The Hong Kong Polytechnic University

Institute of Textiles & Clothing

Mechanisms of Pilling Formation and Reduction by Attrition Methods

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CERTIFICATE OF ORIGINALITY

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_________________________ (Signed)

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ABSTRACT

In this study, the mechanisms of the fuzz and pilling formation were studied in order to develop an effective anti-pilling treatment. With the appreciation that the root of the pilling problem is the existence of a limited amount of pillable fuzz in the fabrics, physical treatments that include acceleration of fuzz generation and fuzz removal were proposed.

Acceleration methods for fuzz generation, including tumbling, flat abrasion and brushing, have been investigated. Attrition methods, including the use of laser and lint shaver, have been also explored. The effects of the treatments were assessed by Random Tumble Pilling Tester and ICI Pilling Box. Based on these assessments, promising anti-pilling treatments were identified. The experimental results of knitted fabrics made from both conventional and Nu-Torque^{TM} ring yarn indicate that the identified treatments could effectively increase the pilling resistance of worsted knitted fabrics by accelerating the fuzz generation and reducing the amount of potential pillable fuzz on the surface of the fabric. A wear trial on treated commercial sweaters also indicates that the treatment is also effective on finished garment. Assessment results show that the treatment does not affect colour, bursting strength and thermal insulation property of the fabric or garments.

Based on the findings achieved, a prototype device was built to implement an efficient fuzz generation of fabrics. The working principle, operation parameters and evaluation of the treated sample are presented. It is a systematic study on the

mechanisms and feasibility of effective anti-pilling treatments towards the commercial application.

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Chapter 1 Introduction

1.1 Background of Study

Pilling is a fault in which entangled fibres cling to the cloth surface during wearing or laundering, giving a poor appearance to the garment. The entanglements of loose fibres that form balls on the fabric surface are called ‘pills’. The development of pills on a fabric surface not only results in an unsightly appearance, but also initiates the attrition of the garment and causes premature wear. Therefore, pilling has been a serious problem for the apparel industry. As a result, research on pilling has drawn attention from many researchers since the mid-1950s.

Over the years, many anti-pilling treatments have been developed to increase the pilling resistance of fabrics. Generally, these treatments can be classified into three categories, namely physical, chemical and biochemical methods (Ukponmwan, Mukhopadhyay, & Chatterjee, 1998). However, complete elimination is rare as there are too many factors affecting the pilling which can only be controlled limitedly.

Recently, a new yarn modification technique Nu-Torque™ has been developed at the Hong Kong Polytechnic University. Results have shown that Nu-Torque™ worsted yarn has different properties compared with conventional ring yarn, such as lower twist, lower yarn hairiness, softer handle, and less residual torque. Lower hairiness may lead to better resistance to pill. However, the pilling tendency of the fabrics made from such yarns has not yet been studied thoroughly.

In this study, the pilling tendency of Nu-Torque™ worsted knitted fabrics in real and simulated wear will be studied. The pilling formation process in Random Tumble Pilling Tester will be studied. Moreover, potential anti-pilling treatments will be explored and investigated, if necessary.

1.2 Aim and Objectives

The research study is aimed to study the pilling resistance of worsted fabric knitted by Nu-Torque™ yarns and potential anti-pilling treatments with the following objectives:

1. To study the pilling behaviour of the knitted fabrics made from Nu-Torque™ yarns by using the Random Tumble Pilling tester, ICI Pilling Box and Modified Martindale Tester.

2. To investigate various anti-pilling treatments for different types of worsted knitted fabrics, including Nu-Torque™ and conventional fabrics.

3. To explore various physical processes for anti-pilling treatments and identify promising ones.

4. To identify the mechanisms and processing parameters for the identified potential anti-pilling treatments

1.3 Significance and Values

A review of the literature concerning the pilling problem of fabrics reveals that the anti-pilling treatments used nowadays can not satisfy the industry's requirements as they may adversely affect the other desirable physical properties of the fabrics, or may produce harmful chemical wastes. The treatments are also costly in terms of material, energy and processing expense, and too complicated for multi-fibre blends.

In addition, the pilling tendency of the developed Nu-Torque™ yarn has not been studied thoroughly and a proper anti-pilling treatment is needed in order to retain its superior property.

In this project, anti-pilling treatments for worsted knitted fabrics, which are clean, do not influence other desirable fabric properties, and potential for industrial mass production will be explored. An effective anti-pilling treatment will be identified and investigated.

1.4 Research Methodology and Plan

To achieve the objectives of the project, the following research methodology will be employed:

a) Literature review

Review on literatures will be conducted. Firstly, the existing anti-pilling treatments will be studied with a critical view and the limitations of existing anti-pilling treatments can be identified. Secondly, based on the study of mechanism of fuzz and pilling formation, the idea of potential anti-pilling treatments, which can reduce the pilling tendency of fabrics effectively, can be generated.

b) Study of pilling behaviour worsted knitted fabric

The pilling behaviour of two types of worsted knitted fabric will be investigated. They are made of conventional ring yarns and Nu-Torque^{TM} ring yarns. Fabric samples will be subjected to the tumbling action for pilling acceleration of the Atlas Electric tester of Random Tumble Pilling Test (ASTM D3512-02). The tester was chosen because it is effective for accelerating pilling formation. The number of pills formed on the surface of samples will be plotted against time. This pilling-time curve would be a useful indicator to disclose the pilling behaviour of the fabric samples.

c) Study of the effectiveness of potential anti-pilling treatments

The effect of different treatments on the worsted knitted fabric will be studied. Standard testing methods will be used to evaluate the effectiveness of the treatment on the pilling performance of the fabric samples. ICI Pilling Box method (ISO 129451) is the main method to be used for evaluation as it is a common practice in the wool knitting industry, while Random Tumble Pilling Test (ASTM D3512-02) will be also used for reference.

d) Application of the proposed treatment on the garment samples

The proposed treatment will be applied on the garment samples available in the market. Objective standard testing methods will be used to evaluate the pilling performance and the other fabric properties of the treated and untreated samples. On the other hand, subjective evaluation will be used to investigate the effect of the treatments on the fabric handle and comfort.

e) Development of a prototype device

After a potential treatment is developed, a prototype of the device which can provide the treatment will be developed. By so doing, the treatment can be studied in a more thorough manner as the treatment provided is repeatable. The parameters of the device will be investigated in term of treatment effectiveness.

1.5 Outline of Thesis

This thesis consists of six chapters. Chapter 1 introduces the background, objectives, the significance and values, as well as the methodology of this investigation. Chapter 2 briefly reviews previous investigations on the pilling mechanism, factors affecting the formation of pilling, existing anti-pilling treatments, and attrition treatment. Chapter 3 provides experimental details of the proposed treatment. It includes the material preparation, working procedure and assessment methods adopted in the study. Chapter 4 is mainly concerned with the results and discussions of the experiments mentioned in chapter 3. A more effective treatment with identified parameters is determined by the analysis of the results of the experiments. Chapter 5 describes details of a prototype device made based on the findings achieved in chapter 4. The working principle, operation parameters and evaluation of the treated and untreated samples are presented. Finally, Chapter 6 provides a conclusion. The discussions of the limitations and recommendations for future work are also included.

Chapter 2 Literature Review

2.1 Introduction

Studies of pilling were firstly published in 1954 (Stryckman & Leclereq, 1973b). It has been suggested that pilling did not exist before 1945. This statement may be true due to the fact that knitted garments became much more widely available and their use has increased since 1945. It is a well known fact that, knitted garment pills more than woven garments. In addition, there has been a fashion trend towards lighter and softer fabrics which are more likely to pill. This is particularly true for high quality fine rather than coarse wool and blend garments.

2.2 Pilling and fuzz generation

2.2.1 Definition of pilling

Pilling is a phenomenon exhibited by fabrics formed from staple spun yarns. Pills are masses of tangled fibres that appear on fabric surfaces during wear or laundering, resulting in an unsightly appearance and an unpleasant handle. The structure of pill is divided into two parts, namely the “head” and the “stalk”. The “head” consists of entangled fibres and contaminants, while the “stalk” consists of the anchor fibres only.

Sivakumar and Pillay (1981) defined pills as bundles of entangled fibres formed on the surface of fabrics during rubbing or wear.

Sridharan (1982) defined pilling as a physical process appearing on the surface of a garment, taking the form of small balls made up of fibres, sometimes with contaminants. These fibres give a bad appearance to the garment.

The International Fabricare Institute's Education and Consumer Relations Departments (1988) defined pilling as the ' formation of small tangles of fibres or balls on the surface of a fabric'. The pills cling to the surface because the fibres are still anchored to the yarns in the fabric. Pilling changes the appearance and texture of the fabric.

2.2.2 Pilling mechanism

The number of pills on a fabric surface at any time is the result of a dynamic equilibrium between two opposing effects, pill formation and pill wear off (Conti & Tassinari, 1974; Gintis & Mead, 1959). Through abrasion, loose fibres are pulled to the fabric surface and form a layer of 'fuzz'. The loose fibres are then entangled by the applied abrasion to form pills. As the abrasion continues, the anchor fibres are eventually broken and the pills break off. When the rate of pill formation and the rate of pill break off are equal, an equilibrium state exists. When the abrasion lasts long enough, the source of loose fibres becomes exhausted, the rate of pill formation decreases and the total number of pills decreases. After an initial period of pill growth, the total number of pills is plateaued and then decreased as pill loss increases.

Therefore, the complicated pilling mechanism can be summarised in the following three stages (Figure 2.1):

- The fuzz formation by fibre migration to the fabric surface during wear or test
- The entanglement of the fuzz into the pills
- The wearing –off of the pills under the stress of abrasion

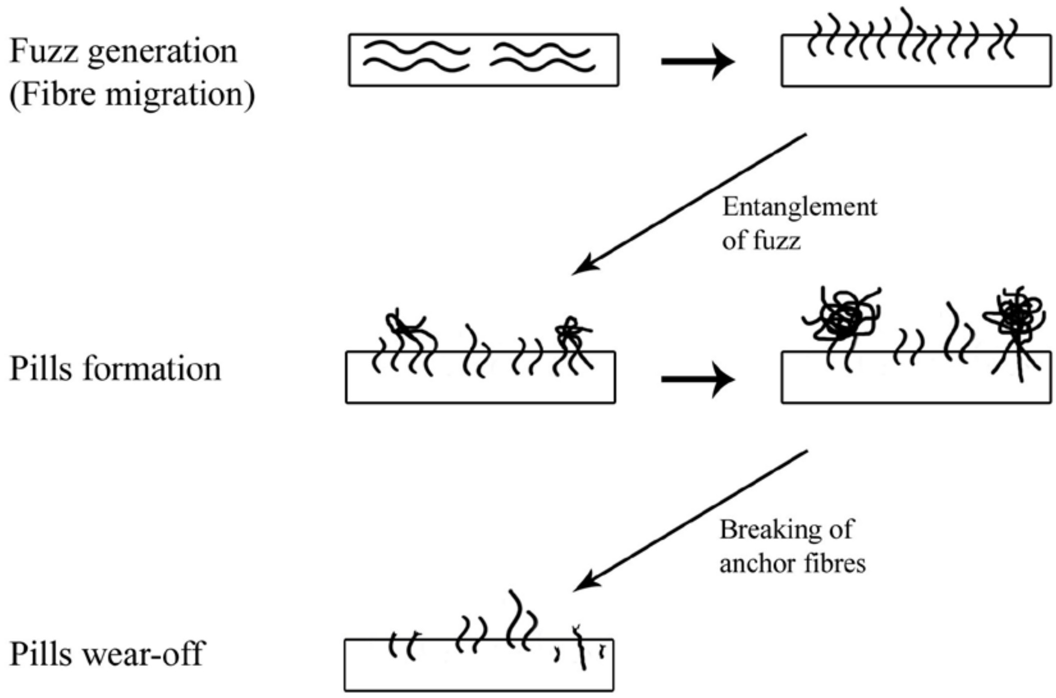


Figure.2.1 A schematic diagram for stages of pilling

The three stages of the pilling mechanism do not occur successively. In practice, two or three steps may happen simultaneously. Cooke and Arthur (1981) proposed that there is a reversible equilibrium existed between the pillable fuzz and pills, the pills and worn off-fuzz pills, as well as the pills and worn-off fuzz.

a) Mechanism of fuzz formation

As mentioned above, the formation of fuzz is the very beginning of the formation of pills. There have been many studies on the formation of fuzz. For example, Clark and Hearle (1983) conducted a series of experiments and found that rubbing the fabric surface by an applied load will produce a frictional force on the fibres. This force can be resolved into two components, one along the fibre axis and the other perpendicular to the fibre axis. The axial force will tend to drag the fibre out of the fabric surface, but the axial force cannot produce the movement of fibre into the fabric as the fibre will not maintain this axial compressive forces. If the frictional force is greater than the cohesive force between the fibres, then the fibres will migrate to the surface to form fuzz.

b) Pillable fuzz

Conti and Tassinari (1974) showed that each type of fibre had the existence of the critical height below which no entanglement of fibres would be occurred. The critical height of wool fibre is 0.714cm. With the length equal to or greater than the critical height of the fibre at which pilling occur, it is defined as pillable fuzz.

Besides, Conti and Tassinari (1975) mentioned that there is a critical number of fibre per unit area, that is, the minimum number of fibre necessary to form a stable pill.

Westenberg (T.N.O, 1963) measured the fineness of constituent fibres of pills in a wool knitted fabric. Mainly finer fibres were found in the pills. This indicates that there is preferential migration towards the yarn exterior of fibres of low rigidity. By measuring the fibre length, it was also proved that most of the fibres in the pill consist of broken fibres. His finding was further confirmed by Cooke (1984) who showed that finer fibres in wool knitwear were incorporated into the pill core. Thus it seems that pillable fuzz comes from the broken fibre and those with smaller diameter.

c) Limited supply of fuzz

Gintis and Mead (1959) measured the rate of fuzz formation in several fabrics which were brushed for certain period. The results show that, during the initial period of brushing, the amount of fuzz was raised to a maximum value and then levelled off.

As the weight loss in the fabric sample was very small due to the limited number of the worn-off pills, many researchers considered the pilling to be a self-limiting process. Richards (1962) found that the plain knitted fabric produced 117mg/65cm^2 of pills which represented about 9% of the initial mass per unit area.

Cooke (1984) also investigated this by selecting knitted garments produced from lamb and merino types of wool and included both worsted and woollen yarns. The garments were worn for three days and then washed. The cycles were repeated. The density and the location of the pills and fuzz were recorded. The results show that the worsted garments showed pill limitation after six day wear period, while the woollen garments showed reductions in the pill density only after three wash cycles. With the aid of scanning electron microscopy and yarn-sectioning techniques, they confirmed that the fatigue cracking was restricted to the fibre of diameter about 30μm and greater. The finer fibres, which were less than 20μm, were incorporated in pills.

All of the above findings support the statement by Omura *et al* (1969) that the amount of fuzz trends initially to increase sharply and then levels off as it approaches a nearly horizontal asymptote. It implies that the amount of pillable fuzz is limited in supply. Therefore, it seems that shearing fuzz in the early stage of abrasion is an efficacious method of pilling control.

2.3 Factors affecting pilling

2.3.1 Introduction

Factors affecting pilling can be classified into external and internal factors. The external factors are produced by the external conditions such as the application of lubricant to increase the pilling tendency of the fabric. The internal factors are the inherent properties of the textile materials such as the fibre, yarn and fabric properties.

Beltran, Wang and Wang (2005) conducted a study ranking the contribution of various fibre, yarn and fabric attributes to the pilling of wool knitwear. On the basis of an artificial neural network modelling, a combination of sensitivity analysis, forwards/backwards search and genetic algorithms was used to identify the importance of various fibre/yarn/fabric input parameters. The three different techniques show broad similarities in their assessment of important parameters for affecting fabric pilling. As shown in Figure 2.2, the fabric cover factor has the most effect on pilling, followed by yarn count, thin places, fibre length, yarn twist, etc.

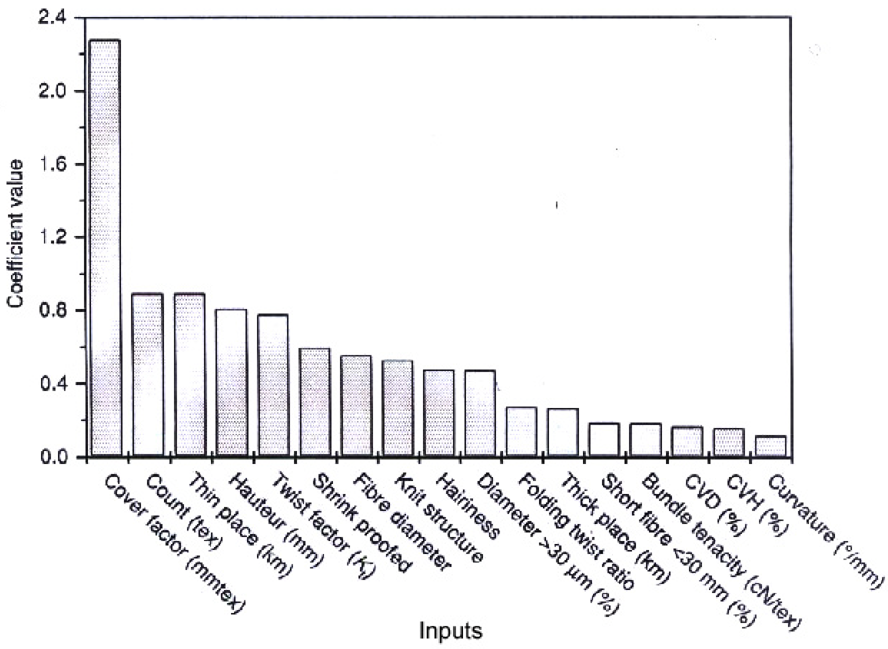


Figure 2.2 Mean sensitivity values from the three different techniques

(Beltran *et al*., 2005)

To verify the findings of input feature selection, input factors deemed to have a small effect on the predicted pilling output, such as fibre length and diameter variations and curvature, were removed and the subsequent performance statistically compared to the original multi-layer perception. Although removing the "unimportant" input parameters do not cause any significant difference at the 5% significance level, 10 input features affecting pilling still seems to be too many. It means that the pilling behaviour of the fabric is affected by numerous factors at the same time, and one singles factor is great enough to produce pilling problem.

Moreover, there are many limitations in controlling the internal factors. For example, the higher the linear density of the fibre, the lower the pilling tendency will be. Theoretically, the linear density of the fibre can be increased to the value which causes no pilling. However, it would make the fabric too stiff in handle and not suitable for wearing.

Therefore the internal factors affecting the pilling tendency can be modified to minimize the pilling problem, but complete elimination is rare as there are too many factors affecting the problem and only can be controlled limitedly.

2.3.2 Fibre properties

The fibre properties affect the tendencies of fuzz formation, the entanglement, and the pill wear-off in various extents.

a) Fibre type

Gintis and Mead (1959) studied the fuzz tendency of various textile fibres along with several important single fibre properties. They found that nylon is the most prone towards fuzzing as it has high strength and moderate inter-fibre friction. Wool and acetate are low-tenacity fibres. They break instead of pulling out, resulting in short fuzz. Viscose, Darcon, and Orlon are the intermediate performers.

Duckett and Goswami (1984) designed a multi-stage apparatus for characterizing the cyclic-torsional-fatigue behaviour of a single fibre. They found that those fibres which fatigue readily, such as cotton, low-pill polyester fibre, and fine wools, tend to form tight and hard pills. The inclusion of these fibres in blends with fibres such as nylon or Vincel readily changes the pill morphology and the rate of pilling formation.

Pilling on wool fabrics is a serious defect. Omura *et al* (1969) found that wool fibres have the maximum values in number of pills which exist over a wide range of cycles. This feature is absent in other fibres. Besides, pills can be produced on wool fabrics by slight abrasion and soon reach a stationary state. They decrease gradually in number as they have a longer life than pills on fabrics of acrylic, cotton and their blends. Pills on wool fabrics are also distinctly large and thick, so visible that pilling is so common on wool products.

b) Fibre length, finess and cross-section

Continuous filaments do not normally form pills (Anonymous, 1988). It is because they do not abrade or break easily and therefore fuzz is not easily to be generated. In staple-yarn fabric, the longer the staple, the less the pilling is observed in general because there are fewer protruding fibre ends per unit area (Sridharan, 1982). Longer fibres are also more firmly secured in the yarn due to the greater inter-fibre friction.

An increase in the linear density of fibre causes a decrease of the pilling tendency of the fabric (Richards, 1962). It is because the higher the linear density, the higher the flexural rigidity of fibre.

A circular cross-section with a smooth surface of the fibre allows the fibre to come to the surface of a fabric and forms pills. The pilling tendency falls with an increased flatness of the fibre if an irregular cross-section is used (Gintis & Mead, 1959).

c) Inter-fibre friction and fibre crimp

The higher the inter-fibre friction, the less is the pilling tendency (Sridharan, 1982). It is affected by the surface characteristic of the fibre. In general, an increase in the crimp level of fibre leads to the reduction of the pilling as the crimp increase the inter-fibre friction. Moreover, the weak points of tenacity at the crimp apices make the fibres easy to break (Sridharan, 1982). In particular case, when the fibres are situated outside the yarn, the pilling tendency will be increased with increasing the fibre crimp. It is because the high crimp of the fibre provides high chances for fuzz entanglement (Cooke, 1984). The straight fibre crimp provides better cohesion of inter-fibres with greater fibre friction to limit fuzz formation. The spiral fibre crimp gives least fibre cohesion than the zigzag fibre crimp.

