in the basic structure of the two classes of fabric motivated the present study to investigate the formation of fuzziness and pills in non-woven fabrics.

Many studies of the abrasion of non-woven fabrics focus on parameter optimization using the Martindale test [12]. Samples are evaluated by comparing images [2, 13, 14] or by measuring weight loss [1, 14], but these results provide no insight into the mechanism of damage. Wang *et al.* [15] made SEM observations of a bi-component fabric after abrasion and identified two damage mechanisms. The polypropylene (PP) sheath of a bi-component fiber can peel and wear away owing to thermal-induced shrinkage and thermal oxidative degradation of the PP. Also, as with woven fabrics, fibers can be pulled out and rolled up during abrasion. However, the mechanism of fuzziness formation at the initial stage of abrasion for non-woven fabrics is still poorly understood. In the present paper, we explore this question using experiments in which early stages of the abrasion process can be observed *in-situ*.

2. Experimental methods

The experimental system used for *in-situ* abrasion observations is shown in Figure 1. A fabric sample of dimensions 200 mm $\times$ 200 mm was attached to the top surface of a stationary frame and an abradant was moved over the fabric using a computer-numerical-control [CNC] machine with a changeable head. This system is capable of executing any abrasion pattern within the fabric sample, including the lissajous figures used in the Martindale test, but here we chose a simple 120 mm back and forth pattern in the x-direction, as shown in Figure 1. During abrasion, the surface of the fabric can be viewed from above, through an optical microscope, and also from the side, using a digital camera. A nominal contact pressure of 690 Pa was used, which is consistent with that used in the Matindale test (0.1 psi). To assess the variability of the observed phenomena, six experiments were conducted for each test condition.

2.1. Fabric samples

The fabric samples that were tested were manufactured from single-component polypropylene fibers of approximately 20 ± 2 μm diameter, bonded by a calender heat press. The

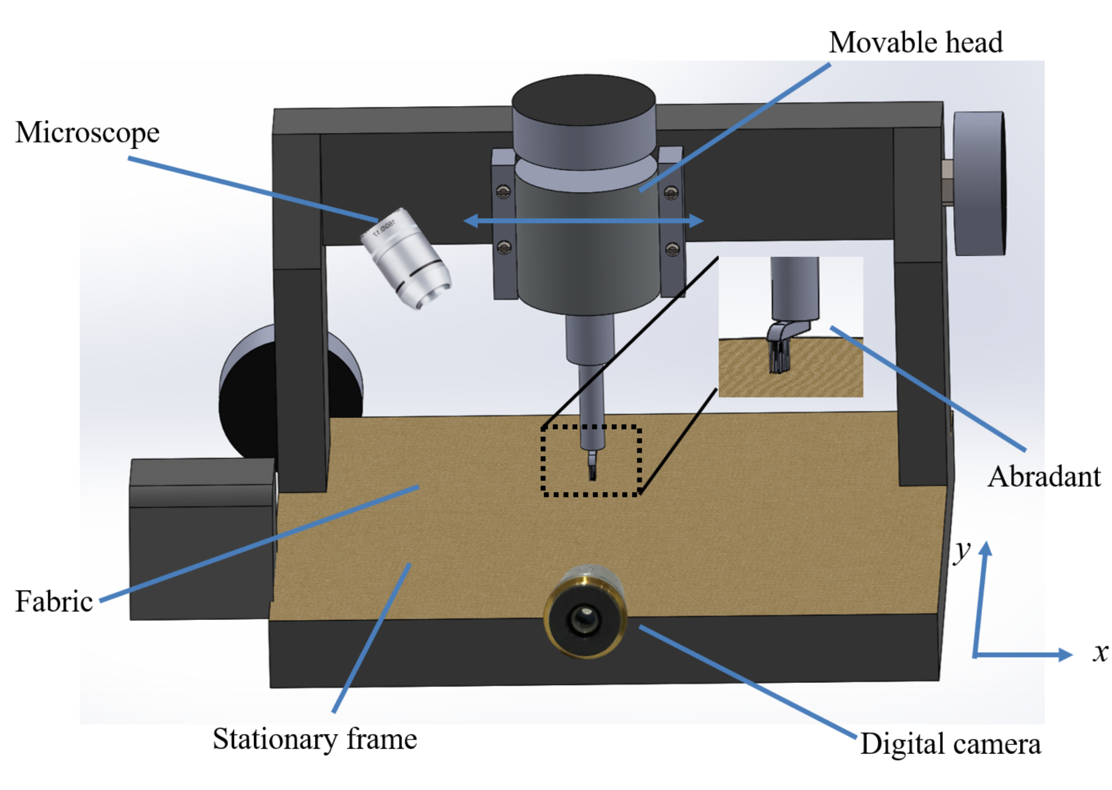

Figure 1: A schematic illustration of the system used to study the mechanism of pill formation *in-situ* during abrasion. The upper camera records the morphology of the fabric when the abradant moves to the orange dashed area.