2.3.3 Yarn properties

The yarn properties are contributed by the fibre properties and the spinning parameter.

a) Yarn type

The spinning technique used to make the component yarns has a significant impact on the pilling tendency of a fabric. Ring spun yarn is more resistant to pilling than rotor spun yarn; while both of them are worse than air-jet-spun yarns, which produce fabrics with much improved pilling control (Alston, 1992). The high pilling resistance of air-jet-spun products is attributed to the yarns' tightly wrapped structure, which inhibits the formation of free fibre ends. On the other hand, the low pilling resistance of rotor-spun products is due to the poor fibre orientation of the yarn, which causes it to fuzz more initially.

Recently, a new yarn modification technique, Nu-Torque^{TM} spinning, has been developed at the Hong Kong Polytechnic University (Hua, Tao, Cheng, & Xu, 2007; Lau & Tao, 1997; Tao, 1996; Tao, Lo, & Lau, 1997; Tao & Xu, 2002; Xu & Tao, 2003, 2008; Yang, Tao, Xu, & Lam, 2007). The Nu-Torque^{TM} yarn has a torque-balanced structure and the residual torque is then reduced or eliminated. It is produced by a torque reduction device installed between the yarn guide and front rollers on a conventional ring spinning frame. Fibres are rearranged and optimised by changing the state of fibres in the spinning triangle. Results have shown that Nu-Torque^{TM} worsted yarn has different properties compared to conventional ring yarn, such as lower yarn hairiness, softer handle and less residual torque. Lower hairiness may benefit to pilling resistance. However, higher pilling tendency may be resulted as the fibres are looser packed. By the way, the pilling tendency of the developed Nu-Torque^{TM} yarn has not been studied thoroughly and a proper anti-pilling treatment is needed in order to retain its superior properties.

b) Yarn count, twist and hairiness

In a study on knitted fabric, pilling is observed to be less for yarns of finer count as the fibres are held more firmly (Richards, 1962). The higher the twist in the yarn, the less is the pilling. It is due to the higher compactness and less protruding fibre in the yarn (Anonymous, 1988). Yarns with higher hairiness have more protruding fibres, which increase the pilling tendency as the fibres are easier to entangle with other fibres or contaminants (Stryckman & Leclereq, 1973a)

c) Yarn blend and plying

In general, a fabric made from a blend fibres pills more than in a similar fabric made from only one of the blend components, as there is incompatibility between the fibres (Sridharan, 1982). Fabrics made from singles yarns are more prone to pilling than those produced from plied yarns, the reason behind is that the second twisting of the plied yarns causes the protruding fibres on the surface of a singles yarn to be secured (Sivakumar & Pillay, 1981).

2.3.4 Fabric properties

Since fabric is formed by the combination of fibres and yarns, the fibre and yarn properties affecting pilling may be brought forward and affect the pilling tendency of the fabric. Besides, the pilling tendency of a fabric is also affected by its fabric structure.

a) Fabric type

Pilling can be found in woven and knitted fabrics, while knitted fabric is easier to form pill than the woven fabrics. Since knitted fabric is in a series of loops, greater amount of yarn surface are exposed, making them more susceptible to abrasion in wear. Moreover, knitted fabrics generally constructed with low twist staple yarn to give a soft, bulky feel and appearance. This gives more chances to develop pills onto the fabric surface(Cooke, 1984).

b) Fabric compactness

The fabric construction has a significant impact on the tendency to create fuzz and eventually pill. The pilling tendency falls with an increase in the number of ends and picks per unit area and with a reduction in the length of floats (Sridharan, 1982).

c) Fabric structure

Pilling tendency will be increased when the knitted fabrics have greater relaxation (Cooke, 1984). It is because the loop strain will be released in relaxation and then the fibre migration is enhanced. Therefore, the pilling tendency is increased. Richard (1962) found that rib fabrics pilled slightly more than plain fabrics with the same stitch length.

d) Dyeing and finishing parameters

Dyeing and specifically finishing can exert great influence on the pilling tendency of a fabric. Fabric tenacity may be increased or decreased after dyeing, as well as the fabric surface roughness, hairiness and inter-fibre friction (Sridharan, 1982). It really depends on the method of dyeing and dye stuff used.

2.4 Anti-pilling treatments

Over the years, many anti-pilling treatments have been developed to increase the pilling resistance of fabrics. Two approaches have been taken to prevent pills from accumulating on fabric surfaces (Schindler, 2004) and three types of method, including physical, chemical and biochemical (Ukponmwan et al., 1998) can be used. The first approach is to inhabit the formation of pills. It can be achieved by removing protruding fibres using physical and biochemical methods or bind the fibres into the fabric surface using chemical method. The second approach is to cause the pills to fall off the fabric as soon as they are formed. This can be accomplished by reducing the fibre strength using chemical methods.

2.4.1 Physical methods

a) Shearing or cropping

Shearing or cropping is a well known method that can reduce the pilling of fabrics. In practice, this technique is only applicable to smooth faced fabrics as if the fabric surface of knitted fabrics is irregular; technically it is very difficult to shear knitted fabrics (Stryckman & Leclereq, 1973b).

b) Brushing

Brushing treatments aim to remove the maximum amount of fibres to reduce hairiness, thus, brushing is often recommended for reducing pilling (Stryckman

& Leclereq, 1973b). Generally it only removes the wild fibres loosely anchored in the yarn. If brushing is too severe, it will pull out a large number of fibres and increase the hairiness.

c) Singeing

The singeing treatment involves melting the tips of thermoplastic fibres emerging from the fabric surface, transforming them into small balls invisible to the naked eye when the process is performed properly (Stryckman & Leclereq, 1973b). It is advisable to spray the fabric with water before treatment and to use a cooling device immediately following passage through the flame. It is essential to dye before singeing, as the absorption characteristics of the melted fibre are very different from those of the fibre before singeing.

d) Ultraviolet Radiation

Ultraviolet radiation is first suggested by ICI (B.P 1,120,036) in 1964 as a method for reducing pilling tendency of woven or knitted fabrics composed largely of synthetic thermoplastic high-strength yarns. It aims to avoid any subsequent fibre migration by spotting weld the fibre in the yarns.

In 1998, K. Millington (1998) introduced an anti-pilling treatment for knitted fabrics called Siroflash. This process involves the exposure of the fabric or garment surface to short wavelength ultraviolet radiation (UVC), followed by a mild wet oxidation treatment. The UVC exposure is confined to the surface fibres and selectively weakens them relative to the bulk fibres responsible for fabric strength. As the surface fibres are much weaker after treatment, no anchor fibres are available to secure pills to the fabric surface. This method is effective in fibres like wool which is sensitive to UV, thus limited in other fibre types or blends.

e) Blends with elastomeric yarns (Spandex)

When a fabric knitted with underfeed elastomeric yarn, the fiber-fiber friction increases and this can reduce pilling (Marmarali, 2003).

2.4.2 Chemical methods

Several chemical finishing approaches have been used to prevent pills from accumulating on fabric surfaces. The first approach is to prevent loose fibres from forming the initial ‘fuzz’ by applying polymeric coatings that bind the fibres into the fabric surface. The second chemical finish approach is to cause the pills to fall off the fabric as soon as they are formed. This can be accomplished by reducing fibre strength.

a) Latex treatment

An elaborate treatment devised by the Wool Industries Research Association (WIRA) (BP 819,747) involves powdering a small amount of flexible adhesive (butadiene latex or acylonitrile butadiene) on the back of the knitted fabric. It has the advantage of not forming a continuous film, but it firmly fixes numerous fibres, thus reducing pilling. The fabric handle can be retained, but unfortunately, the application is limited as the fabric will be discoloured under long exposure to air and light.

b) Shrink-resist treatment of wool

Shrink-resist treatments are based on chemical degrading processes and chlorine treatment. They can be applied to all wool and wool blended fabrics. These treatments prevent the fibre migration to form fuzz. Hence, pilling tendency can be reduced. However, the treatments can reduce the tearing strength of the fabrics and worsen the fabric handle (Feldtman & McPhee, 1964).

c) Treatment by quaternized amphiphilic peptides

Gomez et al (1994) studied different chemical treatments with quaternized amphiphilic peptides in 1994. It was found that there was a remarkable improvement in preventing pill formation in samples treated with reactive agents in the presence of these amphiphile molecules, which leads to a reduction in the movement of fibres in the yarns.

d) Treatment by aqueous dispersions of self-crosslinking polyacrylates

A study of the treatment of wool with a series of self-cross-linking polyacrylates has shown a wide range of possible uses in wool finishing (Feldtman & McPhee, 1965). The softer polyacrylates give better resistance to felting, a higher increase in abrasion resistance, pilling, and increases in tensile strength with no significant changes in stiffness, tear strength, or wrinkle recovery. Reduced felting is probably due to partial covering of fibre surfaces by polymer rather than to fibre bonding, but some bonding can occur and this may produce such properties of polymer-treated wool as reduced pilling and resistance to tumble drying.

2.4.3 Biochemical methods

Enzyme treatment

The concept of treating fabrics with enzymes to improve surface properties was first developed in Japan in 1989. It is gaining popularity because of its beneficial effects on the environment. The enzyme treatment usually improves surface properties by digesting protruding loose fibres. Hence, it increases the pilling resistance of fabric. However, the treatment lowers the resistance of abrasion and bursting strength (Chikkodi, Khan, & Mehta, 1995).

The Technical Research Centre of Finland, VTT, has developed an enzyme-based process for finishing wool, called Washwool®. It permits repeated water washing of wool without shrinkage, felting or pilling. It is an environmentally benign protease enzyme process based on natural raw materials and generating completely biodegradable waste products.

2.4.4 Disadvantages of existing chemical and biochemical anti-pilling treatments

Although many effective chemical treatments are available, the other properties of the fabrics might be adversely affected by the chemicals used. The treatment causes degradation of wool's natural moisture transmission properties, the natural soft touch that is one of wool's selling points, and reduction in the wool's strength. In most of the cases, chemical wastes are also harmful and lead to serious pollution. For example, chlorination produces toxic by-products AOX (Absorbable Organic Halogen Compounds), which appear in the effluent, may ultimately generate toxicity in the whole food chain by being taken up by aquatic organisms (Stryckman & Leclereq, 1973a). As mentioned before, fabrics after latex treatment may be discoloured under long exposure to air and light. For the biochemical treatment of using enzyme, although it is effective and environmentally friendly, the process is very complicated and time consuming as it involves many steps. Most of the enzyme used is activated in alkaline media, which may cause fibre damage to the wool fibre and results in lower resistance of abrasion and bursting strength (Bahi, Jones, Carr, Ulijn, & Shao, 2007; Chikkodi et al., 1995). Similar to that of chemical treatments, the disposal of chemical wastes is costly and may also cause pollution to the environment. It seems that most of the side-effects come from the chemicals used. Chemical and biochemical treatments are fibre specific thus it becomes very complicated or impossible to treat blends of different chemical composition.

2.5 Attrition treatments

As the root of the pilling problem is the existence of pillable fuzz in the fabrics, while the supply for pillable fuzz is limited, reducing the amount of potential pillable fuzz could inhabit the formation of pills and reduce the pilling tendency of fabrics.

The idea was also confirmed in experiments by Omura *et al* (1969), who found that the amount of fuzz generated trends initially to increase sharply and then levels off as it approaches a nearly horizontal asymptote. Even with the same abrasion, no new pill was generated in the areas where pills formed and wore off. Therefore, they suggested that shearing fuzz in the early stage of abrasion may be an efficacious method of pilling control. However, the suggestion of shearing fuzz in the early stage is not an effective treatment as there is still much potential pillable fuzz in the fabric. They will migrate out under a long duration of abrasion action and form pills finally. Therefore, pillable fuzz should be firstly generated out of the fabrics before the shearing process to remove the fuzz on the fabric surface.

For those physical treatments commonly in used, such as shearing and cropping, most of them are only applicable to smooth faced fabrics but not suitable for irregular knitted fabrics (Stryckman & Leclereq, 1973b).

Laser is regarded as a potential tool for the fiber attrition treatment. A laser is a device that emits light (electromagnetic radiation) through a process called stimulated emission. The term "laser" is an acronym for Light Amplification by Stimulated Emission of Radiation. The laser was invented in 1960 (Beach, Shotwell, & Essue, 1993) . Basically, a laser consists of a cavity, with mirrors at the ends, filled with gain material. Some of the advantages of using lasers include that the laser cutting edge does not get dull and the laser can be computer-controlled to achieve reliable production.

The carbon dioxide laser (CO_2 laser) was one of the earliest gas lasers developed and it was invented by Kumar Patel of Bell Labs in 1964 (Patel, 1964). It is very versatile and practical. It produces an output in the far infrared region (over 10,000nm). (Beach et al., 1993) A wide range of CO_2 lasers is available, with the power outputs ranging from low-power (1 w) to high-power lasers (kw class) in material processing applications. CO_2 lasers are available in pulsed or continuous wave outputs.

2.6 Conclusion

Review of the literature concerning the pilling problem of fabrics reveals that the anti-pilling treatments used nowadays can not satisfy the industry's requirements as they may adversely affect the other desirable physical properties of the fabrics, or may produce harmful chemical wastes. The treatments are also high in cost or too complicated for industrial mass production. In addition, the pilling tendency of the developed Nu-Torque^{TM} yarn has not been studied thoroughly and a proper anti-pilling treatment is needed in order to retain its superior property.

It seems that anti-pilling treatment which meets the increasing expectation of the users should be developed in advance. In order to achieve so, the mechanism of pilling was studied in deep. It reveals that the formation of fuzz is the very beginning of the formation of pills. The fuzz, which may form pills, comes from the broken fibre and those with smaller diameter in the fabric. Removing the pillable fuzz seems to be a key to reduce the pilling tendency of fabrics.

Some researchers suggested that shearing fuzz in the early stage of abrasion may be an efficacious method of pilling control. Although the amount of pillable fuzz was found to be limited in supply, the suggestion of shearing fuzz in the early stage is not as effective as expected. This is due to the fact that there is still much potential pillable fuzz in the fabrics, which will migrate out under a long duration of abrasion action and form pills finally. Therefore, pillable fuzz should be firstly generated out of the fabrics before the shearing process to remove the fuzz on the fabric surface.

Based on the earlier works mentioned above, physical treatments, include acceleration of fuzz generation and fuzz removal, will be investigated as a potential anti-pilling treatment in this project. The principle and processes involved will be studied systematically. Then the effectiveness of the treatments on worsted knitted fabric will also be examined though experiments and the results will be discussed in detail in later sections.

Chapter 3 Experimental Details

In the last chapter, a review of the literature reveals that the pillable fuzz is the main cause of pilling problem. The pillable fuzz can be increased by migration of fibres during wear or testing. For a given fabric, the amount of pillable fuzz is limited. Thus one may accelerate the process of fuzz generation and then remove the fuzz in order to reduce fabric pilling tendency.

Based on this hypothesis, in this chapter, various methods will be proposed for such a purpose and the experimental details will be provided. It includes the material preparation, working procedure, methods to be used in the treatment and evaluation methods. All the experimental results are discussed in next chapter.

3.1 Sample preparation

3.1.1 Yarn sample

a) Undyed yarns

In the following experiments, two types of worsted yarn were used. They were Nu-Torque^{TM} ring yarn and conventional ring yarn. The Nu-Torque^{TM} ring yarn has a low twist factor and a modified yarn structure (Tao & Xu, 2002) that leads to a torque-balanced structure and thus the residual torque in the yarn is much reduced.

Wool roving of 750tex (specifications are listed in Table 3-1) was used to spin 24Nm (41.67 tex) Nu-Torque^{TM} singles ring yarn with a low twist factor of 55 on Zinser 451 worsted ring spinning machine. Conventional singles ring yarn 48Nm (20.84 tex) was also spun by the same machine using the same type of roving with a twist factor of 75. Two 48 Nm singles conventional yarns were then plied together to form a 2/48Nm piled conventional yarn with ply-twist as 318 TPM. The piled conventional yarn was used for knitting instead of singles because it is difficult in practice. The singles Nu-Torque ring yarn was adopted for knitting owing to its low residual torque, sufficient strength and soft handle. The conventional singles ring yarns were prepared to provide a comparison to the Nu-Torque singles ring yarn in studying the pilling behaviour of the fabrics made from these two types of yarn.

The fibre properties and main spinning parameters are listed in Tables 3-1 and 3-2 respectively.

Table 3-1 Roving specifications

Roving count	750 tex
Fibre length Hauteur	71.2mm
CVH	39.8%
Fibre diameter	18. 6 microns
CVFD	21.6%
Fibre percentage over 30 microns	0.9%

Table 3-2 Nu-Torque™ and conventional ring yarns spinning parameters

	Nu-Torque™ singles ring yarn	Conventional singles ring yarn	Conventional 2-plied ring yarn
Yarn count	24Nm (41.67 tex)	24Nm (41.67 tex)	2/48Nm (20.84 tex) (ply-twist: 318 TPM)
Yarn twist factor (α)	55	75	75
Spinning speed	9000rpm	9000rpm	9000rpm

b) Dyed yarns

Dyed Nu-Torque™ and Conventional singles ring yarns were prepared by hank dyeing in Wing Wah Dyeing Co. Ltd. The general dyeing process flow and machines involved were reported below.

Cone→ Yarn hank making→ Dyeing→ Finishing→ Winding into cone

Dye stuff used is Lanasol. The dyeing processes are shown in Figure 3.1. Figure 3.2 shows the hank dyeing machine used and the machine details is shown in Table 3-3.

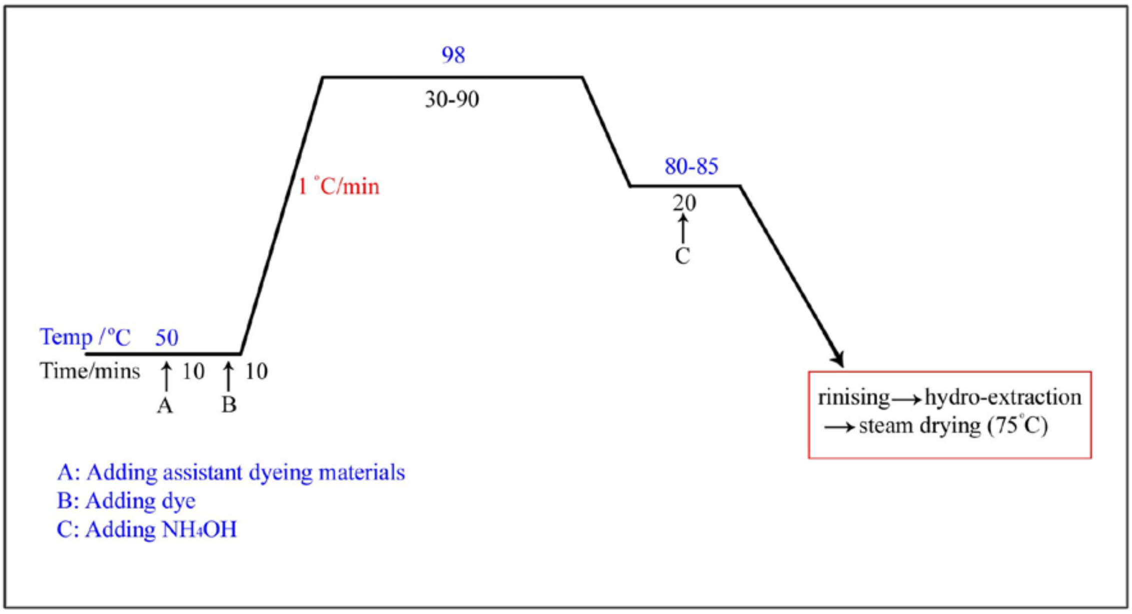


Figure 3.1 Yarn dyeing process using Lanasol

Equipment:

- **Two-stick cabinet type hank dyeing machine**

Figure 3.2 Two-stick cabinet type hank dyeing machine

Table 3-3 Hank dyeing machine details:

Supplier	Tung Shing Dyeing Machine FTY. Ltd
Dyeing method	Two-stick hank
Heating method	Direct and indirect
Type	TS10
Number	01250243
Water flow speed (rpm)	Low-Middle-High
Temperature range (℃)	24-100
Yarn loading	10Lb

3.1.2 Fabric sample

Plain knitted fabrics were produced using the 24Nm Nu-Torque™ singles yarns with a relatively low cover factor 1.22 by 16-gauge Wealmart flat V-bed knitting machine, which is shown in Figure 3.3. The conventional knitted fabrics, prepared by singles (1/24Nm) and piled conventional yarn (2/48Nm), were knitted using the same knitting machine with the same cover factor. All knitted fabrics were then conditioned at least 24 hours under standard atmospheric conditions (65 ± 2% RH, 20 ± 2 °C) before testing.