density of the samples was 15 ± 0.5 g/m^2, and the thickness of the fabrics was 0.10 ± 0.03 mm. The tests were conducted at $23\,°\text{C} \pm 1\,°\text{C}$ and relative humidity of $45\% \pm 5\%$. Figure 2 shows representative optical and scanning-electron-microscope [SEM] images of fabrics bonded at 135 °C and 153 °C, respectively. The SEM images were obtained using an FEI Helios 650 Nanolab SEM/FIB. The bonding sites can be clearly seen in the images, with a center-to-center distance of about 1.5 mm. While the morphology of these two samples appear to be similar in the optical images, the SEM suggests less complete fusing in the fabric that was bonded at the lower temperature.

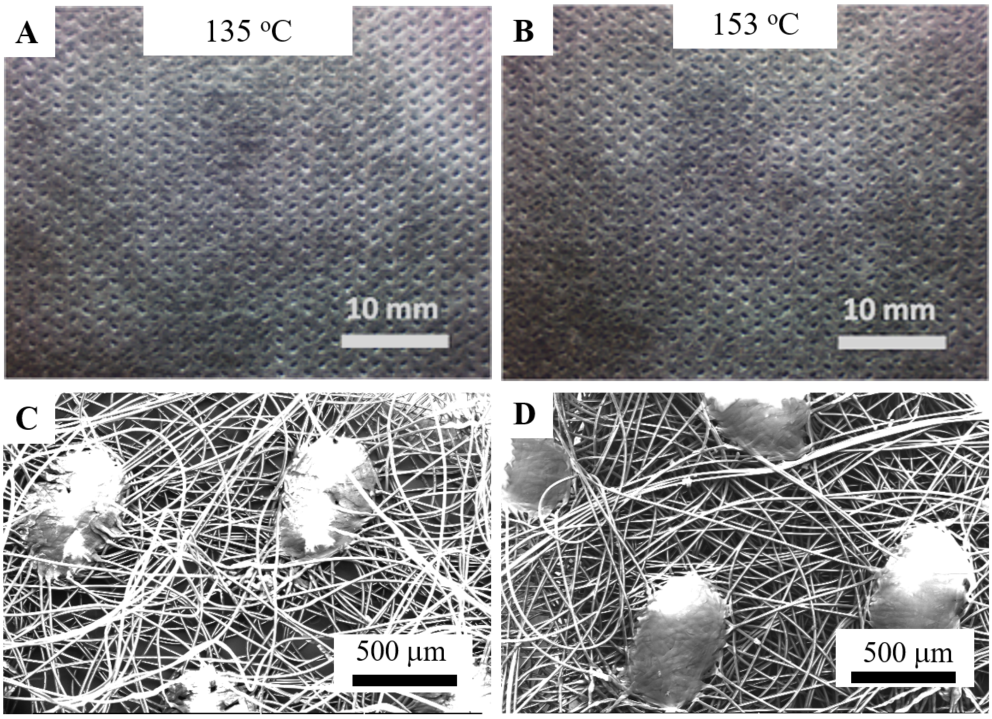

Figure 2: Optical image of fabric bonded (A) at 135 °C and (B) at 153 °C, before abrasion. Corresponding SEM images are shown in (C) and (D) respectively, and suggest less complete fusing of the fibers at the lower bonding temperature.

2.2. Choice of abradant

In preliminary experiments, we used a wide range of abradants, including both fibrous materials [non-woven fabric, knitted fabric and toothbrush] and non-fibrous [silicon carbide, glass]. Qualitative results showed that pills are formed more readily when the abradant is fibrous, presumably because of the possibility of entanglement between the fibers of the fabric and those of the abradant. It is advantageous to use an abradant with a relatively small nominal contact area, since the abraded surface can only be imaged after the abradant has passed. We therefore used a 'soft' toothbrush with a nominal contact area of length 26 mm in the sliding direction and 11 mm perpendicular to the sliding direction. There were 6.5 ± 0.3 bristles/mm^2, each of length 9.5 mm and diameter 0.13 ± 0.02 mm.