Equipment:

◆ **Flat V-bed knitting machine**

Figure 3.3 Wealmart flat V-bed knitting machine

3.1.3 Garment sample

In order to have a thorough evaluation of effectiveness of the proposed treatment, tests on garment samples have been also conducted using the sweaters available in the market. Two types of sweater were bought. They have the Woolmark – the symbol of quality for pure new wool. The details of the sweaters after testing are listed in Table 3-4.

Table 3-4 Measured fabric data of sweaters

		Blue Sweater	**Grey Sweater**
Brand		Lamb	Snowflake
Material		100% lambs wool	100% lambs wool
Fabric density	**CPI**	17	17
	WPI	11	11
Loop length		0.84cm	0.85cm
Yarn count		2/18Nm	2/18Nm
Cover factor		1.17	1.16
Fabric weight		3.31g/100cm^2	3.25g/100cm^2

3.2 Working procedure

As discussed in the literature review, pilling tendency cannot be reduced by shortening the surface fibres beyond the critical pillable length only; it should follow an acceleration of the fibre migration to the fabric surface in order to reduce pillable fuzz as much as possible. Thus, the treatment mainly involves two steps: acceleration of fuzz generation, and fuzz removal.

The first step of the treatment is about the acceleration of fibre migration to the fabric surface. As there is a preferential migration of the fibres inside the fabric, pillable fuzz, formed by broken and finer fibres, would firstly come out to the fabric surface. The process attempts to make the pillable fuzz come out to the fabric surface as much and as efficient as possible in a short time, so that a larger amount of pillable fuzz can be removed in the later process. To achieve so, mechanical methods such as tumbling, flat abrasion or brushing action, can be used. In the second step, the generated fuzz layer can be removed by attrition methods, such as the physically process using lint shavers, singeing devices or laser singeing devices.

The working procedure of the proposed treatment is shown in Figure 3.4.

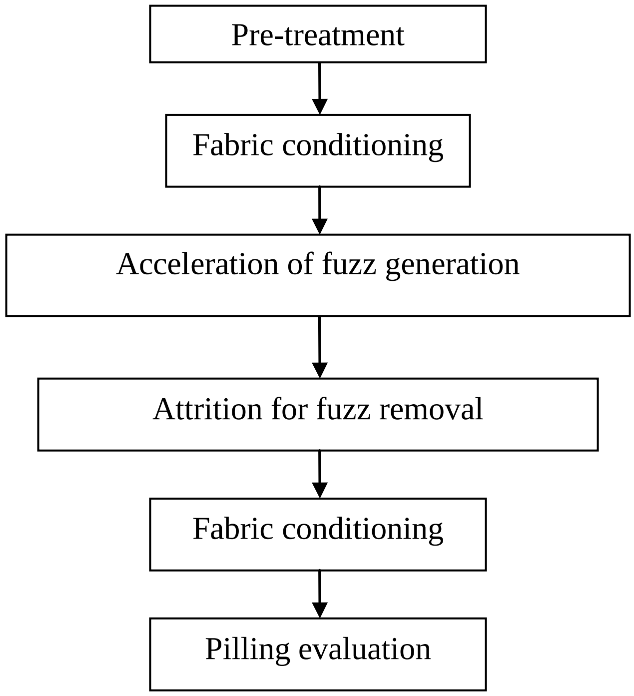


Figure 3.4 Working procedure of the proposed treatment

3.2.1 Pretreatment

In order to allow the pillable fuzz easily migrate to the fabric surface, the fabric samples were pre-treated by a 30-second steaming to reduce the internal stress of the yarns and 10-second air suction was applied to cool down the steamed fabrics and remove extra moisture. The effectiveness of the pre-treatment was evaluated by comparing the difference in amount of fuzz removed and pilling grade.

3.2.2 Acceleration of fuzz generation

Acceleration of fuzz generation is a process attempting to draw the pillable fuzz out to the surface of a fabric in a relatively shorter period of time. It can be achieved by mechanical methods such as tumbling, flat abrasion or brushing action.

For tumbling, ICI Pilling Box and Atlas Electric Tester were used. For flat abrasion, Modified Martindale Tester was used. These testers, which are originally designed for the accelerated pilling evaluation, have been adopted as the devices for acceleration of fuzz generation. Although they carry the same function, the effectiveness and mechanism of each tester are different. All of these testers for acceleration of fuzz generation were used individually. Unlike tumbling and flat abrasion, although there are machines for fibre raising on fleece fabrics, a standard brushing machine for sweaters is not easily available. Thus, the types of brush, brushing direction, duration of brushing and so on, should be studied and optimized.

In the following sections, the acceleration methods mentioned above will be discussed in detail one by one.

3.2.2.1 Tumbling action of ICI Pilling Box

ICI Pilling Box (Figure 3.5) is a tester for evaluation of pilling and the tumbling action can be used to accelerate pilling formation. With reference to the standard ISO 129451, fabric samples were cut into specimens of 114 x 114mm size and were put onto plastic tubes. According to the working procedure mentioned before, the specimens were first conditioned for at least 24 hours under standard atmospheric conditions (65 ± 2% RH, 20 ± 2 $^{\circ}$C). The weight of all the specimens was recorded. The specimens underwent 14,400 revs in ICI Pilling Box. They were conditioned and the weight before and after the tumbling was recorded.

<u>Equipment:</u>

- **ICI Pilling Box**

Figure 3.5 ICI Pilling Box

3.2.2.2 Tumbling action of Atlas Electric Tester

Atlas Electric Tester of Random Tumble Pilling Test (Figure 3.6) was uesd to accelerate pilling formation. Two-folded fabrics were cut into specimens of 105 x 105mm size with reference to the standard ASTM D3512-02. The edges were secured by over-lock stitch. They were conditioned for at least 24 hours under standard atmospheric conditions (65 ± 2% RH, 20 ± 2° C). The weight of all the specimens before and after tumbling was recorded.

<u>Equipment:</u>

- **Atlas Electric Tester of Random Tumble Pilling Test**

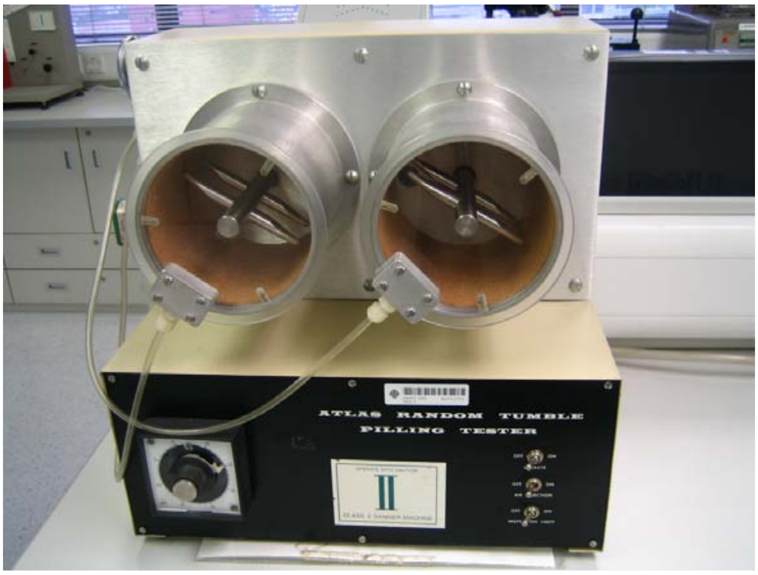


Figure 3.6 Atlas Electric Tester of Random Tumble Pilling Test

3.2.2.3 Flat abrasion action of Martindale Tester

In the previous sections, the tumbling action for acceleration of fuzz generation is investigated. The tumbling action seems to be effective in generating fuzz and pills, however, it also seems be too severe to the fabrics. It has technical problems for application, such as uneven treatment on different area on the fabric and difficult to be used as a treatment for garments. As a result, one of the alternative acceleration methods, flat abrasion, is studied in this section.

Martindale Tester (Figure 3.7) was investigated to accelerate fuzz formation. With reference to the standard ISO 12945-2, Modified Martindale method, circular specimens of Nu-Torque™ fabrics were prepared on sample holders with a diameter of 90mm. Dead weight was added and the pressure applied was 0.68kPa. According to the working procedure mentioned before, the specimens were rubbed against with different abradent materials using the Martindale Tester for the acceleration of fuzz generation. As the specimens passed over a friction surface, fibers come out and form fuzz and pills.

Equipment:

◆ **Martindale Tester**

Figure 3.7 Martindale Tester

3.2.2.4 Brushing action

One of the possible drawbacks of the flat abrasion is the wearing out of abradent. In order to avoid the problem, brushing treatment was investigated.

Brushing slightly was recommended as a treatment for reducing pilling (Stryckman & Leclereq, 1973b) by removing the wild fibres loosely anchored in the yarn. In this experiment, however, brushing was used as a fast method to generate the pillable fuzz in the fabrics to the fabric surface. The parameters of the brushing treatment, including, type of brush hair, brushing direction, number of brushing times and brushing cycles, etc. are studied in the following sections.

a) Type of brush

Different types of brush, which are shown in Table 3-5, were used to brush the worsted knitted fabrics. Leica Stereoscan 440 Scanning Electronic Microscope (SEM) was then used for studying the surface of some of the brush hair. The results were used to explain the different behaviors in generating fuzz on the fabric surface.

Table 3-5 Details of brushes

Type of brush	**Image of the brush**	**Remarks**
Common toothbrush		◆ Common type of toothbrush
Super Soft toothbrush		◆ Toothbrush with very dense, soft and pointed hair
Electric toothbrush		◆ Electric toothbrush with rotational and up-and-down movement

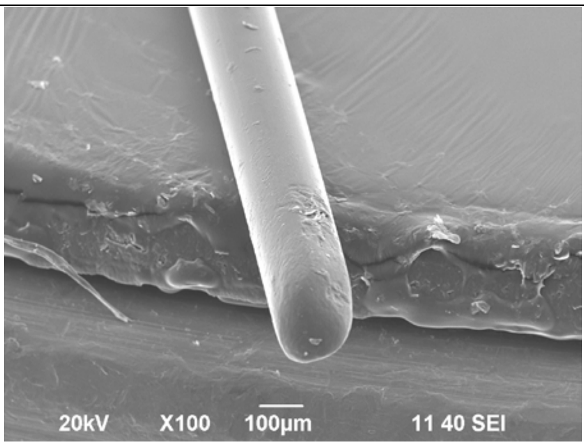
Brush A		◆ Brush with very dense and soft hair used for removing dust
Brush B		◆ Brush used for removing dust
Brush C		◆ Shower brush with the largest size

Table 3-6 Observed features of different types of brush

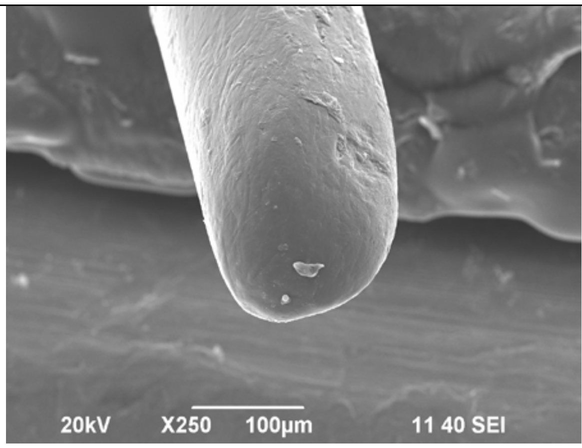
Type of brush	Observed features
Toothbrush	Effective on generating fuzz by brushing
Super Soft toothbrush	Ineffective on generating fuzz by brushing
Electric toothbrush	Effective on generating fuzz by mechanical movement
Brush A	Ineffective on generating fuzz by brushing
Brush B	Very effective on generating fuzz by brushing, but the hair hooks fibres and may cause fabric damage
Brush C	Effective on generating fuzz by brushing

Different types of brush hair were investigated and the results are shown in Table 3-6. The hair of Super Soft toothbrush and brush A was found to be too soft to generate fuzz on the fabric surface by brushing, thus, they were not chosen for the brushing treatment study afterward. Although brush B is very effective on generating fuzz by brushing, the hair hooks fibres and may cause fabric damage. The reason for this can be explain by the SEM images which are shown in Figure 3.10. Unlike the other brush hair, the head of the hair of brush B is very irregular and the shape is just like a hook. The irregular shape may be come from improper cutting of hair. The irregular head hooks the fibres on the fabric surface causing damage to the fabric.

As a result, common toothbrush, electric toothbrush and brush C have been chosen as the brushes used in the study of brushing treatment.

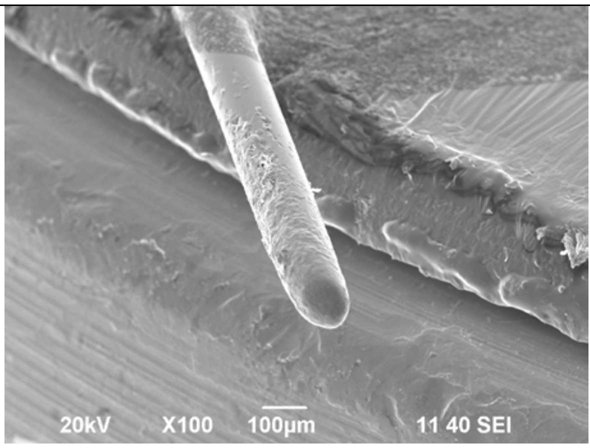


(a) Magnification: X100

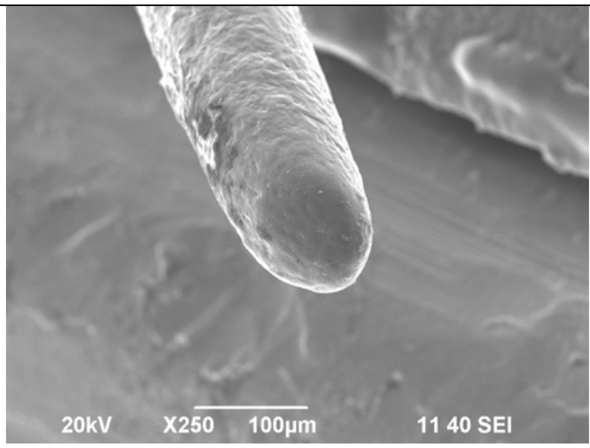


(b) Magnification: X250

Figure 3.8 Common toothbrush



(a) Magnification: X100



(b) Magnification: X250

Figure 3.9 Electric toothbrush

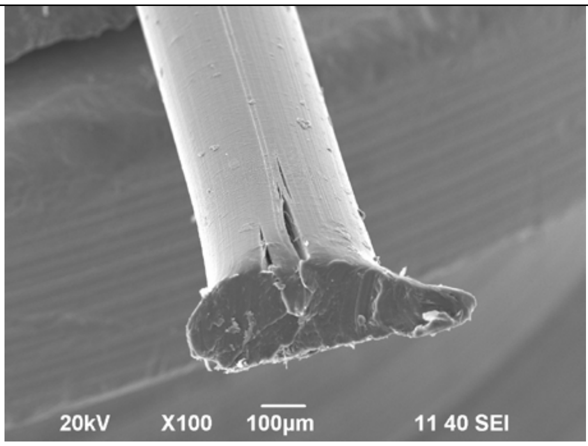
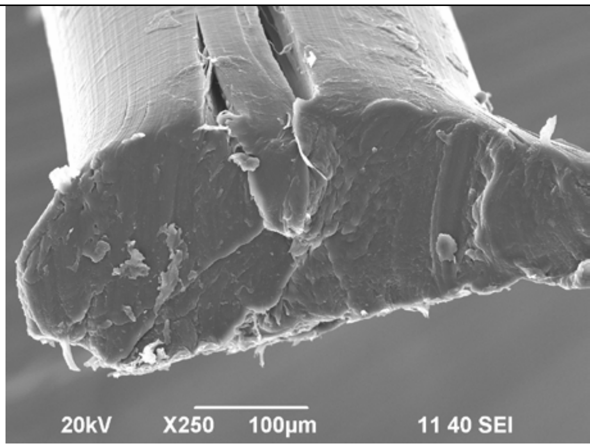
 (a) Magnification: X100	 (b) Magnification: X250

Figure 3.10 Brush B

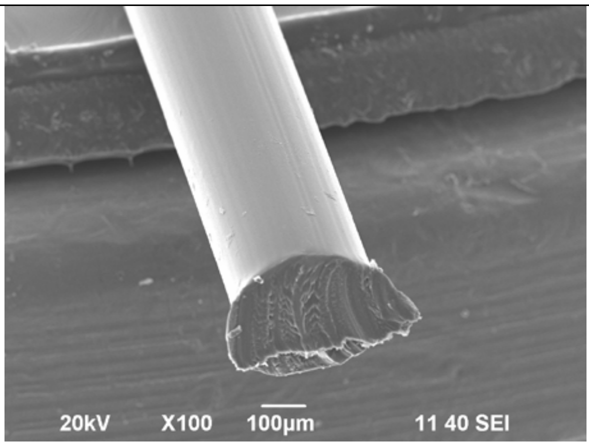
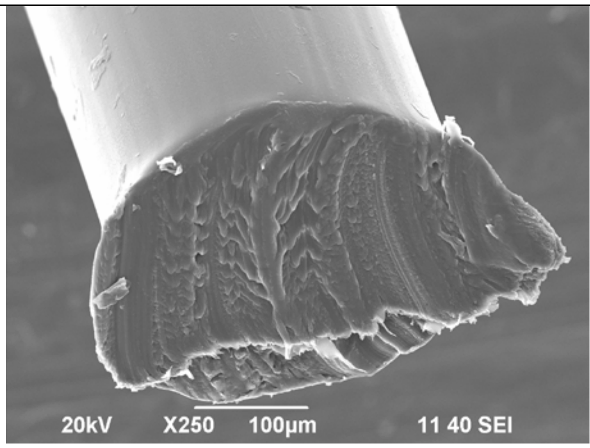
 (a) Magnification: X100	 (b) Magnification: X250

Figure 3.11 Brush C

For the study of brushing treatment**,** fabric samples were prepared by folding in half and cutting into specimens with size 105 x 105mm. The edges of them were secured by over-locking stitch. The specimens were conditioned for at least 24 hours under standard atmospheric conditions (65 ± 2% RH, 20 ± 2° C). Their weight was recorded. Samples A to E were brushed according to Table 3-7, while sample F served as a control. Their weight after brushing was recorded. The generated fuzz on the fabric surface was shaved with a lint shaver, which is mentioned in section 3.2.3.2. The fabric samples were conditioned again for at least 24 hours under standard atmospheric conditions. After their weight was recorded, the specimens were tested by Random Tumble Pilling Test. The specimens were then evaluated by a subjective method by comparing with the standard photos.

Table 3-7 Brushing details

	A	B	C	D	E	F
Type of brush	**Toothbrush**	**Electric toothbrush**	**Electric toothbrush**	**Brush C**	**Brush C**	**---**
Remark		**brushing by movable head only**				**control**
brushing time per each side (mins)	**5**	**5**	**5**	**2**	**5**	**---**

b) Direction of brushing

Direction of brushing can be divided into wale-wise and course-wise. The direction and number of brushing are listed in Table 3-8.

Table 3-8 Brushing details

Sample	No. of brushing	
	Wale-wise	Course-wise
Nu-Torque^{TM} fabric	50	0
	0	50
	25	25
	0	0

c) Number of brushing-and-shaving cycles

After investigating the effect of brush and brushing direction, in this section, the effect of the number of brushing-and-shaving cycles used in the proposed treatment was studied.

Fabric samples were treated by repeated cycles of brushing-and-shaving. As shown in Figure 3.12, a brushing-and-shaving cycle consists of 50-times of brushing and a shaving of fuzz layer. The amount of fuzz removed was recorded after each cycle of brushing-and-shaving. Maximum of five cycles were treated on both of Nu-Torque^{TM} fabric and conventional fabric, with and without steaming pretreatment. The specimens after one and two cycles were compared by testing with ICI Pilling Box Method.

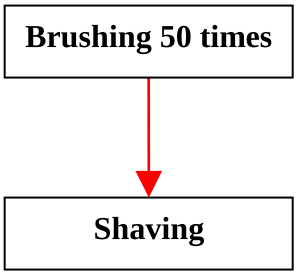


Figure 3.12 A brushing and shaving cycle

d) Brushing treatment on commercial sweaters

In order to have a thorough evaluation of the proposed treatment, tests on garment samples were also conducted using the sweaters available in the market. Two worsted sweaters which are made from 100% lambs wool were bought from the market. The details of the sweaters are mentioned in section 3.13. The garment samples were conditioned for at least 24 hours under standard atmospheric conditions (65 ± 2% RH, 20 ± 2° C). The samples were cut into specimens with size 114 x 114mm. The specimens were brushed with the red shower brush (brush C) with 50 times and the generated fuzz on the fabric surface were shaved with a lint shaver. Their weights before and after shaving were recorded. The specimens were tested by ICI Pilling Box Method. The specimens were then evaluated by a subjective method by comparing with the standard photos.

3.2.3 Methods for fuzz removal

In this project, only physical methods are considered for the fuzz removal process so as to avoid the drawbacks brought by chemical or biochemical treatments. In this section, the use of laser and lint shaver for the fuzz removal was investigated.