3. Results and discussion

3.1. In-situ observation of the abrasion process

Abrasion experiments were performed on the fabric bonded at 135 °C, and the top and side views were recorded on video. A nominal contact pressure of 690 Pa was used, which is consistent with that used in the Martindale test (0.1 psi). Back-and-forth motion was imposed over a range of 120 mm at 5 cycles per minute, with a uniform nominal speed of 20 mm/s.

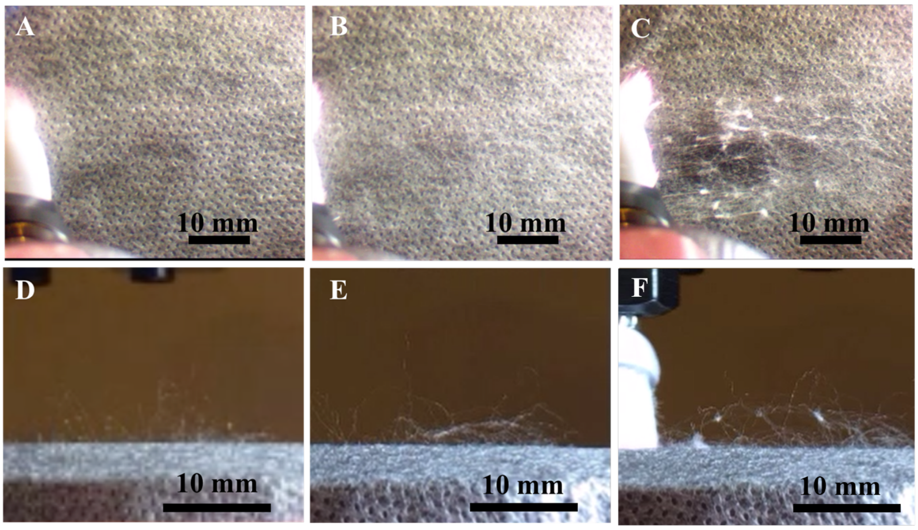

Figure 3: Top view (A-1, B-1, C-1) and side view (A-2, B-2, C-2) of the fabric bonded at 135 °C, after 10, 20 and 30 minutes of abrasion respectively with a soft toothbrush.

Figure 3 (A,B,C) shows selected frames from the *in-situ* video after 10, 20 and 30 minutes of abrasion respectively, representing three stages in the pill formation process. Figure 3A [10 minutes, 50 cycles] shows the development of 'fuzziness' consisting of fibers pulled out from the fabric. In Figure 3B [20 minutes, 100 cycles], entanglement and twisting of these pulled-out fibers can be observed. This is regarded as a precursor to pill formation. Finally, in Figure 3C [30 minutes, 150 cycles], we see the development of pills attached to the fabric by a few fibers. With continued abrasion beyond 150 cycles, some of the pills become detached, but also new pills form.

3.2. Morphology of fuzziness

Fuzziness can result from fiber fracture, or from fibers being pulled out of the fabric without fracture. Fabric specimens abraded to the initial stage of fuzziness [Figure 3A] were examined under the SEM to determine which mechanism is the most prevalent. Four distinct mechanisms were identified. These are characterized by the inset cartoons in Figure 4, and exemplified by representative SEM images.

Type 1 and 2 involve fiber fracture, between bond sites [Type 1] or adjacent to a bond site [Type 2]. In both cases, the fracture is identified by a circle in Figure 4. Notice that for Type 2, the fracture exhibits a locally damaged or fused region, whereas for Type 1, the fracture is clean.

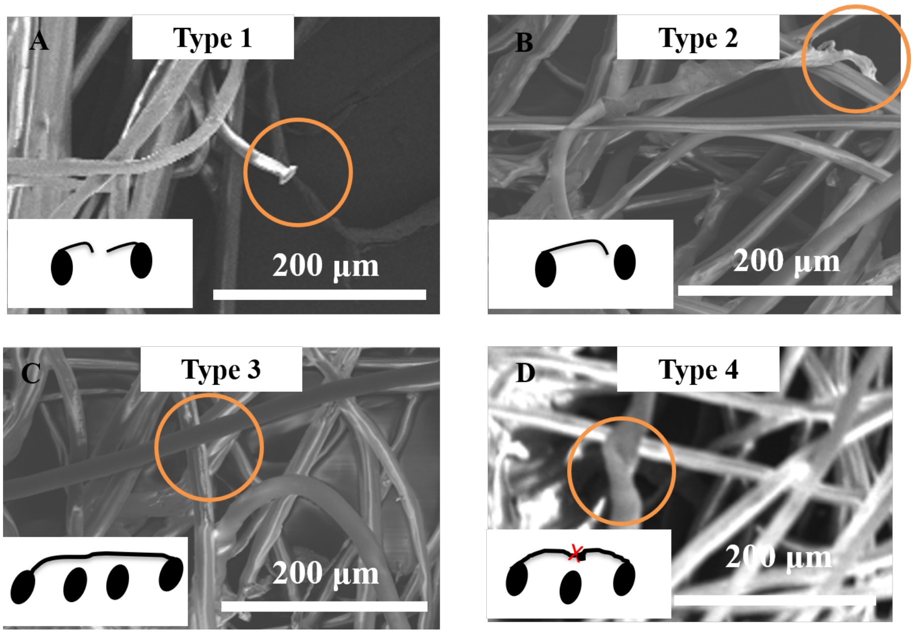

Figure 4: Forms of fabric damage associated with fuzziness: Type 1: Fiber fracture between bond sites; Type 2: fiber fracture at a bond site; Type 3: Pull-out of a locally unbonded fiber; Type 4: Detachment of an unbroken fiber from one or more bond sites. The cartoon insets give a clearer picture of these mechanisms.

Types 3 and 4 describe situations where a fiber is pulled from the fabric without fracture. In Type 4 the fiber is separated from one or more bond sites as shown by the existence of locally damaged regions. By contrast, Type 3 describes fibers that exhibit no such regions, indicating that they probably 'by-passed' several potential bond sites in the original fabric manufacturing process. The fiber direction is somewhat influenced by the manufacturing direction, but the fiber length between bond sites has a broad distribution and indeed fibers passing between bond sites without attachment are clearly visible in the SEM images of Figure 2 [C and D].

This distinction is seen more clearly in higher magnification optical images such as Figure 5, which is a top view of fibers pulled out to a location above the main body of the fabric. The blue arrows (i) in this figure indicate regions where an unbroken fiber has been detached from a bond site, whereas the red arrow (ii) indicates a fiber which is longer than the bond spacing [1.5 mm], but which shows no sign of bond site detachment. Examination of a large number of images of this kind show that Types 3 and 4 occur more frequently than Types 1 and 2. In other words, the fuzziness generated consists primarily of pulled out unbroken fibers at this stage.

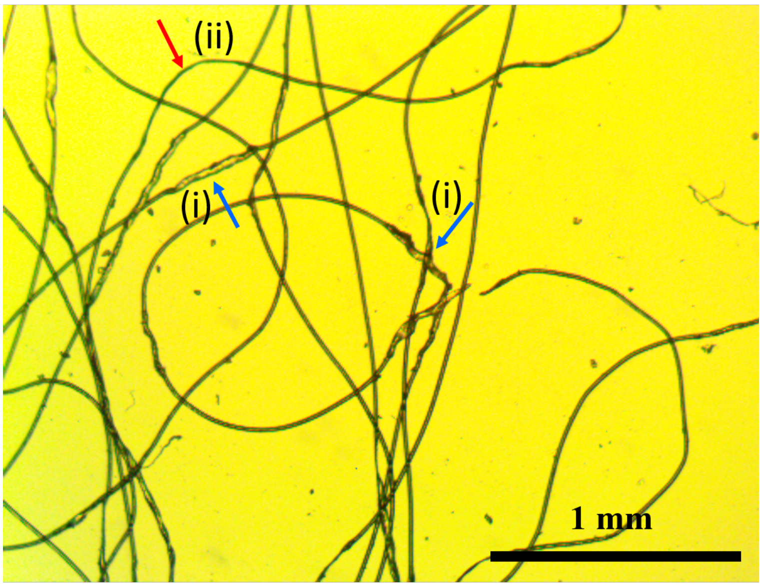

Figure 5: Higher magnification optical image of fuzziness. The blue arrows (i) identify damaged regions on fibers pulled out from bond sites [Type 4] and the red arrow (ii) indicates an unbonded and unbroken fiber [Type 3].