3.2.3.1 Use of Laser

A carbon dioxide laser system was used in the experiments. Figure 3.13 shows the laser system composed of laser head, computerised control and chamber. The laser specifications are shown in Table 3-8.

Equipment:

◆ **Carbon dioxide laser system**

Figure 3.13 Carbon dioxide laser system

Table 3-9 Laser specifications

Parameters	**Specifications / Features**
Manufacturer Model	GFK Marcatex FLEXI-150
Laser medium and wavelength	CO_2; 10.6µm (10.4µm - 11.2µm)
Laser class and wave mode	Class 4, Pulsed laser (Quasi-continuous wave laser)
Power(W) Energy (mJ/p)	Power: 100W (60W -230W) Pulse energy: 5mJ – 230mJ; Pulse activation time : <45µs
Beam Divergence	<2.5mrad; Linear polarization perpendicular to laser head
Beam Diameter	0.7mm

◆ **Power dictator and power meter**

	
Figure 3.14 Newport high power dictator	Figure 3.15 Newport optical power/energy meter
Model no. : 818P-250-25	Model no. : 842-PE
Certificate no. : 179930-090113	Certificate no. : 179091-081014

a) Laser Singeing

Fabric samples with generated fuzz and pills were firstly prepared by the acceleration methods. The laser beam then emitted and evenly scanned the fabric surface by the computerized system and movable mirrors with preset laser energy. Squares sized 2 x 2 cm on the fabric surface were exposed to the laser beam. The point where the laser touches the surface should be on the focal plane of the laser's optical system, and is usually synonymous with its focal point. This point is typically small and only the area inside this focal point is significantly affected when the laser beam passes over the surface. In this experiment, the laser beam was focused on the fuzz and pills on the fabric surface, thus, the base fabric was not being damaged. The energy delivered by the laser heat up the fuzz and pills, makes them fracture and flake off the surface (as shown in Figure 3.16). 30 dpi of laser beam and 40x40am lens were used. The duration and the grayscale of the laser beam used are shown in Table 3-9. The power density of the laser beam measured by Newport high power dictator (Figure 3.14) and optical power/energy meter (Figure 3.15) is shown in Figure 3.17 . The power density used in the experiment is about 0.5 – 2.7 W/cm^2.

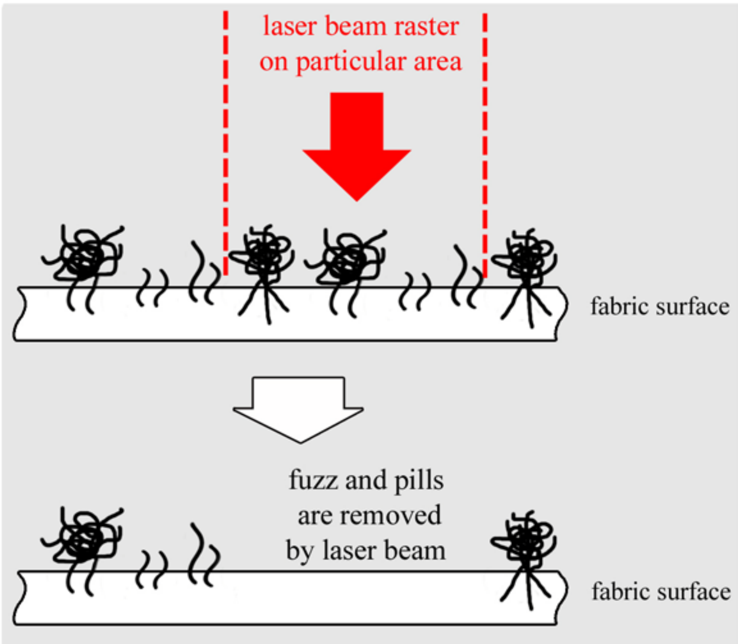


Figure 3.16 Fuzz and pills are burnt by laser beam

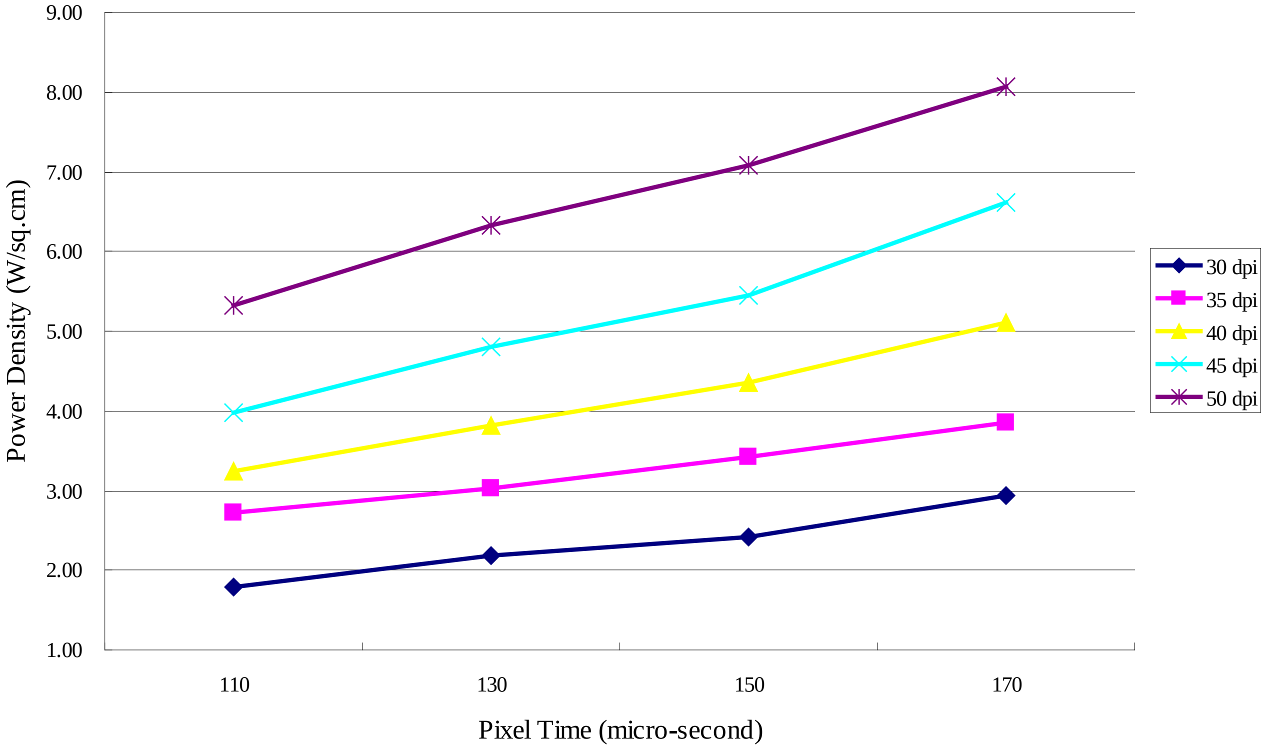


Figure 3.17 Power density of the laser beam

Table 3-10 Parameters of laser beam

Duration (μs)	**Grayscale**			
	100%	**75%**	**50%**	**25%**
160	No.1	No.2	No.3	No.4
150	No.5	No.6	No.7	No.8
140	No.9	No.10	No.11	No.12
130	No.13	No.14	No.15	No.16

b) Laser cutting

The singeing method described above may damage the fabric surface due to the limitation of focus depth. As an alternative method, laser cutting technique was used in this experiment. Fabric samples with fuzz and pills were prepared and put on a curved surface of a moving belt as shown in Figure 3.18 and Figure 3.19. High energy laser beam of 2.378W with speed 100 bits/ms was emitted controlled by the computerized system and movable mirrors. The laser beam cut the fuzz and pills off the fabric surface horizontally as shown in the following figure.

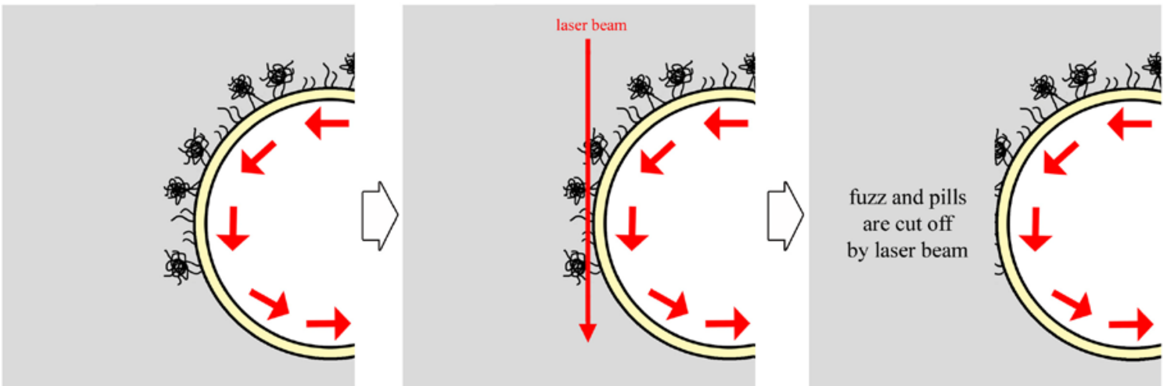


Figure 3.18 Fuzz and pills are cut off by laser beam

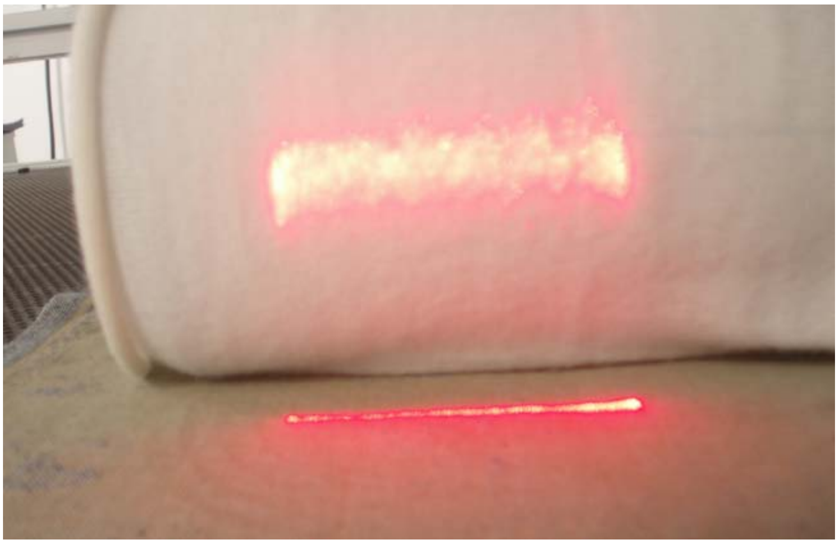


Figure 3.19 Laser beam focused on fuzz and pills

3.2.3.2 Use of lint shaver

Lint shaver can be used to shave off the generated fuzz and pills. Figure 3.20 shows a lint shaver. There is a rotatable blade installed in the shaver. It is covered by a dome-shaped metal plate with many holes on it. When it is moved by hand on the fabric surface, the fuzz and pills on the fabric surface enter into the shaver through the holes on the metal plate. The fuzz and pills are then cut by the blade; on the other hand, the base fabric is protected from the blade by the metal plate. The metal plate is in dome-shaped in order to give a larger contact surface, thus more fuzz and pills are able to enter the shaver and to be cut. Through repeating shaving, most of the fuzz and pills on the fabric surface can be cut off. The effectiveness of the lint shaver is discussed further in section 4.3.2.

Equipment:

Figure 3.20 A lint shaver

3.2.4 Washing

Washing is a severe process to garments. Garments usually become fuzzy after washing. In order to verify if the treatment is still effective after washing, treated samples were washed according to TM31, 7A, for 1 cycle with an automatic washing machine, which is shown in Figure 3.21, and they were then left to be flat dried. The experimental results are discussed in section 4.2.1 for fuzz generation accelerated by tumbling, and those by brushing in section 4.2.3.6.

Equipment:

◆ **Automatic washing machine**

Figure 3.21 Automatic washing machine

3.3 Pilling evaluation Methods

For pilling evaluation, the specimens were mainly tested by ICI Pilling Box Method according to the standards ISO 129451 as it is recommended by IWS for worsted products. In addition, Random Tumble Pilling test (ASTM D 3512-02) was also used for some fabrics to evaluate the effectiveness of the proposed treatment.

3.3.1 ICI Pilling Box Method

ICI Pilling Box Method (ISO 129451) is an international test method. It is intended to determine the resistance to pilling and change of appearance in apparel fabrics. The test is applicable to all knitted fabrics.

In order to conduct the test, four specimens with size of 114 x 114mm are required. They are put onto plastic tubes. According to the standard, 14400-revolution is recommended for the worsted knitted fabric samples. In this study, each of the specimens was evaluated by the subjective evaluation and graded by 5 evaluators.

3.3.2 Random Tumble Pilling Test

Random Tumble Pilling test is an international test method. It is used to check pills on all types of textile samples due to physical friction in cork-lined chambers, according to the standard ASTM D 3512-02. The textile samples are kept in the cork lined chambers. Rotatable impellers made of stainless steel inside each chamber keep samples moving inside the chambers, causing abrasion on its surface. Beside the impellers there is a normalized air pressure injection to increase the movement of the samples.

In this study, three specimens were cut with the size of 105mm x 105mm after they were folded. Folding was required as to prevent the specimens to curl as there is an inherent feature of wool single jersey fabrics that the fabric edges tend to curl inwards. The edges of the specimens were secured by over-lock stitch instead of using glue, as the glue hardens the fabric edges and causes extra fabric damage during the tumbling process. 30 minutes of testing for the worsted knitted fabric samples is recommended by the standard. Finally, each of the specimens was evaluated by the subjective evaluation and graded by 5 evaluators.

3.3.3 Study of pilling tendency of fabric samples

The spinning technique used to make the yarns has a significant impact on the pilling tendency of a fabric. Nu-Torque^{TM} is a newly developed spinning technology and the pilling tendency of the Nu-Torque^{TM} worsted knitted fabric has not been studied thoroughly. Before further experiments to be conducted, it is necessary to study the pilling tendency of this type of fabrics.

In this section, Atlas Electric tester, the tester of Random Tumble Pilling test (ASTM D 3512-02), was used to study the pilling tendency of both of the fabrics made from Nu-Torque^{TM} and conventional singles ring yarns. For every single test, three specimens were prepared with size of 95mm x 135mm after they were folded. Folding was done in order to prevent the specimens to curl as there is an inherent feature of wool single jersey fabrics that the fabric edges tend to curl inwards. The edges of the specimens were secured by over-lock stitch instead of using glue, as the glue hardens the fabric edges and may cause extra fabric damage during the tumbling process. The fabric samples were kept moving inside the chambers and abraded with the cork-lining in the chambers of the tester. Fuzz were then generated on the fabric surface and formed pills.

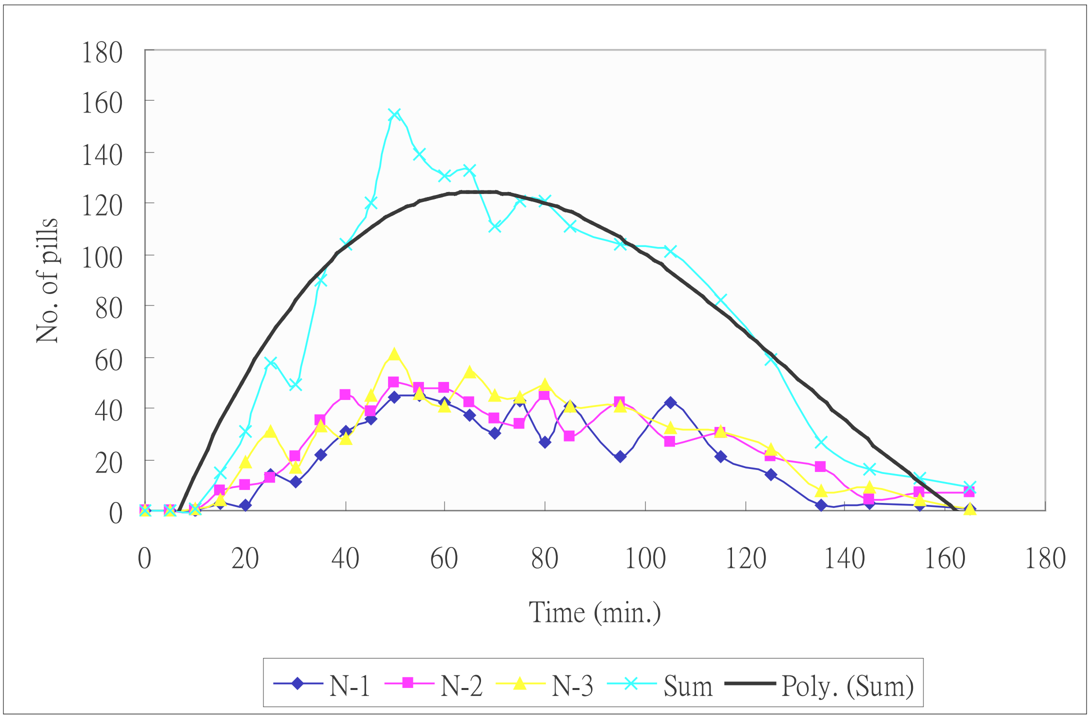
The change of the number of pills on the fabric during the process was recorded. During the first hour of the test, each specimen was taken out from the Atlas Electric tester and the number of pills on the fabric was counted at every 5 minutes interval, and it was counted at every 15 minutes interval afterward. The curves of the pilling formation of the fabrics were plotted and discussed in next chapter.

Chapter 4 Results and Discussions

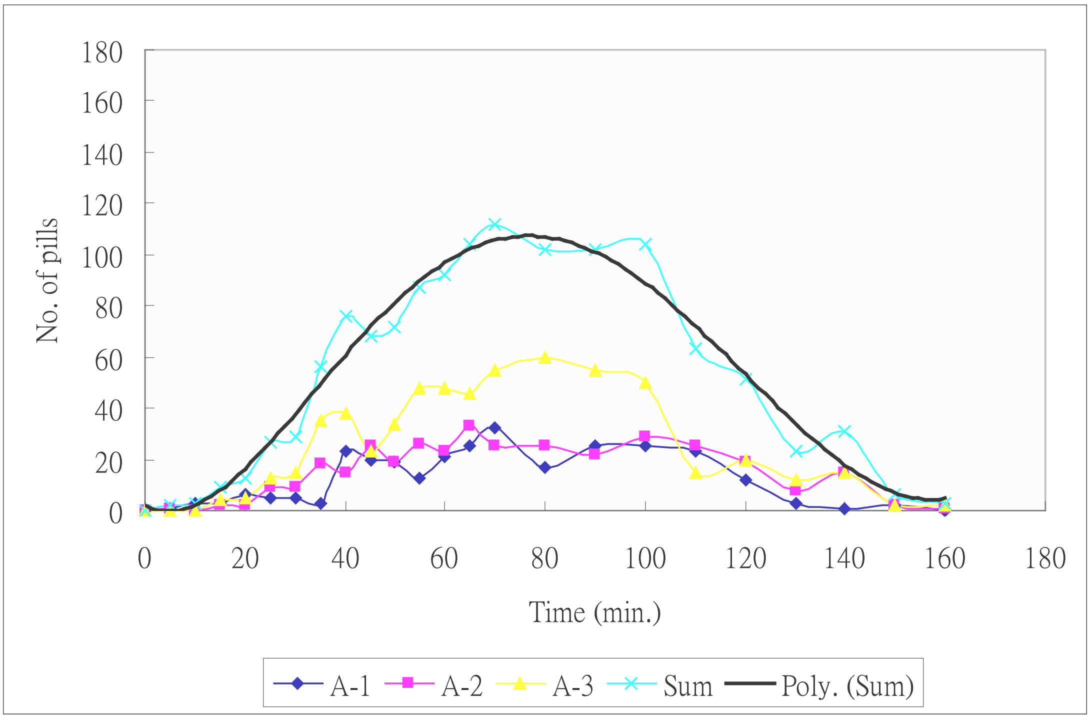
In this chapter, the results of the experimental details of which were given in the last chapter will be presented and discussed one by one.

4.1 Pilling process of fabric samples

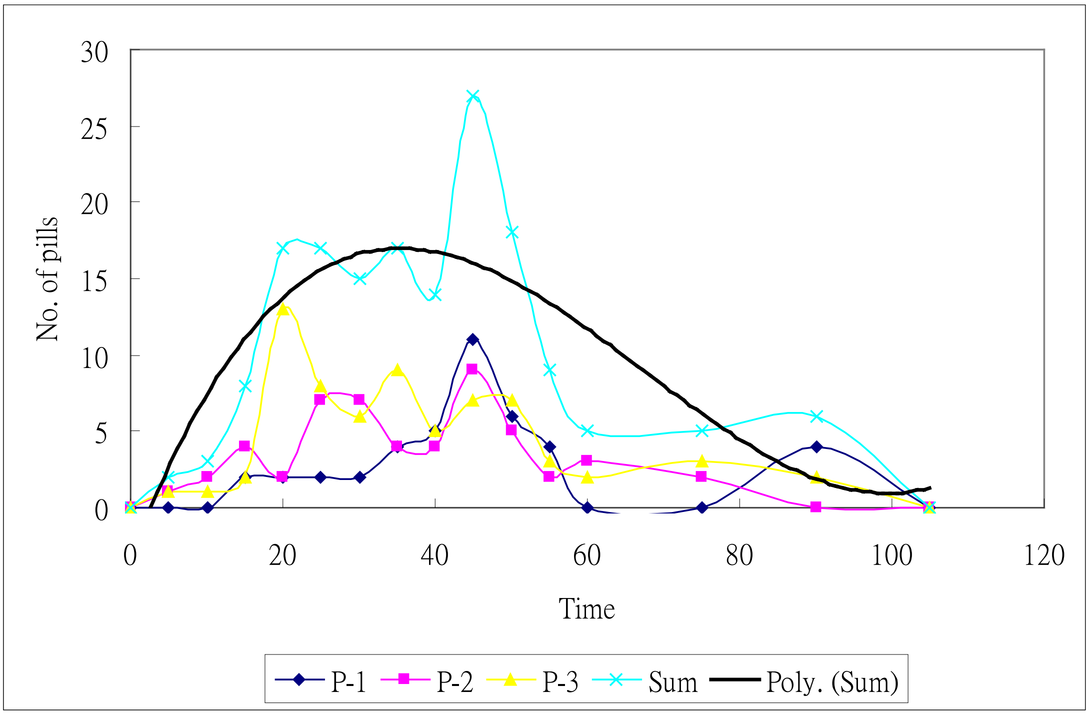
Figure 4.1 is the pilling-time curves obtained by Random Tumble Pilling test. The numbers of pills of three duplicates of Nu-Torque^{TM} and conventional fabrics against time are presented graphically. The pilling-time curves of the summary of the number of pills of all the specimens are also plotted and a trend line was drawn in black.



(a) Nu-Torque™ fabric – singles yarn (1/24Nm)



(b) Conventional fabric – singles yarn (1/24Nm)



(c) Conventional fabric – plied yarn (2/48Nm)

Figure 4.1 Number of pills versus time

i) Fabrics of singles yarns

The results of the curves of the fabrics of two singles yarns are similar. There is an increase of number of pills in the beginning and it becomes to drop after 60 minutes of the test for Nu-Torque™ fabric and 75 minutes for conventional fabric. It is probably due to the rate of the pill formation exceeding that of pill wear-off at the beginning and vice versa after the peak has been reached.

By comparing with the two fabrics of singles yarn, a slightly more pills were found on the Nu-Torque™ fabrics than the conventional fabrics. The steeper slope of its pilling curve indicated the higher speed of pilling formation than that of conventional fabric. The pilling-time curve of Nu-Torque^{TM} fabrics also reaches its peak earlier than the conventional fabric. One of the probable reasons is that there is a difference in twist factor. As the lower the yarn twist factor, the easier for the fibres to migrate as there is less internal stress in the yarn to secure the fibres in position. As a result, Nu-Torque^{TM} fabric with lower yarn twist factor has a slightly greater pilling tendency than the conventional fabric.

ii) Fabric of plied yarns

For the fabric of plied yarns, the number of pills formed is much smaller than that of fabric of singles yarn, the reason being that the plied yarn is formed by two finer yarn (48Nm) plied together. As mentioned in section 2.3.3, since fibres are held more firmly in finer yarn, the migration of the fibre to the fabric surface is restricted. The second twisting also causes the fibres protruding on the surface of a singles yarn to be more secured with the other ends inside the yarn. The curve of the fabric of plied yarns reaches its peak around 30 minutes of the test, which is the earliest among all the fabrics, and it drops afterward.

iii) Supply of pillable fuzz

The supply of pillable fuzz is revealed by the trend of the pilling-time curve. If the supply of pillable fuzz is unlimited, the number of pills will reach a saturated level and the pilling-time curves will become flat. However, the decrease of the number of pills implies there is a drop in the rate of formation of pills. The dropping is probably due to the decrease of amount of pillable fuzz and it implies that the amount of pillable fuzz of the fabric is with limited supply. As more and more pillable fuzz come out to the fabric surface forming pills and wear off, the total amount of pillable fuzz in the fabric decreases and less pills can be formed.

The distribution patterns of the curves are similar to those reported by Omura *et al* (1969) for pilling formation of conventional worsted fabric. Therefore, the pilling behaviour of the two types of fabric is more or less the same. It indicates that the supply of pillable fuzz is limited.

4.2 Methods of acceleration of fuzz generation

4.2.1 Tumbling action and steaming pretreatment

Using the methods described in section 3.2.2.1 and 3.2.2.2, the fabric samples were treated for acceleration of fuzz generation, followed by removal of developed fuzz and pills layer as described in section 3.2.3.2. They were tested with the pilling. The summary of pilling results is shown in Table 4-1. In order to have a clearer picture of the results, bar charts were drawn and the findings are discussed afterward.

Table 4-1 Summary of the pilling results

	Pre-treatment	Equipment used for acceleration of fuzz generation	% Weight loss after fuzz removal	Pilling test	Pilling grade	CV%
Nu-Torque™ fabric	---	---	---	ICI	**1.5****	42.2
	---	---	---	RT	**2****	14.1
	---	---	0.22	ICI	**3**	21.2
	---	---	0.22	RT	**4**	24.8
	---	RT	1.89	RT	**4.5**	6.7
	---	ICI	0.89	ICI	**3**	0
	---	RT	1.91	ICI	**2.5**	16.3
	steaming with air suction	RT	2.33	ICI	**4.5****	10.4
	steaming without air suction	RT	2.04	ICI	**4.5**	18.1
Conventional fabric with plied yarn	---	---	---	ICI	**1.5****	31.0
	---	---	---	RT	**4.5**	11.9
	---	---	0.44	ICI	**3.5**	20.5
	---	---	0.44	RT	**4.5**	6.4
	---	RT	0.83	RT	**5**	0
	---	ICI	1.28	ICI	**4.5**	11.1
	---	RT	1.84	ICI	**4**	17.7
	steaming with air suction	RT	1.77	ICI	**4.5****	9.5
	steaming without air suction	RT	1.57	ICI	**4.5**	19.5

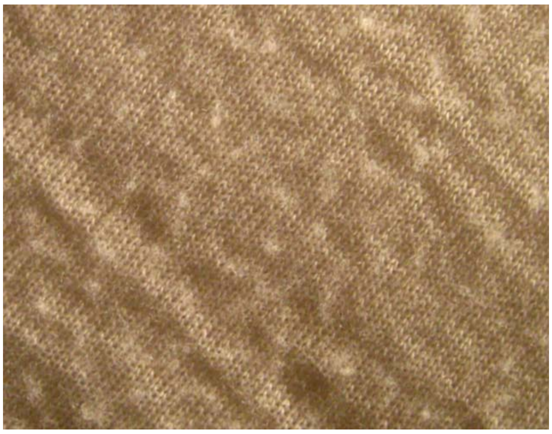
Key: RT = Atlas Electric Tester /Random Tumble Pilling Test,
ICI = ICI Pilling Box/ ICI Pilling Box Method

**Notes: images of the fabric samples are shown in Figure 4.2 and 4.3

(a) Image of treated sample (Pilling Grade 4.5)

(b) Image of control sample (Pilling Grade 1.5)

Figure 4.2 Images of Nu-Torque™ fabric after ICI Pilling Test

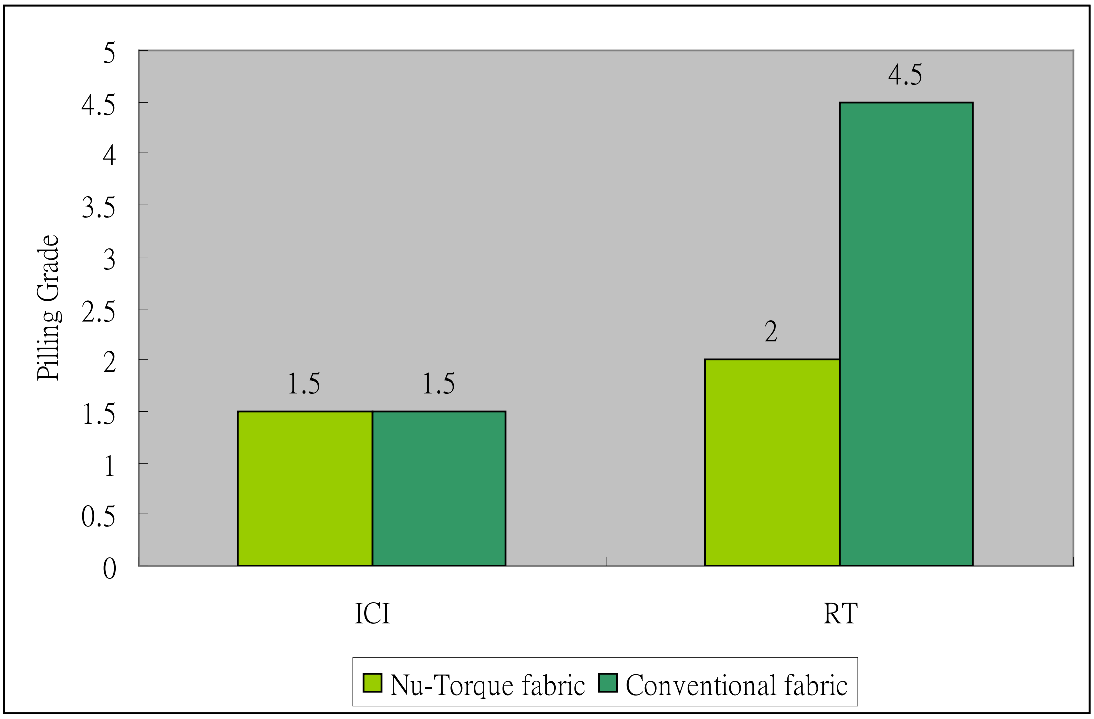


(a) Image of treated sample (Pilling Grade 4.5)

(b) Image of control sample (Pilling Grade 1.5)

Figure 4.3 Images of conventional fabric after ICI Pilling Test

i) Difference in pilling tests



Key: ICI = tested by ICI Pilling Box method, RT= tested by Random Tumble Pilling test,

Figure 4.4 Results of pilling test

Figure 4.4 shows that there is a marked difference between ICI Pilling Box and Random Tumble Pilling tests for the conventional fabric. This may be due to the difference in mechanism of testing. Table 4-2 shows the weight change of fabrics after pilling test. The percentage of weight loss of the fabrics after the test of Random Tumbling Pilling is about triple of that of ICI Pilling. This reveals that Random Tumbling Pilling is a more severe method to the fabrics, even though the 30-minute testing time is only one eighth of that of ICI Pilling.

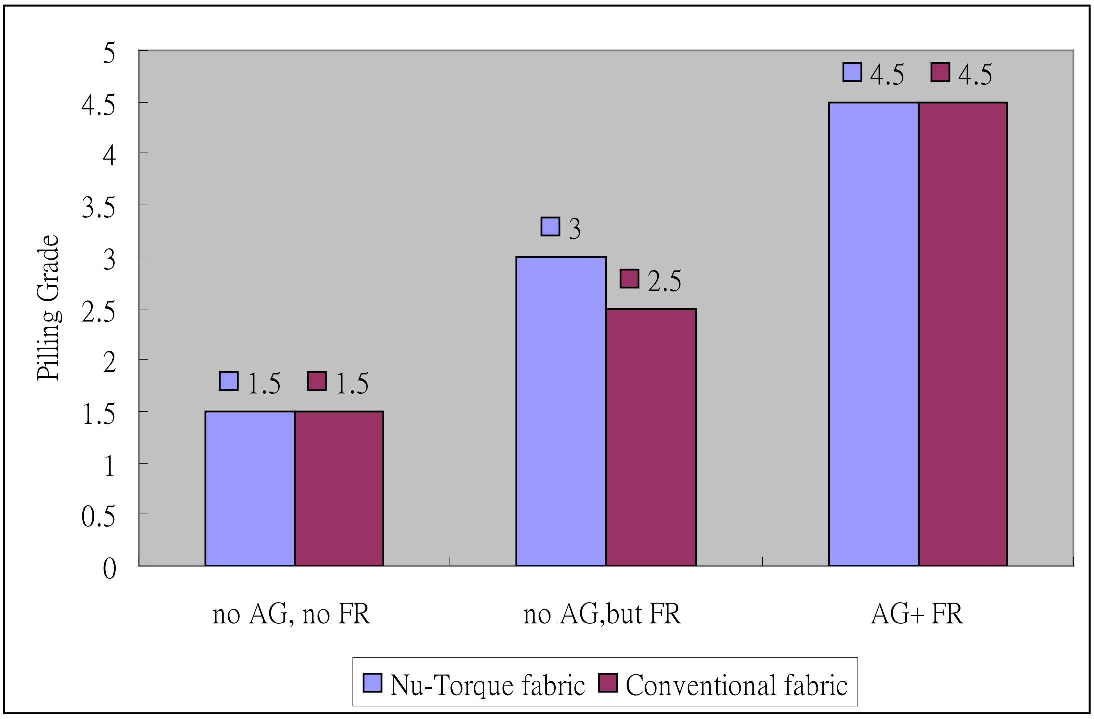
The high-speeding severe actions inside the chamber of Atlas Electric Tester draw fibres to the fabric surface at a faster rate. Fuzz is easy to be formed in Random Tumbling Pilling, but at the same time, the fibres are easy to be worn away. Many fibres are worn out before they entangle into pills. For ICI pilling, which is with milder action, the fibres are not easily worn away before pills can develop. Therefore, this gives maximum chance of pill formation and the pilling grade of the fabrics are low.

In the actual wearing condition, pilling is a slower process. It seems that ICI pilling, which is a slower process, reflects the usage better. It is also commonly used in the wool knitting industry. Thus, ICI Pilling Box Method was selected as the standard pilling test in the studies afterward.

Table 4-2 Weight change of fabrics after pilling test

Pilling Method	Material	Weight loss after pilling (g)	% Weight loss	CV%
ICI Pilling Box	**Nu-Torque™ fabric**	0.015	0.4	7.4
	Conventional fabric	0.012	0.3	20.4
Random Tumbling Pilling	**Nu-Torque™ fabric**	0.047	1.1	13.1
	Conventional fabric	0.045	1.1	1.7

ii) Importance of acceleration of fuzz generation

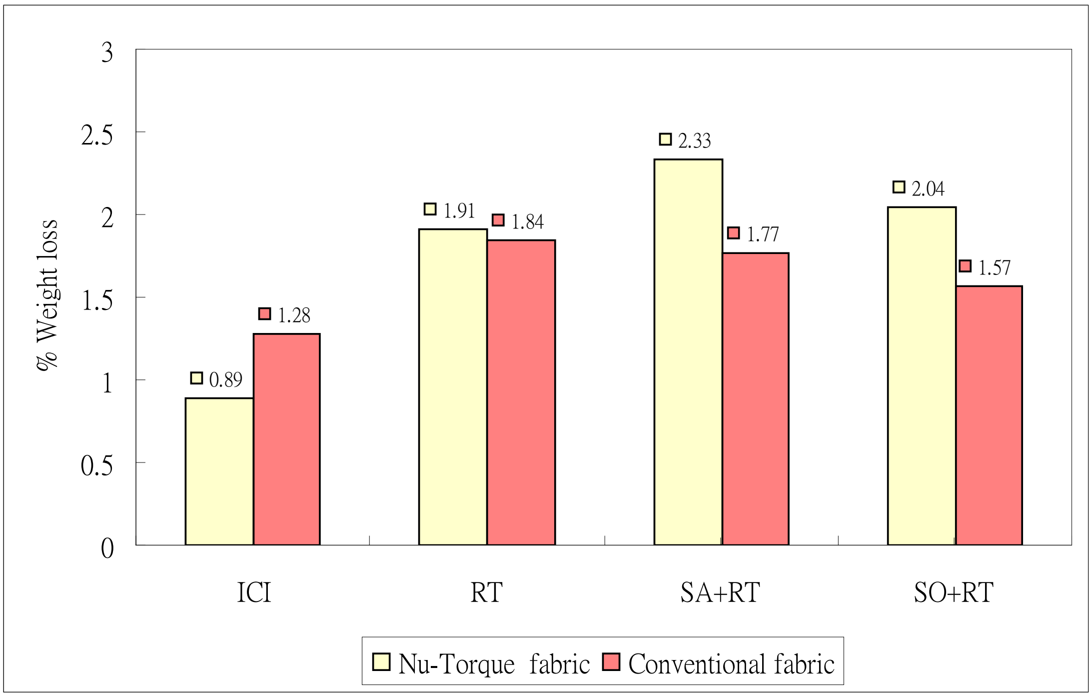


Key: AG = acceleration of fuzz generation, FR= fuzz removal

Figure 4.5 Pilling result with and without acceleration of fuzz generation

Figure 4.5 shows the pilling result with and without acceleration of fuzz generation by Atlas Electric Tester. For those fabric treated with fuzz removal but without acceleration of fuzz generation, their pilling grades are higher than the fabric without any treatment but lower those with acceleration of fuzz generation. This result indicates that acceleration of fuzz generation takes an important role in the treatment to maximize the amount of potential pillable fuzz to be reduced.

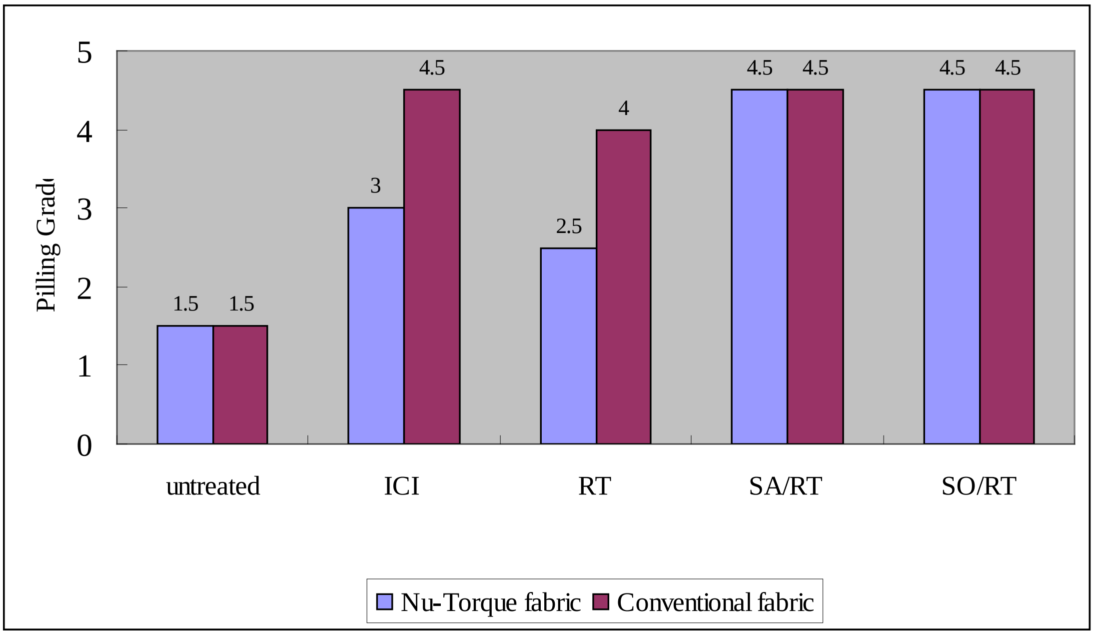
iii) The improvement in pilling performance after different methods of acceleration of fuzz generation



Key: RT= by Atlas Electric Tester, ICI = by ICI Pilling Box,

SA= steaming with air suction, SO= steaming without air suction

Figure 4.6 Percentage of weight loss after fuzz removal



Key: RT= by Atlas Electric Tester, ICI= by ICI Pilling Box,

SA= steaming with air suction, SO= steaming without air suction

Figure 4.7 Pilling result of ICI Pilling Box Method

Figure 4.6 shows the percentage of weight loss after different methods of acceleration of fuzz generation and fuzz removal. Figure 4.7 depicts the pilling results. The pilling of the untreated samples of both the Nu-Torque™ and conventional fabrics is poor (grade 1.5). It was found that all the treated fabric samples have higher pilling grade than those untreated. For those without steaming pre-treatment, the pilling grade of Nu-Torque™ fabrics increased 1 to 1.5 grades, while 2.5 to 3 grades for that of conventional fabrics. Nu-Torque™ fabrics have smaller improvement probably due to its higher pilling tendency as mentioned before.

The improvement in pilling performance is due to the reduction in pillable fuzz of the fabric samples after the two processes of acceleration of fuzz generation and fuzz removal. Although fuzz could still be found on the samples, only a few small pills were found after long duration of tumbling action of testing. It implies that the fuzz on the fabric surface is below the critical value of fuzz height or density, and it is less pillable. Thus, the attrition treatment can inhabit the formation of pills on fabrics due to the limited supply of pillable fuzz.