3.3. Pill precursors

We recall from Section 3.1 and image B-2 of Figure 3 that pill formation is generally preceded by fiber entanglement and other morphological features that may be regarded as pill precursors. Some typical forms are shown in Figure 6, with the first two being the most prevalent. Wavy fibers account for about half of observed precursors, and twisted fibers for about 25%.

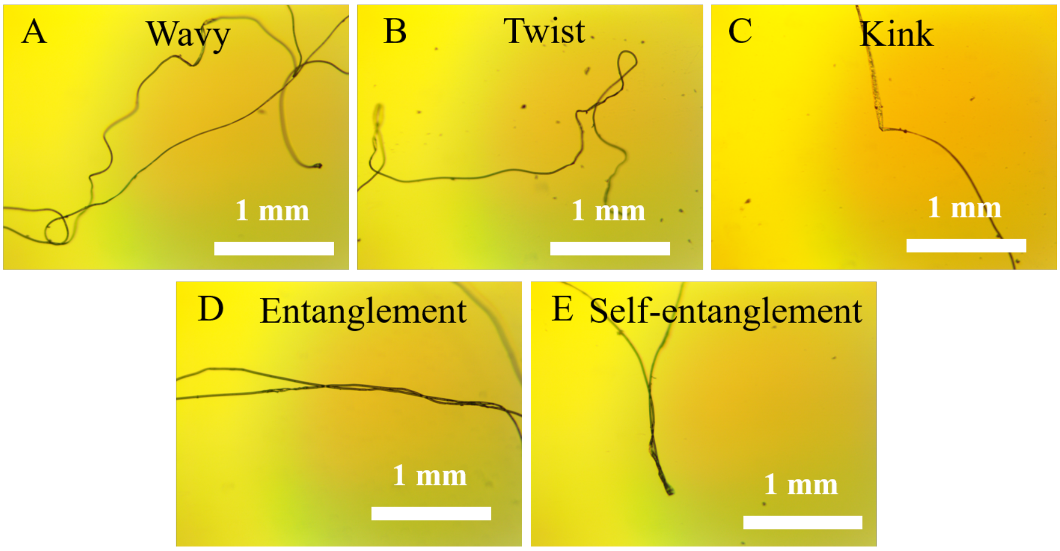

Figure 6: Types of precursor morphology.

3.4. Pill morphology and correlation with precursors

Figure 7 shows typical pills formed in the abrasion process. These can be characterized as *ball pills* [Figure 7A], which are approximately equi-axed, or *long pills* [Figure 7C], in which one dimension is significantly larger than the other two.

Ball pills are typically anchored to the fabric by only a few fibers, as shown in Figure 7B. By contrast, long pills are anchored at both ends, as shown in Figure 7D, and most of the fibers in the pill are approximately aligned with the long dimension.

In the experiments described in Section 3.1, most of the pills formed are ball pills, and we recall that wavy fibers are the most common precursors observed. In fact, all kinds of precursors can often be seen in the vicinity of a partially formed ball pill.

Geometrical considerations suggest that entanglements should be the most appropriate precursor for long pills, but the relative scarcity of these makes it impossible to establish such a correlation from the results of Section 3.1. We therefore experimented with different abradants to find one that generates a preponderance of long pills, the most effective being a small pad of silicone rubber, as shown in Figure 8A. Back-and-forth motion of amplitude approximately equal to the length of this pad in the sliding direction (≈ 7 mm) then generates more than 50% entanglement precursors, a typical example being shown in Figure 8B. The resulting long pills are shown in Figure 9B.