Percentage of weight loss after removal of generated fuzz and pills seems to be one of the main factors affecting the pilling result, as the more fuzz to be removed, the fewer pills can be formed. This is shown in the experimental results. After all, it seems that the amount of fuzz to be removed in order to reduce the pilling tendency of a worsted knitted fabric is about 2% of the total initial weight of the fabric.

iv) Steaming as pre-treatment

Fabric samples with steaming pre-treatment gave higher pilling grades regardless the type of fabric. The pre-treatment improved the pilling grade of the Nu-Torque^{TM} fabrics from 2.5 to 4.5, which is the same as that of conventional fabrics. The effect of the pre-treatment can be further proved by the increase in percentage of weight loss after fuzz removal process, which implies that more pillable fuzz was removed. Those samples with air-suction applied even gave a greater percentage of weight loss. Thus, with the aid of pre-treatment, both fabric samples are able to get high performance in pilling test.

Steaming pre-treatment seems to be able to relax the fabric. As the tension in the yarn become less, the fibre insides are easier to migrate to the yarn surface. The application of air-suction also seems can assist the migration of the wool fibre by drawing the fibres out to the fabric surface slightly after the relaxation. The action is more effective to Nu-Torque™ fabric, which may due to the looser yarn structure of the Nu-Torque™ yarn. This may also be the reason why the percentage of weight loss after removal of generated fuzz of Nu-Torque™ fabric is always higher than that of conventional fabric.

v) Methods of acceleration of fuzz generation

Atlas Electric Tester is a more effective acceleration method than ICI Pilling Box. For the same pilling grade, the process of acceleration of fuzz generation required 4hours in ICI Pilling Box, while only 30 minutes is required using Atlas Electric Tester. The tumbling action is effective, however, it seems to be too severe to the fabrics. It also has technical problems for application, such as uneven treatment on different areas on the fabric and difficult to be applied on garments. As a result, alternative pilling acceleration methods with high efficiency but milder to the fabrics, such as flat abrasion and brushing, have been investigated and are discussed in the following sections.

vi) Fabric samples

As Nu-Torque™ fabric has a higher pilling tendency than that of the conventional fabric. In order to obtain a clearer observation of the effectiveness of the treatment, the Nu-Torque™ fabric was chosen for the experiments afterward.

4.2.2 Flat abrasion by Martindale Tester

As described in section 3.2.2.3, specimens were rubbed against with different abradent materials using the Martindale Tester. The number of pills on the specimen was counted after particular revolutions and the results are shown in Table 4-3.

Table 4-3 Pilling test results of flat abrasion

Abradent material	**no. of pills**			
	100 revs	**200revs**	**50 revs after shaving**	**100 revs after shaving**
Nu-Torque™ worsted knitted fabric	85	128	0	2
Standard abradent (coarse woven wool)	156	128	7	18
cork	126	148	36	63

The results show that the rate of generation of fuzz and pills depends on the type of abradent material. There was a sharp drop in number of pills formed after the fuzz removed by lint shaver regardless of the type of material was used. Using Nu-Torque^{TM} worsted knitted fabric as the abradent gave the best result. It seems that fabric rubbing with the same material as itself is the most effective in drawing the pillable fuzz to the fabric surface. In addition, the afterward fuzz removal process can remove most of the pillable fuzz and lower the pilling tendency of the treated fabrics.

Flat abrasion seems to be an effective mean to accelerate the fuzz generation, and the action is also milder to the fabrics when compared with tumbling action. Nevertheless, flat abrasion may not be the best choice for fuzz generation. When the fibres are drawn to the fabric surface to form fuzz and pills in the abrasion action, the abradent is wearing out at the same time, no matter what kind of abradent is used. The wearing out of the abradent seems to be severe and it is a difficult to be used as an industrial method. As a result, an alternative pilling acceleration method, brushing, is discussed in the following section.

4.2.3 Brushing action

As referring to the section 3.2.2.4, acceleration of fuzz generation by brushing action has been investigated and it is discussed in this section.

i) Type of brush hair

Table 4-4 Record of weight change and pilling test result of Random Tumble Pilling Test

	A	**B**	**C**	**D**	**E**	**F**
Type of brush	**Toothbrush**	**Electric toothbrush**	**Electric toothbrush**	**Brush C**	**Brush C**	**---**
Remark		**brushing by movable head only**				**control**
brushing time per each side (mins)	**5**	**5**	**5**	**2**	**5**	**---**
Weight loss after brushing and fuzz removal process **(% of original weight)**	2.7	1.8	2.3	2.5	3.3	0.2
Pilling grade	4.5	4.5	4.5	4.5	4.5	4
CV%	11.1	14.8	13.3	11.1	13.3	11.8

Table 4-4 shows weight change and pilling grade of Random Tumble Pilling Test. Weight loss after brushing and fuzz removal process was about 2-3% of the original weight, while the loss without brushing was only about 0.2%. The results show that all of the methods accelerated the fuzz generation in the brushing treatment. Brush C generated the largest amount of fuzz through brushing. It is probably because of its largest size among all of the brushes. The images of the fabric surface before brushing, after brushing and after shaving are shown in Figures 4.8, 4.9 and 4.10 respectively. The amount of fuzz was increased by brushing and reduced to even a lower amount than before brushing by shaving with a lint shaver.

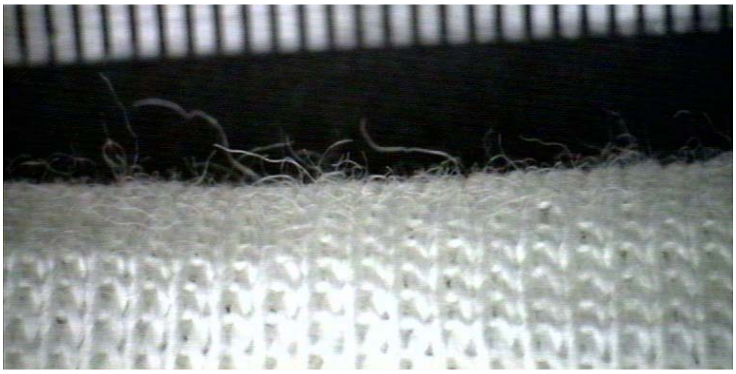


Figure.4.8 Fabric surface before brushing

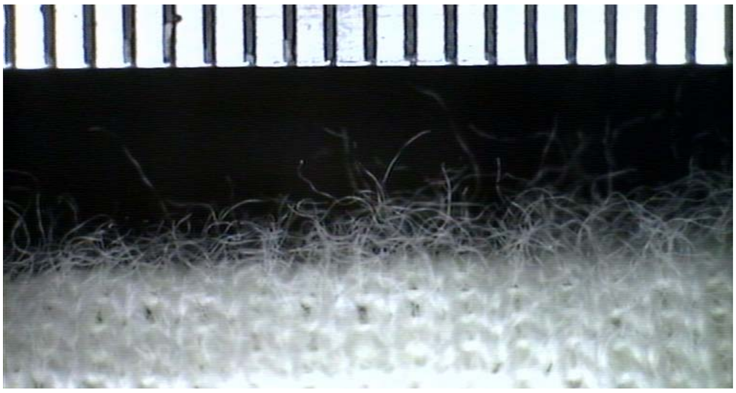


Figure.4.9 Fabric surface after brushing

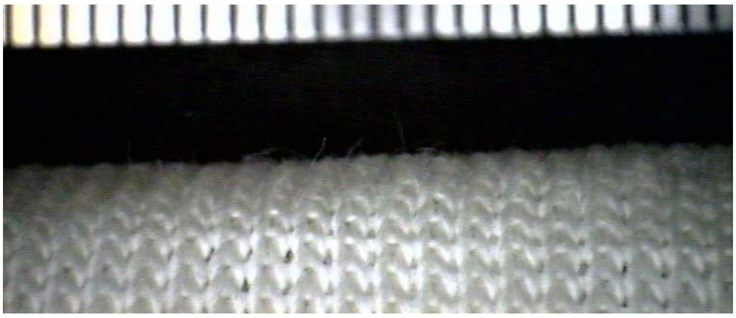


Figure.4.10 Fabric surface after shaving

By comparing with the result of that generated fuzz by tumbling, the generated fuzz by brushing seems to be even more effective i.e. less time and effort are required. The treatment on different parts of the fabric is also evener than using tumbling action. Besides the higher efficiency and evenness, it seems that brush hairs have less wearing-out problem than the abradents used in flat abrasion action.

b) Direction of brushing

Table 4-5 Results of ICI Pilling Box Method

Sample	**brushing time**		**% weight loss**	**CV%**	**Pilling Grade**	**CV%**
	wale-wise	**course-wise**				
Nu-Torque™ fabric	**50**	**0**	1.93	7.18	4.5	11.2
	0	**50**	2.72	10.3	5	4.3
	25	**25**	2.30	1.16	5	5.5
	0	**0**	---	---	1.5	42.2

Table 4-5 shows the results of the treated fabrics tested by ICI Pilling Box Method. All the treated specimens had marked improved pilling grade. The pilling grades of those being brushed in wale-wise direction were 4.5, while others were 5. From the percentage of weight loss, brushing the fabric in course-wise direction only is the most effective, and the less effective one is in wale-wise direction only. Brushing in course-wise only and brushing in both directions seems to be more effective to generate fuzz than brushing in wale-wise direction only. Since brushing in both directions provides the similar effect with brushing in course-wise only, it was used in the experiments afterward in order to eliminate unknown influence, such as the effect of direction to particular fabric structure or material.

b) Steaming pretreatment

Table 4-6 Results of ICI Pilling Test Method on samples with steaming pretreatment

Sample	Pretreatment	Brushing	Shaving	% Weight loss	Pilling Grade	CV%
Nu-Torque™ fabric	---	yes	yes	2.30	5	9.1
	steaming	yes	yes	2.32	2.5	23.6
Conventional fabric with plied yarn	---	yes	yes	1.91	5	5.0
	steaming	yes	yes	2.10	4.5	11.2

Table 4-6 shows the result of the treated fabric samples with and without steaming pretreatment. It shows that more fuzz was generated and shaved off for those after the steaming pretreatment. The results imply that steaming pre-treatment made the internal stress of the yarns released and fibers were then easier to migrate to the fabric surface to form fuzz. However, their pilling grades were found lower than those without steaming pretreatment.

In using tumbling action for fuzz generation, steaming seems be a useful pre-treatment to improve the effectiveness of the proposed anti-pilling treatment; however, it is not the same case for using brushing action. The difference may due to the difference in mechanism between tumbling and brushing action in fuzz generation. Tumbling is a much more severe action than brushing. It acts on the whole fabric in all directions and provides enough force to draw the fibres from inside the fabric to both sides of the fabric surface to form fuzz. On the other hand, as only one side of the fabric was brushed, the acceleration of fuzz generation is not as completely as the tumbling. Some of the pressure-released fibres deep inside the fabric did not receive enough driving force to migrate to the fabric force under the brushing action on the fabric surface only.

Although tumbling action seems to be more effective on generating fuzz, in consideration of the influence to the fabrics and ease of application of the treatment, brushing action is still preferred.

c) Number of brushing-and-shaving cycles

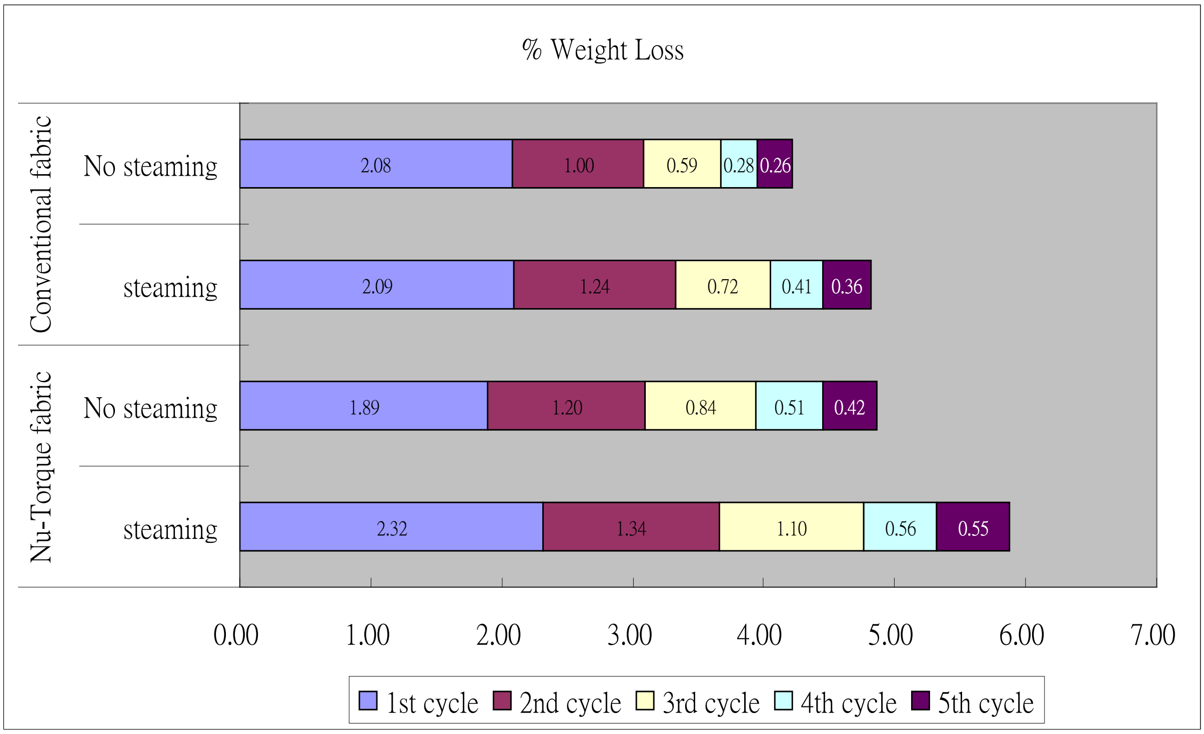


Figure 4.11 % weight loss of fabric samples after each brushing-and-shaving cycle

Figure 4.11 shows percentage of weight loss of fabric samples after each brushing-and-shaving cycle. The results show that the percentage of weight loss of the specimens of the latter cycle was smaller than that of the former cycle. After a total of five brushing and shaving cycles, the steaming-pretreated specimens showed a larger percentage of weight loss than those untreated. It implies than steaming pre-treatment can release the internal stress in the yarn and fibers are more ready to migrate to the yarn surface and form fuzz.

Table 4-7 ICI Pilling Grade Value of fabric after 1 and 2 cycles of brushing and shaving

Samples	Treatment		Pilling Grade	CV%
	Pretreatment	No. of (Brushing + shaving) cycles		
Nu-Torque™ fabric	No Steaming	1	4.5	9.1
		2	5	5.0
	Steaming	1	2.5	23.6
		2	3.5	17.9

Table 4-7 shows the result of pilling of the samples after one and two brushing-and-shaving cycles. Those specimens treated with two cycles have higher pilling grades. This shows that an increase in brushing-and-shaving cycles can further reduce the pilling tendency by removing more amount of pillable fuzz.

d) Brushing treatment on commercial sweaters

Table 4-8 Results of ICI Pilling Box Method of the sweaters

Samples	Treatment	Pilling Grade	CV%
Blue sweater	**---**	2**	37.4
	Brushing + shaving	4.5**	9.1
Grey sweater	**---**	3	38.6
	Brushing + shaving	5	6.1

**Notes: images of the fabric samples are shown in Figure 4.12

As referring to section 3.2.2.4, the proposed treatment was applied on the garment samples, that is, blue and grey sweaters. The pilling results of the treated samples are shown in Table 4-8. The results show that the proposed treatment can increase the pilling grade from 2 to 4.5 for the blue sweater, and from 3 to 5 for the grey sweater. The treatment seems to be workable on the finished garment available in the market, even they are dyed and finished.

As the blue sweater has a higher pilling tendency than that of the grey sweater. In order to obtain a clearer observation of the effectiveness of the treatment, the blue sweater was chosen for the experiments afterward.

(a) Image of treated sample

(Pilling Grade 4.5)

(b) Image of control sample

(Pilling Grade 2)

Figure 4.12 Images of blue sweater after ICI Pilling Test

4.3 Methods of fuzz removal

After the pillable fuzz is generated, the next step is to remove the generated fuzz layer. Two approaches were investigated including laser ablation and mechanical shaving.

4.3.1 Use of Laser

a) Laser singeing

After the fabric samples exposed to the laser beam with its scanning level as described in section 3.2.3.1, brown squares were found, which are shown in Figure 4.13. The fuzz and pills were heated up, and carbonized and evaporated. Figure 4.14a and 4.14b show the images of the fabric surface exposed to the laser beam and after slight rubbing. The fibres in the fuzz and pills became brittle and easy to be rubbed out. Pills were found to be easier to be carbonized than the fuzz. It seems that the fibre balls are easier to absorb and store the laser energy than the protruding fibres. The base fabric was yellowed. The level of yellowing depends on the level of the laser energy. The higher the laser energy, the darker the color of the laser exposed area.

Dyed fabric surface exposed to laser beam is shown in Figure 4.15. Similar to the undyed fabric, the fuzz and pills on the fabric surface were also and carbonized. They have become brittle and easy to be rubbed out. However, the high energy laser beam lightened the dyed fabric. This probably is due to the vaporization of the dye stuff by the high energy of the laser beam.

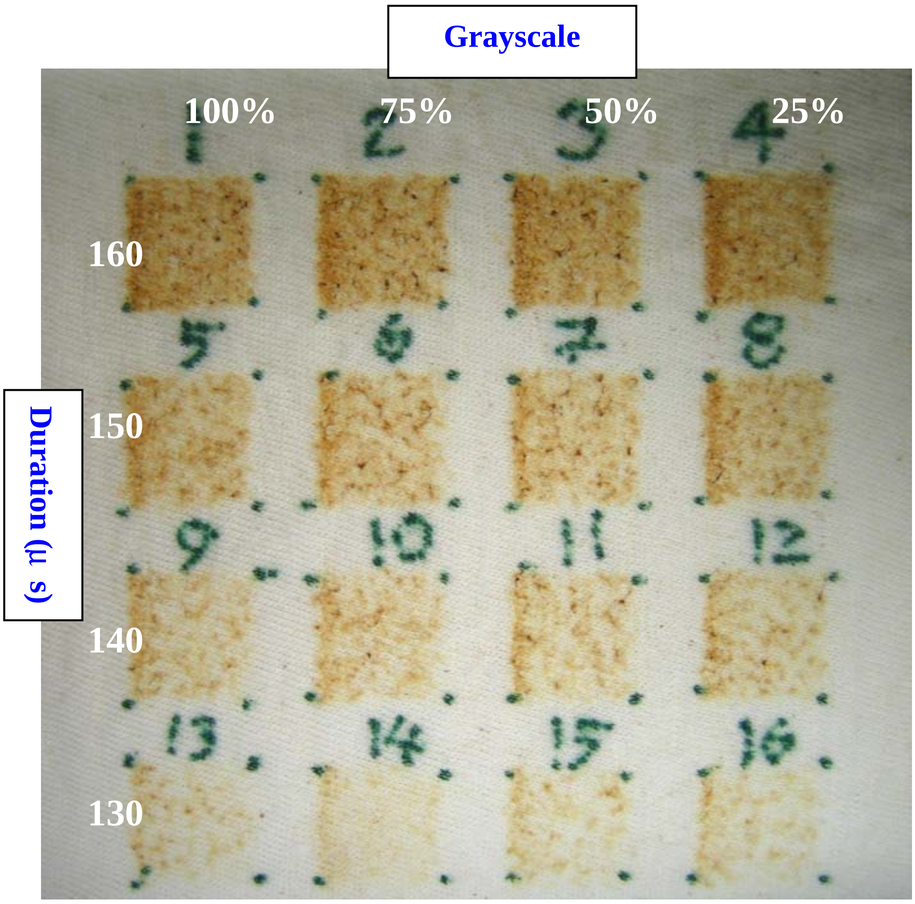
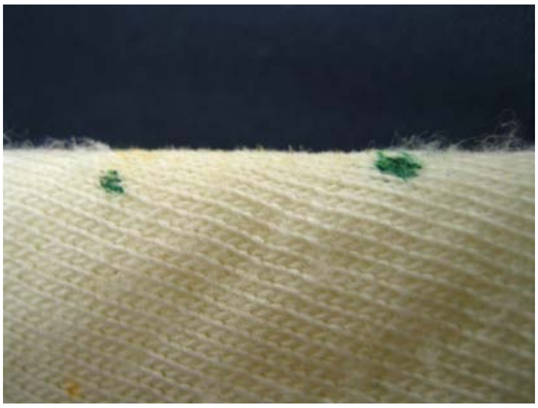


Figure 4.13 Fabric surface exposed to laser beam

(a) Overhead view



(b) Side view

Figure 4.14 Grey fabric surface after exposing to laser beam and rubbing

(a) Lower laser energy

(power density: 4W/cm^2)

(b) Higher laser energy

(power density: 5.5W/cm^2)

Figure 4.15 Dyed fabric surface exposed to laser beam

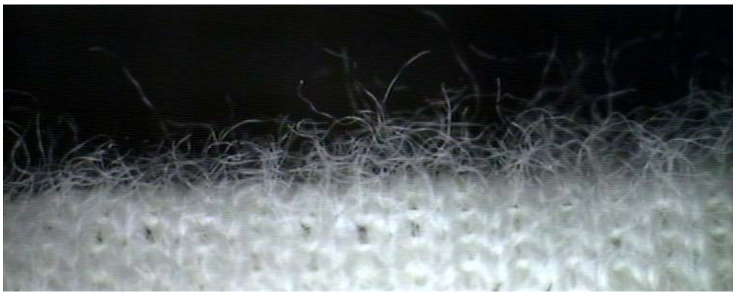
b) Laser cutting

Regarding to section 3.2.3.1, laser beam was used to cut the fuzz and pills on the fabric surface, which is shown in Figure 4.16. Fuzz and pills were cut off but light brown lines were found on the fabric surface. Similar to that of laser singeing, the high energy of the laser beam made it yellow.

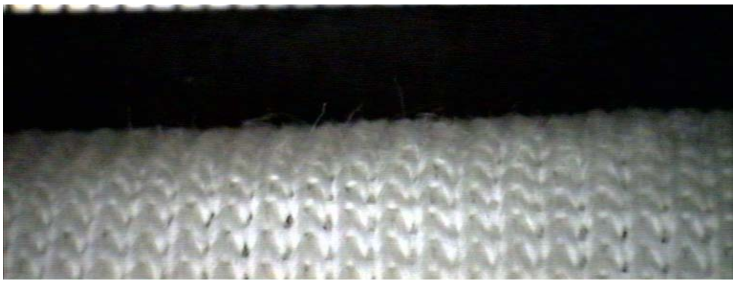
Figure 4.16 Wool fabric surface after pills cut by laser beam

4.3.2 Mechanical shaving

Figures 4.17 and 4.18 show the images of the fabrics before and after shaving. It can be seen that the fuzz on the fabric surface are removed after shaving with a lint shaver. The use of lint shaver seems to have many advantages over the use of laser. Firstly, use of lint shaver is more convenient than using laser as it is easier to be control. Secondly, the fabric is also less likely to be damaged if the worker shaves the fabric with care. Thirdly, the quality of the treatment is easier to be controlled by repeating of shaving. In addition to these, the capital cost of using lint shaver is lower than that of using laser. However, the use of lint shaver requires a lot of man power and it is time consuming as the shaver is small. It is good enough for laboratory scale but it may be not suitable to be use in mass production.



(a) Fabric surface before shaving



(b) Fabric surface after shaving

Figure 4.17 Images of Nu-Torque™ Fabric

(a) Fabric surface before shaving

(b) Fabric surface after shaving

Figure 4.18 Images of blue sweater

4.4 Washing on sweater

As referring to section 3.2.2.4, the effect of washing on the treated sweaters has been investigated.

Table 4-9 Results of ICI Pilling Box Method on the effect of washing

Samples	Treatment	Pilling Grade	CV%
Blue sweater	**control**	2	37.4
	washing	1	24.9
	brushing + shaving	4.5	9.1
	washing + shaving	4.5	8.1
	brushing + shaving + washing	4	9.1

Table 4-9 shows the pilling results of sweaters with and without washing. Specimens after the washing process got the worst grade 1. Washed specimens after fuzz removal got the same grade as the brushed specimens after fuzz removal. It seems that washing gave the similar effect of fuzz generation on the fabric as that of brushing. The brushed and shaved specimens after washing got a slightly lower grade than those before washing. The results show that washing only has a small effect on the treated fabric and it seems that the most desirable time for the anti-pilling treatment is after garment washing and before packaging.

4.5 Conclusion

Acceleration of fuzz generation, including tumbling action, flat abrasion action and brushing action, has been investigated. All of them were found to be effective in acceleration of fuzz generation. Among them, brushing action seems to be the one with the mildest action and less problem of wearing-out of material and easiest for industrial applications. As a result, the brushing action was chosen as the method of acceleration of fuzz generation for further investigation of the anti-pilling treatment.

Using laser beam in removing fuzz and pills on the fabric surface were found to be workable. Laser singeing can heat up the fuzz and pills, and make them brittle and easily to be rubbed off. Laser cutting can also be used to cut the fuzz and pills off. However, there are some drawbacks of using laser beam. The base fabric will be yellowed by the high energy of the laser beam. It can even lighten the dyed fabric. Changing colour after treatment is undesirable for any processing.

The color depth of yellowing decreases with the reduction of energy level of laser beam. This implies that cutting the fuzz and pills without yellowing of base fabric may be achieved by a finer adjustment of the laser energy. However, the carbon dioxide laser used is designed for laser cutting and engraving using a very high energy level. It was found that the laser energy become unstable when a lower energy level laser is emitted. It seems the laser energy level is not able to be adjusted finely with the existing equipment.

Laser cutting of fuzz and pills on fabric surface requires very sophisticated technique. Since energy level to be used is high, the laser beam should be stable and sweeping accurately in order not to affect the base fabric. More than that, continuous wave laser, which is more stable and evenly swept, should be used instead of pulsed laser.

Use of laser for fuzz removal process is more suitable for mass production; however, there are still many technical problems to be solved. On the other hand, although using lint shaver requires much more man power and time, it has many advantages over than using laser: it is easier to be controlled; the fabric is less likely to be damaged if the worker shaves the fabric with care; assurance of better quality of treatment; and the capital cost is also lower than that of using laser. As a result, the mechanical shaving was adopted for further development of prototype apparatus.

Chapter 5 Prototype Development and Applications

This chapter presents an investigation of a prototype of brushing device, including the prototype design of brushing device, working principle, operation parameters, evaluation of the treated fabric samples, and wear trial of treated garment samples.

5.1 Details of the prototype of brushing device

A home-made laboratory device was used for this study. Figure 5.1 shows the brushing device. The details of the device are shown in Table 5-1. It has a rotatable brush and a movable board. They are driven by two direct current motors of 12V. The speed of the motors can be controlled by varying the voltage with the power supplier as shown in Figure 5.2.

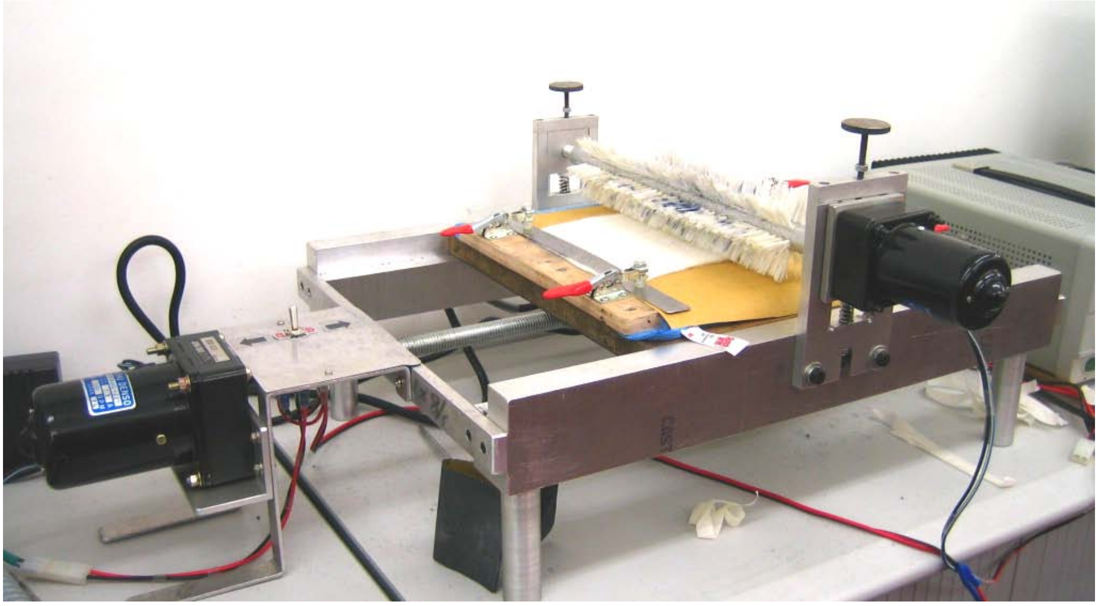


Figure 5.1 Prototype of brushing device

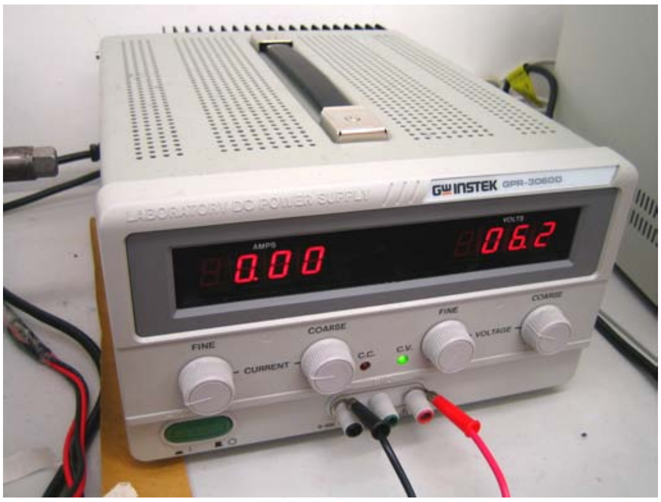
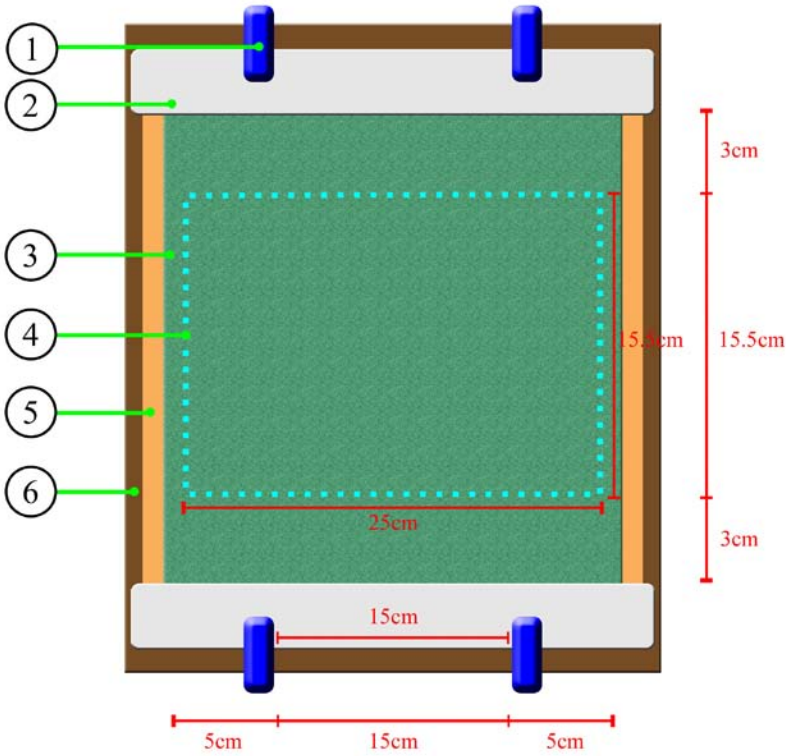


Figure 5.2 DC power source

Table 5-1 Specifications of the prototype brushing device

Length of rotatable brush	25cm
Length of brush hair	2.5cm
Maximum movable distance of movable board	20cm
Measured moving speed of movable board (energy supply: 6V – 12V)	0.25cm/s - 0.55cm/s
Measured brushing speed (energy supply: 6V – 12V)	2.5rev/s - 4 rev/s
Distance between the clips at one end	15cm
Area of treatment	25cm x 15.5cm

There are clips and metal plates on the movable board for holding fabric samples, which is shown in Figure 5.3. The board is driven by motor and the moving direction is changeable. Pattern paper is placed in between the board and the fabric sample in order to reduce the slippage of the fabric in the brushing process.



Key:

1. Clip
2. Metal plate
3. Fabric sample
4. Area of brushing
5. Paper
6. Movable board

Figure 5.3 Movable board

The rotatable brush is 25cm long and the cross section is shown in Figure 5.4. It is made of a metal rod with radial brush hairs. The brush hairs come from the red shower brush described in previous chapter 3. The hairs are stuck into the holes of the metal rod by glue.

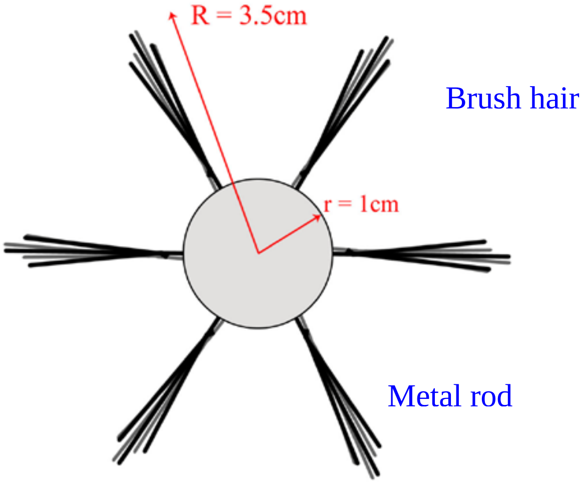


Figure 5.4 Cross-section of rotatable brush

5.2 Operational parameters

In this section, a study of the parameters of the brushing device, including moving direction and speed of movable board, was conducted. It aims to achieve a high efficiency in accelerating the fuzz generation which is comparable to that of brushing with human hands.

5.2.1 Experimental

a) Samples

Fabric samples of Nu-Torque™ fabric and the blue sweater were used in the following experimental studies. They were conditioned at least 24 hours under standard atmospheric conditions (65 ± 2% RH, 20 ± 2 ° C) before used in the experiments.

b) Moving direction of board

With the movement of the movable board, fabric samples were able to be carried and brushed evenly. There are two moving directions of the movable board as described in Figure 5.5. Tension is built up in the contact area between the fabric and the brush when the movable board is moving in the opposite direction to the brushing. The influence of the tension building on the amount of fuzz generated is investigated in this section.

Fabric specimens were fixed on the movable board by the clips and metal plates in turns. After the rotatable brush had been switched on, specimens were carried by the movable board: some moved in the same direction with the brushing; some moved in the opposite direction to the brushing; and some were brushed in both directions for a cycle. The speed of the rotatable brush was 4 rev/s (12V power supply) and the speed of the movable board was 0.55cm/s (12V power supply). The specimens were then weighed before and after the brushing. There was an area of 15x15cm on the specimens were shaved by a lint shaver. Their weight change after shaving was recorded and compared.

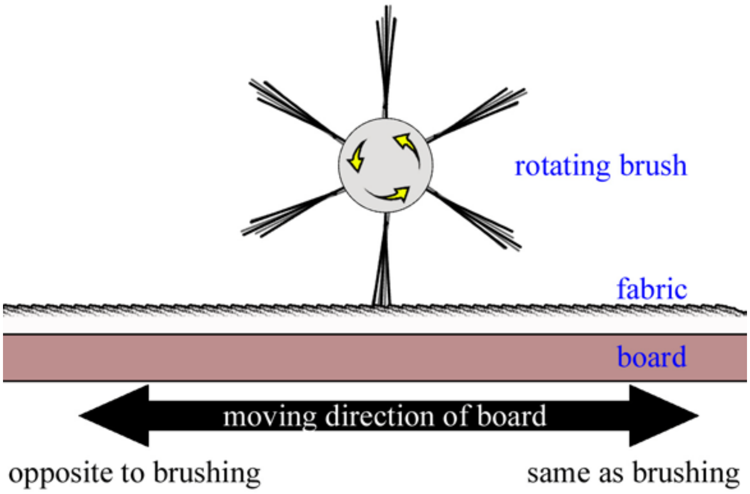


Figure 5.5 Moving direction of movable board

c) Speed of movable board

The duration of the brushing period is dependant on the speed of the rotatable brush and movable board. In this section, the effect of the speed of the movable board on the amount of fuzz generated, where the speed of rotatable brush is keep constant, was investigated.

Fabric specimens were fixed on the movable board by the clips and metal plates in turns. After the rotatable brush was switched on, the movable board, which carried the specimen, moved for one cycle, i.e. the specimen was brushed in both directions. The speed of the rotatable brush was 4 rev/s (12V power supply). The effect of the speed of the movable board, which is with two levels of 0.25cm/s and 0.55cm/s, was investigated. The brushed specimens were then weighed.

There was an area of 15x15cm on the specimen was shaved by a lint shaver. The weight change after shaving was recorded and compared.

5.2.2 Results and discussion

a) Moving direction of movable board

Table 5-2 Effect of moving direction

Sample	Brushing equipment	Moving direction of movable board	Total weight loss after fuzz removal (g)	CV%	% Weight loss
Nu-Torque™ fabric	Brushing device	same as brushing	0.06	4.5	1.5
		opposite to brushing	0.07	6.8	1.5
		a cycle of brushing	0.10	5.4	2.3
	Brushing with brush C by human hands	(50 brushes)	0.10	1.2	2.3

Table 5-2 shows the total weight loss of the fabric samples, which were carried by the movable board moving in different directions, after fuzz removal in a 15x15cm area. The results show that movable board moved in the direction opposite to brushing gave a slightly higher weight loss. When the board moved a cycle, the total weight loss of the fabric after brushing by the device and fuzz removal by a lint shaver was the same as that brushed by human hands. It implies that when the board moved a cycle beneath the rotatable brush with speed 4 rev/s, the fuzz generated in the carried fabric samples is similar to those brushing by human hands. As a result, the acceleration of fuzz generation by brushing device is achieved by fixing fabric sample on the movable board and moving a cycle beneath the rotatable brush.

b) Speed of movable board

Table 5-3 Effect of speed of movable board

Sample	Brushing equipment	Speed of movable board	Total weight loss after fuzz removal (g)	CV%	Brushing time
Blue sweater	Brushing device	0.55cm/s	0.22	6.6	60s
		0.25cm/s	0.26	5.7	120s
	Brushing with brush C by human hands	(50 brushes/min.)	0.17	3.2	120s

Table 5-3 shows the total weight loss of the fabric samples, which were carried by the movable board moving in different moving speed, after fuzz removal in a 15x15cm area. The results show that the slower the speed of the movable board, the larger amount of fuzz was generated and removed. By comparing with brushing by human hands, the brushing device is much more efficient as more fuzz can be generated with the same brushing time. As the pilling tendency can be further reduced by removing a larger amount of fuzz, 0.25cm/s was used as the moving speed of the movable board in order to increase the amount of generated fuzz.

5.3 Evaluation of treated samples

Other properties of a fabric are always affected after an anti-pilling process. For knitted worsted fabric, thermal insulation and bursting strength are two of the important properties affecting the end use of the fabric. In this section, these two properties as well as pilling tendency and colour change of the treated and untreated fabric samples were investigated.

5.3.1 Experimental

a) Samples

Fabric samples of Nu-Torque™ fabric and the blue sweater were used in the following experimental studies. They were conditioned at least 24 hours under standard atmospheric conditions (65 ± 2% RH, 20 ± 2 ° C) before used in the experiments.

b) Pilling tendency

The pilling tendency of the treated fabric was tested by ICI Pilling Box Method as described in section 3.3.1. The results are discussed in section 5.3.2.

c) Thermal insulation

The thermal insulation of a fabric reveals the ability to keep warmth. Fabric samples were tested by the Kawabata Evaluation System F7, thermal prosperity measurement instrument, which is shown in Figure 5.6. The instrument is divided into several parts, including a KEF-S7 II Thermo-Labo Model 2 Amplifier, a Thermo-Labo BT-Box connected with heaters, a wind tunnel for measuring thermal insulation, and a fan controller.

Dry contact method and dry space method are selected for measuring the thermal insulation of the fabric samples. The heaters connected to the Thermo-Labo BT-Box were switched on firstly. The BT-plate in the Thermo-Labo BT-Box, which is shown in Figure 5.7, was heat up to 35˚C and kept steady. The temperature was used as to simulate the skin temperature of human body. Fabric specimen with size 20x20cm was put in between a 20x20cm foam sample frame and the 10x10cm BT-plate. There was a 10x10cm hole in the centre of the foam sample frame. The edges of the frame were sealed with tapes. The fan at the top of the wind tunnel was then switched on and blew on the fabric specimen with a wind speed of 30cm/s. When the reading reached to the equilibrium, heat loss in 1 minute was counted and recorded. Three readings were taken from each samples and the mean value was calculated. The keeping warmth ratio of each fabric sample, which is the ratio of reduced heat loss with sample to that without sample, was calculated according to the following formulae.

$$\mathbf{W} = \mathbf{w} / \{\mathbf{BT}(^\circ C) - \mathbf{T_a}(^\circ C)\} \times (1m^2 / 100\ cm^2)$$

where,

w *is the average Watt of heat consumption of "BT-Box" in 1 minute*

W *is the heat loss with sample*

BT *is the temperature of BT-plate*

$\mathbf{T_a}$ *is the room temperature*

The keeping warmth ratio is:

$$\boldsymbol{\alpha} = (\mathbf{W_o} - \mathbf{W}) / \mathbf{W_o} \times 100(\%)$$

where,

$\mathbf{W_o}$ *is the heat loss without sample*

W *is the heat loss with sample*

From the shown formulae, it can be seen that the larger the keeping warmth ratio, the higher the ability to keep warmth.