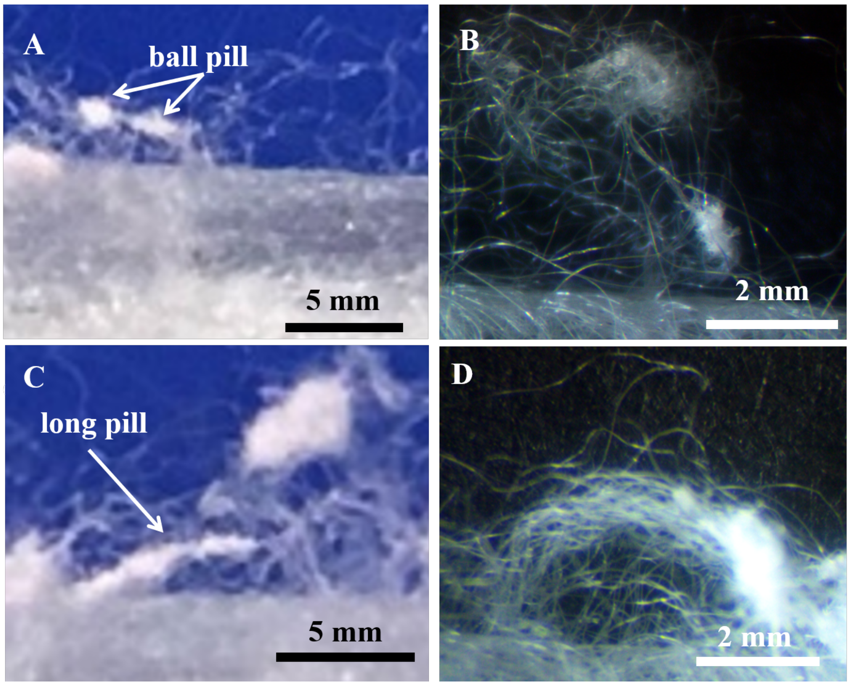

Figure 7: Morphology of ball pills [A,B] and long pills [C,D].

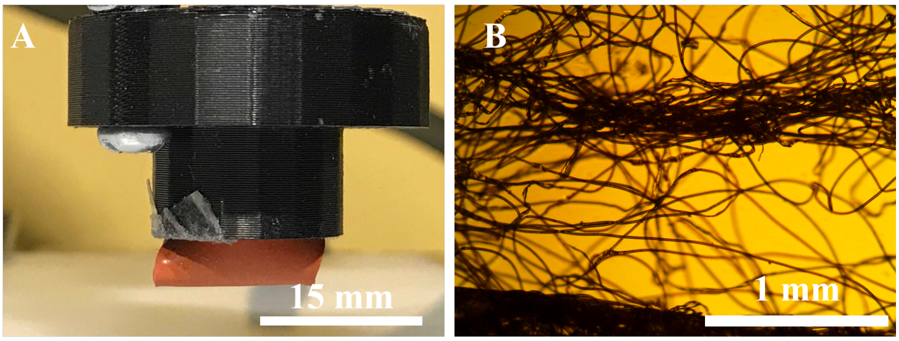

Figure 8: Silicone rubber abradant [A] and resulting entanglements [B].

3.4.1. Long pill orientation

Long pills generally tend to align with their long axes perpendicular to the direction of sliding, but this conclusion is somewhat modified by fabric anisotropy. Examination of unworn fabric shows that fiber orientation is preferentially aligned with the direction of manufacture. In the early stages of abrasion [Figure 9A], long pills tend to align with this direction, indicated by the dashed line. However, as abrasion proceeds they tend to rotate towards an orientation approximately perpendicular to the sliding direction, indicated by the arrow in Figure 9B. Notice also that the pills become ‘thicker’ as abrasion proceeds, indicating that more fibers are entangled. These experiments were repeated with 12 different equispaced sliding directions relative to the machine direction, and in all cases long pills tended to become oriented approximately perpendicular to the sliding direction. We also note that the numbers of ball pills and long pills generated was not found to depend upon sliding direction.

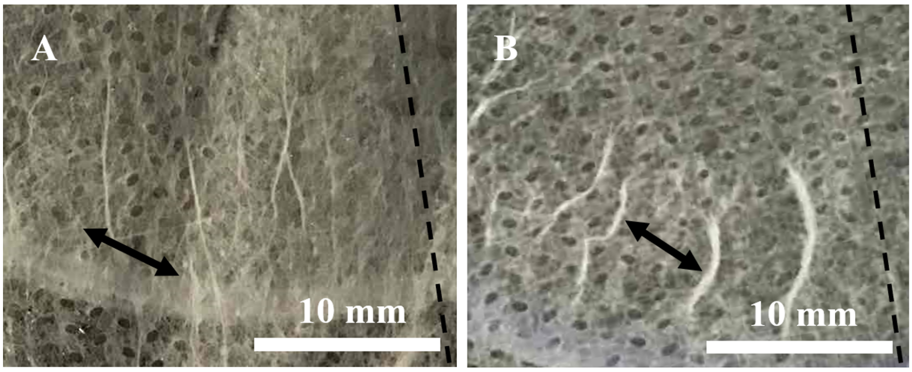

Figure 9: [A] Long pills form initially along the machine direction, indicated by the dashed line, but after continued sliding [B], they become approximately perpendicular to the sliding direction, indicated by the arrow.

3.5. Effect of bonding temperature

The abrasion experiments described so far involve the fabric of Figure 2 (A,C) that was manufactured using a bonding temperature of 135 °C. Corresponding experiments on a fabric bonded at a higher temperature of 153 °C show an initial stage of fuzziness, but this does not then typically lead to significant pill formation. It should be noted however that this improvement in abrasion resistance comes at a cost, in that the resulting fabric is less ‘qualitatively soft’ to the touch, and hence less attractive in applications involving contact with the skin [16], but while the possibility of an optimization between softness and wear resistance is an important question, it is beyond the scope of this paper.

We recall from Section 3.2 that abrasion damage for the 135 °C fabric often starts from a Type 4 process [Figures 4, 5], in which a fiber is detached from one or more bond sites without fiber fracture, and then is pulled out from the fabric. Clearly this process is less likely if the bonding strength is increased.

To test this hypothesis, we performed peel tests on the two fabrics. Several fibers were grasped by a sprung stall clamp and these were then pulled from the fabric using an Instron machine (5940 Series Single Column Table Top System). Figure 10 shows the force-extension curve and representative images at various stages of loading. The maximum force reached is an order of magnitude lower for the 135 °C fabric [Figure 10A] than for the 153 °C fabric [Figure 10B] and since the fibers are the same for the two fabrics, we attribute this to the greater bond strength achieved at 153 °C. If a fiber becomes detached from a bond site without breakage, it will again contribute to the force once the extension increases sufficiently to take up the slack. This behaviour explains the numerous downward jumps in the force extension curve in Figure 10A, and also the greater extension to failure. By contrast, in Figure 10B, most of the fibers break at or near the maximum load point.

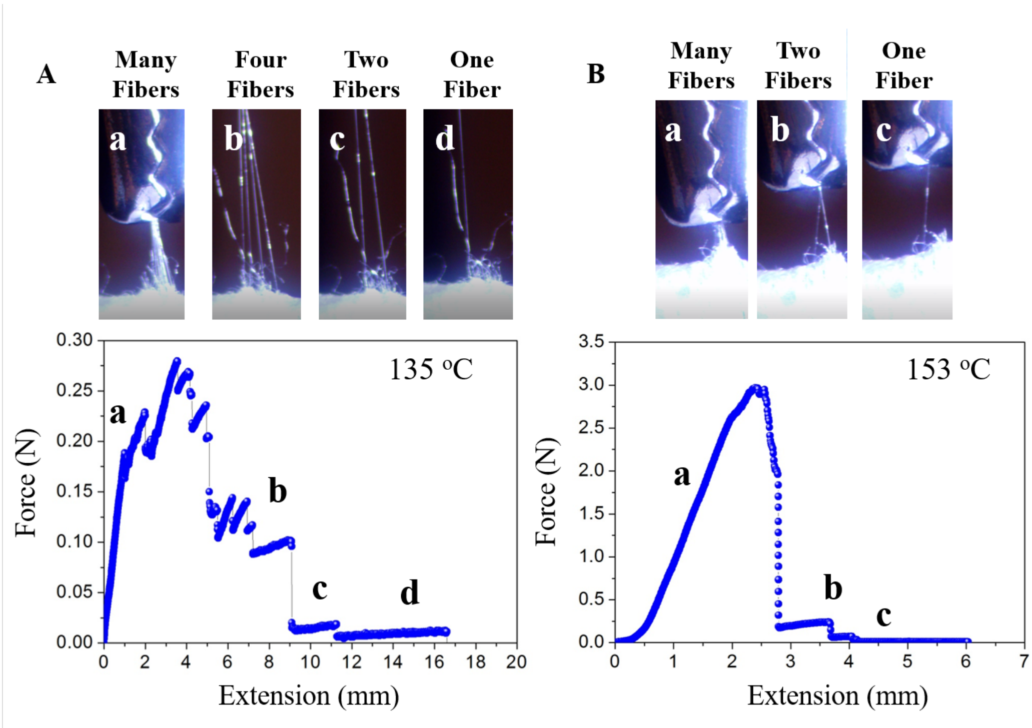

Figure 10: Force-extension curves and representative images for peel tests on fabrics bonded at 135 °C (A) and 153 °C (B).

3.6. Effect of fiber diameter

Since the fabrics tested comprise fibers of very small diameter [≈ 20 μm], it might reasonably be hypothesised that intermolecular [e.g. van der Waals'] forces are involved in the development of pills. We therefore performed some 'qualitative' experiments on fibers of larger diameter, notably human hair [≈ 50 μm] and cotton yarn [≈ 1 mm]. Rolling a group of these fibers between two fingers, twist and entanglement precursors similar to those in Figure 6 are obtained [Figure 11(A,B)], and indeed similar morphologies could be obtained even with a 3 mm cable (C). With the cotton yarn, further 'abrasion' leads to the development of a ball pill [Figure 11(D–F)] if the ends are left free, but a long pill [Figure 11(G)] if the ends are fixed. These results suggest that intermolecular forces do not play a significant rôle in pill formation. Friction may also play a significant rôle in the entanglement and self-adhesion of these fibers. We hope to investigate this mechanism in future research.

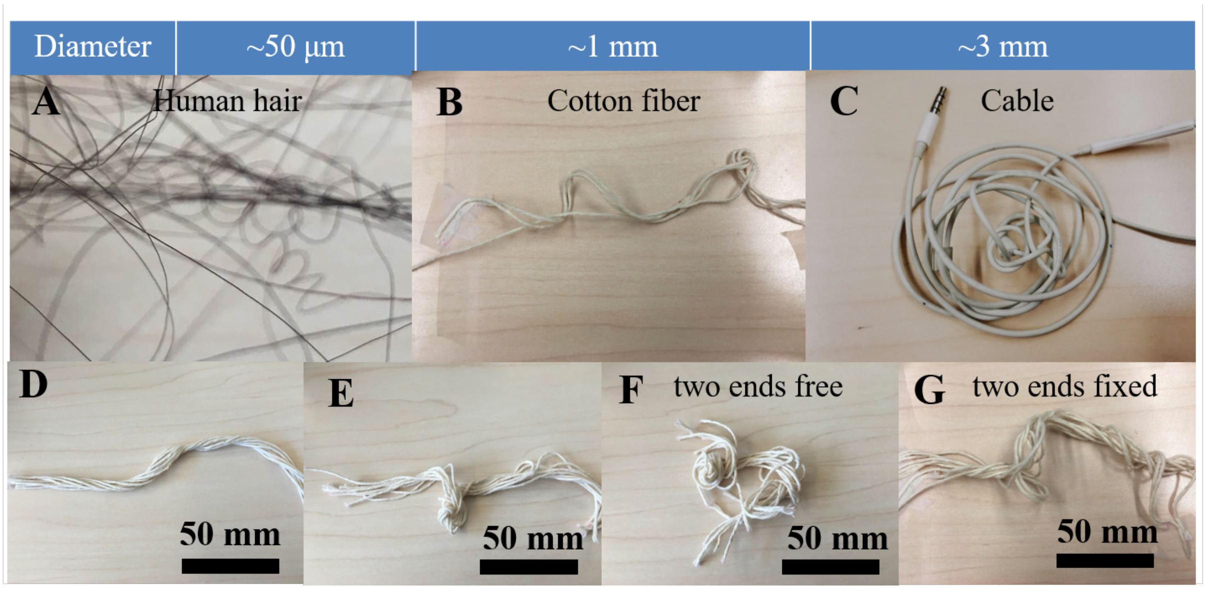

Figure 11: Precursor and pill formation for larger diameter fibers.

4. Conclusions

The development of abrasive damage to a non-woven fabric has been observed using an *in-situ* experimental system. Fuzziness precedes the development of pills and is characterized by pull-out of unbonded fibers or by separation of a fiber from a bond site without fracture. For this reason, increased bond strength obtained by a higher bonding temperature during manufacture reduces abrasion damage.

Various types of pill precursor have been identified. Small amplitude back-and-forth abrasion using a silicone rubber abradant generates 'entanglement' precursors, and leads to the development of long pills, with the long axis perpendicular to the direction of motion. Larger amplitude motion with a fibrous abradant generates a wider range of precursors and leads to a predominance of equi-axed ball pills.

Experiments with larger diameter fibers suggest that adhesive forces between fibers is not a significant factor in pill generation.

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