Equipment:

- **KES-F7 Thermal prosperity measurement instrument**

Figure 5.6 KES-F7 Thermal prosperity measurement instrument

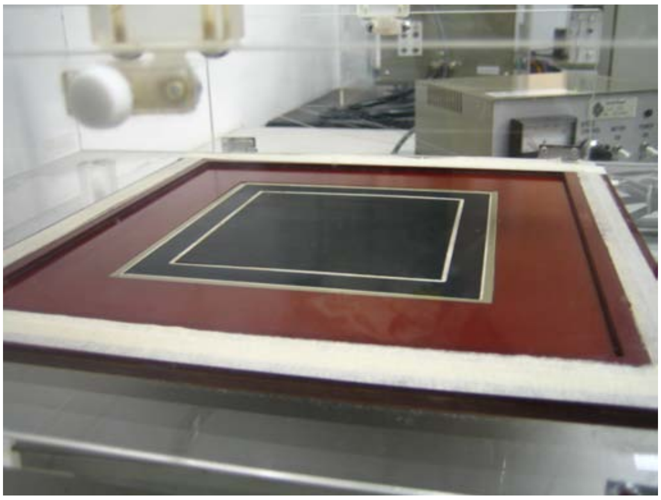


Figure 5.7 The BT-plate in the Thermo-Labo BT-Box

d) Bursting strength

In this experiment, fabric samples were tested with reference to the standard ISO 13938-2 by the Truburst Tester (model 610), which is shown in Figure 5.8. The instrument uses a pneumatic pressure method for the determination of bursting strength and bursting distension of textile fabrics. The bursting strength and breaking time were recorded. Five readings are taken from each samples and the mean value was calculated.

Equipment:

◆ **Truburst Tester (model 610)**

Figure 5.8 Truburst Tester (model 610)

e) Colour change

The diffuse reflectance spectrophotometry (DRS) was used to measure the colour change of samples with and without the attrition treatment. The measurement was performed by using a spectrophotometer of GretagMacbeth™ Color-Eye® 7000A as shown in Figure 5.11. CIE (Commission International de l''Eclairage) measurement system, based on the work of by Wright (1928; 1929) and Guild (1931), was used. Four diffuse reflectance measurements were taken for each sample. The samples were conditioned at least 24 hours under standard atmospheric conditions (65 ± 2% RH, 20 ± 2 ˚ C) before taking the reflectance measurements. The parameters used are as follow:

i) Standard Observer

The colour sensitivity of the eye changes according to the field of view. The CIE defined the standard observer in 1931 using a 2˚ field of view, hence the name 2˚ Standard Observer, and defined an additional 10 ˚ Supplementary Standard Observer based upon a 10 ˚ of view in 1964. Standard Observers (shown in Figure 5.9) are specified in ISO 11664-1:2007, Colorimetry -- Part 1: CIE standard colorimetric observers . As 2˚ Standard Observer is used when the field of view is 4˚ or less, 10 ˚ Supplementary Standard Observer was used in this experiment.

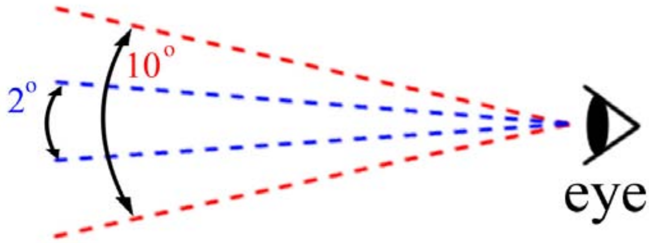


Figure 5.9 2° and 10° Standard Observer

ii) Standard light sources and illuminants

The CIE distinguishes between sources, which are physically reliable sources of light, and illuminants, which are values for theoretical spectral energy distributions. Illuminants A, B, C and D65 have been defined, but B is rarely used. They are specified in ISO 11664-2:2007, Colorimetry -- Part 2: CIE standard illuminants. Standard illuminant A, C and D65 were used in this experiment and the details of them are shown in Table 5-4.

Table 5-4 Standard Illuminants for Colorimetry

Illuminants	Specifiactions
Standard illuminant A	It is intended to represent typical, domestic, tungsten-filament lighting, with a spectral energy distribution corresponding to the colour temperature 2 856 K. It should be used in all applications of colorimetry involving the use of incandescent lighting.
Standard illuminant C	It approximates to overcast daylight simulators, with a spectral energy distribution corresponding to the colour temperature 6770 K. It is derived from Illuminant A by using a liquid filters.
Standard illuminant D_{65}	It is intended to represent average daylight containing a portion of UV radiation, with a spectral energy distribution corresponding to the colour temperature 6 500 K. It should be used in all colorimetric calculations requiring representative daylight.

iii) Colour space

The reflectance spectra of the samples were measured according to $L^*a^*b^*$ colour space as shown in Figure 5.10. It is defined by CIE and specified in ISO 11664-4:2008, Colorimetry -- Part 4: CIE 1976.

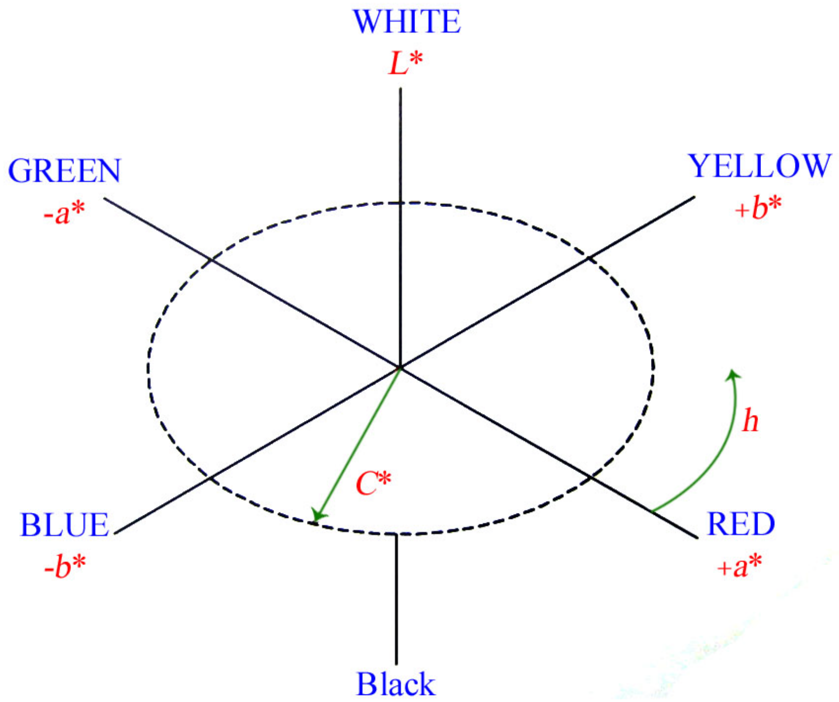


Figure 5.10 CIE $L^*a^*b^*$ colour space in cylindrical coordinates

The reflectance spectra can provide values of coordinates L^* (lightness/ darkness of color), a^* (red/ green ratio), and b* (yellow/ blue ratio) from the CIE $L^*a^*b^*$ (or CIELab) system of equations. On the other hand, C^* is chroma, and h is the hue angle. The value of chroma is zero at the centre and increases according to the distance from the centre. Hue angle starts at the $+a$ (red) axis, at 90° it is at $+b^*$(yellow), at 180° it is at $-a^*$(green), and at 270° it is at $-b^*$(blue).

iv) Colour difference

Total color difference is expressed in term of $\triangle E^*$, which is based on the colour difference parameters namely $\triangle L^*$ (lightness difference), $\triangle a^*$ (red-green difference), and $\triangle b^*$ (yellow-blue difference). Total color difference $\triangle E_{ab}^*$ from a reference color (L^*_0, a^*_0 , b^*_0) to a target color (L^*_1, a^*_1 , b^*_1) in the CIE$L^*a^*b^*$ space is given by:

$$\triangle E_{ab}^* = [(\triangle L^*)^2 + (\triangle a^*)^2 + (\triangle b^*)^2]^{1/2}$$

where

$$\triangle L^* = \triangle L^*_1 - \triangle L^*_0$$

$$\triangle a^* = \triangle a^*_1 - \triangle a^*_0$$

$$\triangle b^* = \triangle b^*_1 - \triangle b^*_0$$

or

$$\triangle E_{ab}^* = [(\triangle L^*)^2 + (\triangle C^*_{ab})^2 + (\triangle H^*_{ab})^2]^{1/2}$$

where chroma difference($\triangle C^*$) and hue difference ($\triangle H^*$) are given by:

$$\triangle C^*_{ab} = C^*_{ab,1} - C^*_{ab,0} = (a^{*2}_1 + b^{*2}_1)^{1/2} - (a^{*2}_0 + b^{*2}_0)^{1/2}$$

$$\triangle H^*_{ab} = [(\triangle E_{ab}^*)^2 - (\triangle L^*)^2 - (\triangle C^*_{ab})^2]^{1/2}$$

Equipment:

◆ **Spectrophotometer - GretagMacbeth™ Color-Eye® 7000A**

Figure 5.11 GretagMacbeth™ Color-Eye® 7000A

Table 5-5 Specifications of spectrophotometer

Repeatability (white tile) Maximum	0.01 RMS ΔE CIELab
Interinstrument Agreement(LAV)	Maximum 0.08 Avg. ΔE CIELab*
Illumination	Pulsed xenon
Measurement Time	<1 second
Spectral Range	360 nm to 750 nm
Wavelength Accuracy	0.1 nm (400 to 700)
Wavelength Precision	0.05 nm (400 to 700)
Wavelength Interval	10 nm
Band Pass	10 nm
Photometric Range	0% to 200%
Photometric Resolution	0.001%
Optical Configuration	Diffuse/8°(illumination/measurement)
	6" (15.2 cm) integrating sphere
	2 spectral analyzers
Transmission	Direct and diffuse
Dimensions	15.25" high, 11" wide, 28" deep,
	(38.7 cm high, 27.9 cm wide, 71.1 cm deep)
Temperature (operating)	60°F to 90°F (15°C to 32°C)
Relative Humidity	0% to 90% (non-condensing)

5.3.2 Results and discussion

a) Pilling tendency

Table 5-6 ICI Pilling Box Method results

<table>
<tr><th rowspan="2">Sample</th><th colspan="2">Treatment</th><th rowspan="2">Pilling grade</th><th rowspan="2">CV%</th></tr>
<tr><th>Acceleration of fuzz generation</th><th>Fuzz removal</th></tr>
<tr><td rowspan="3">Nu-Torque™ fabric</td><td>Brushing by brushing device</td><td rowspan="2">Shaving by lint shaver</td><td>4.5</td><td>9.4</td></tr>
<tr><td>Brushing by human hands</td><td>4.5</td><td>9.1</td></tr>
<tr><td>---</td><td>---</td><td>1.5</td><td>42.2</td></tr>
<tr><td rowspan="3">Blue sweater</td><td>Brushing by brushing device</td><td rowspan="2">Shaving by lint shaver</td><td>4.5</td><td>13.1</td></tr>
<tr><td>Brushing by human hands</td><td>4.5</td><td>9.1</td></tr>
<tr><td>---</td><td>---</td><td>2</td><td>37.4</td></tr>
</table>

Table 5-6 shows the pilling results of the fabric samples. Regardless the type of fabrics, the results of those brushed by brushing device is comparable to those brushed by human hands. Pilling grade 4.5 was achieved by all the treated fabrics. It demonstrates that the proposed treatment is effective to reduce the pilling tendency of the fabric.

b) Thermal insulation

Table 5-7 Results of the keeping warmth ratio

	Treatment	Keeping warmth ratio (%)	CV%
Nu-Torque^{TM} fabric	treated	34.6	0
	untreated	34.6	0
Blue sweater	treated	42.3	0
	untreated	42.3	3.3

The experimental results about the thermal insulation of the fabric samples are shown in Table 5-7. The results show that the keeping warmth ratios of the treated and untreated fabric are the same, regardless the type of fabrics. This shows that the proposed treatment does not affect the thermal insulation property of the fabric.

c) Bursting strength

Table 5-8 Results of the bursting strength

	Treatment		Bursting strength (Pascal per sq.inch)	Height at burst (cm)	Breaking time (s)
Nu-Torque™ fabric	treated	Mean	64.4	12.1	22.4
		CV%	5.0	9.3	2.4
	untreated	Mean	65.1	12.2	23.0
		CV%	3.8	9.1	4.3
Blue sweater	treated	Mean	58.3	12.4	19.4
		CV%	5.8	1.8	4.6
	untreated	Mean	58.7	11.2	19.2
		CV%	6.1	2.8	4.4

Bursting strength test was conducted on the fabric samples and the results are shown in Table 5-8. By comparing the treated and untreated fabric, both the bursting strength of the Nu-Torque™ fabric and blue sweater decreased slightly after the treatment. In order to verify if there is any significant difference between the treated and untreated fabric samples, analysis with Paired T-Test was conducted.

Table 5-9 Results of Paired T-Test on the bursting strength

	Treatment	Sample size	Mean	Standard Deviation	SE Mean
Nu-Torque™ fabric	treated	5	65.06	2.45	1.09
	untreated	5	64.44	3.23	1.44
	difference	5	0.62	5.05	2.26
	p-value	0.80			
Blue sweater	treated	5	58.7	3.56	1.59
	untreated	5	58.28	3.36	1.5
	difference	5	0.42	5.87	2.63
	p-value	0.88			

The table above shows the Paired T-Test result of the bursting strength of fabric samples between the treated and untreated. For 95% confidence interval, the *p*-values of both fabric samples are greater than the level of significance. This indicates that the bursting strength between the treated and untreated has no significant difference statistically. It can be concluded that the proposed treatment does not influence the bursting strength of the fabric.

d) **Colour change**

Table 5-10 Colour difference between the treated and untreated Nu-Torque™ fabric

Illuminant	△*L**	△*a**	△ *b**	△*C**	△*H**	△*E*□
D65	-0.266	-0.040	0.403	0.405	0.002	0.485
A	-0.246	0.051	0.403	0.406	0.029	0.475
C	-0.267	-0.050	0.405	0.409	0.000	0.488

Table 5-11 Colour difference between the treated and untreated blue sweater

Illuminant	△*L**	△*a**	△ *b**	△*C**	△*H**	△*E*□
D65	0.535	0.049	-0.061	0.068	0.039	0.541
A	0.539	0.069	-0.067	0.065	0.071	0.548
C	0.538	0.036	-0.049	0.055	0.026	0.541

Table 5-10 and 5-11 show the colour difference between the treated and untreated samples of Nu-Torque™ fabric and blue sweater respectively. The signs of the differences have the following approximate meanings:

$+\triangle L^*$ = lighter

$-\triangle L^*$ = darker

$+\triangle a^*$ = redder (less green)

$-\triangle a^*$ = greener (less red)

$+\triangle b^*$ = yellower (less blue)

$-\triangle b^*$ = bluer (less yellow)

For the size of $\triangle E$ units, the difference between pure black and pure white is 100units. The larger the $\triangle E$ Value, the larger the amount of colour change of samples. Most used values for commercial colour matching tolerance are set at a $\triangle E$ value of less than 1.0. The results show that the color differences of the treated and untreated samples are very small and well within the tolerance, regardless the type of illuminants used.

5.4 Wear trial of the treated garment

The effect of the proposed attrition treatment on fabric properties has been discussed. However, the actual influence of the treatment on finished garment has not yet been investigated. In this section, a wear trial on a treated garment was established in order to study the effect of the treatment on finished garment.

5.4.1 Experimental

In this experiment, a blue sweater, whose fabric details given in section 3.1.3, was used. Half of the sweater was treated by the proposed anti-pilling treatment. The treated area of the garment is shown in the Figure 5.12. Brushing was used for accelerating fuzz generation. The sleeve was brushed by brushing device and the other parts were brushed by human hands as the brushing area of the brushing device is not large enough for the whole garment. After that, generated fuzz was removed by a lint shaver.

The sweater was then worn seven hours per day for three weeks by a student working in office and laboratory. The sweater has not been washed throughout the process. After wearing, the pilling tendency, comfort, softness and smoothness of the treated and untreated area of the sweater were evaluated by subjective evaluation and graded by five evaluators. A new sweater was also evaluated for comparison.

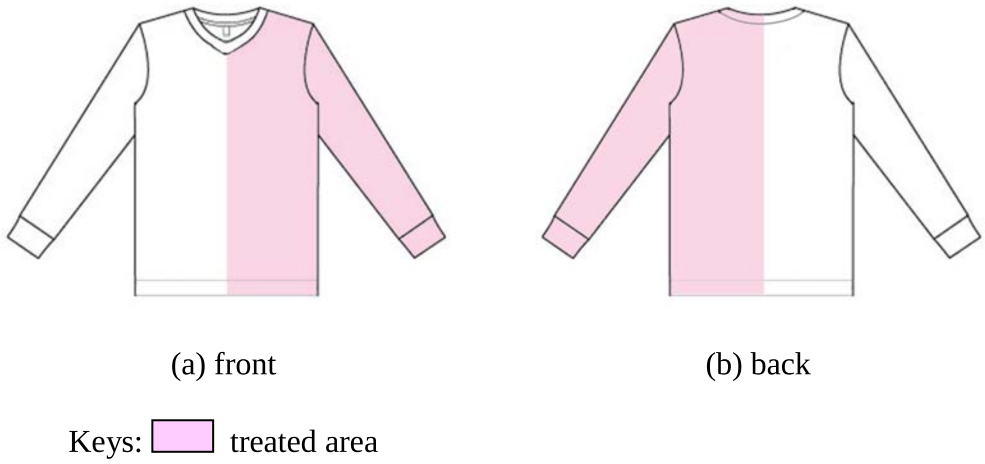


Figure 5.12 Treated area of the blue sweater

5.4.2 Results and discussion

The image of the sweater after wearing is shown in Figure 5.13. Results of the subjective evaluation on the sweater are shown in Table 5-7 and 5-8.

From Table 5-10 and 5-11, the results show that the left part of the worn sweater, which was treated by the attrition treatment, was the best in pilling performance, comfort, softness and smoothness, when compared with the untreated parts of the worn sweater and the new sweater, no matter in terms of the mean value of the grade or number of evaluators agreed. Since there was no chemical used in the treatment, it seems that the difference in comfort, softness and smoothness is due to the fuzz and pills formed on the fabric surface. It implies that fuzz and pills not only badly influence the appearance but also the handle and perception of comfort of a garment.

For the results in comfort and smoothness of the samples, the treated part of the worn sweater has the best performance, while the untreated part of the worn sweater has the worst. The results are matched with the amount of pills and fuzz presented on the fabric surface. Due to the fibres of the sweater are stiff, the larger the amount of the fuzz, the worse the handle of the fabric.

For the result in softness of the samples, the treated part of the worn sweater has the best performance, while the new sweater has the worst. Although the new sweater has less fuzz, it has lower grade than the untreated part of the worn sweater. It may be because the internal stress in the worn sweater was released after wearing and hence became softer in handle.

(a) right part (untreated) | (b) left part (treated)

Figure 5.13 Image of the worn blue sweater

Table 5-12 Results of subjective evaluation on the blue sweaters

Question	**Sample**		**The level of agreement** (according to the 5-point Likert Scale of Summated Rating, 1 = worst, 5 = best)	CV%
1. The part of garment is resistant to pilling	**body**	**L**	4.7	14.3
		R	1.9	47.1
	sleeve	**L**	4.8	9.3
		R	1.7	39.5
2. The part of garment is comfortable	**body**	**L**	4.2	6.5
		R	2.5	56.6
		N	3.3	25.4
	sleeve	**L**	4.4	9.5
		R	2.3	52.4
		N	3.2	23.7
3. The part of garment is soft	**body**	**L**	4.2	6.5
		R	3.6	22.8
		N	3.2	23.7
	sleeve	**L**	4.1	10.2
		R	3.3	25.4
		N	3.1	21.0
4. The part of garment is smooth	**body**	**L**	3.7	18.1
		R	2.9	28.3
		N	3.3	39.5
	sleeve	**L**	4.0	19.8
		R	2.8	46.6
		N	3.2	36.0

Notes: L = left part of the worn sweater (treated), R = right part of the worn sweater (untreated),

N = new sweater

Table 5-13 Results of subjective evaluation on the blue sweaters

(a) Left part (treated) VS right part (untreated) of the worn sweater

		Number of person
Pilling tendency	Left part is better	5
	Right part is better	0
	Both part are similar	0
Comfort	Left part is better	5
	Right part is better	0
	Both part are similar	0
Softness	Left part is better	4
	Right part is better	0
	Both part are similar	1
Smoothness	Left part is better	4
	Right part is better	0
	Both part are similar	1

(b) Left part (treated) of the worn sweater VS new sweater

		Number of person
Comfort	Left part of the worn sweater is better	5
	New sweater is better	0
	They are similar	0
Softness	Left part of the worn sweater is better	4
	New sweater is better	0
	They are similar	1
Smoothness	Left part of the worn sweater is better	3
	New sweater is better	0
	They are similar	2

(c) Right part (untreated) of the worn sweater VS new sweater

		Number of person
Comfort	Right part of the worn sweater is better	2
	New sweater is better	3
	They are similar	0
Softness	Right part of the worn sweater is better	4
	New sweater is better	0
	They are similar	1
Smoothness	Right part of the worn sweater is better	2
	New sweater is better	3
	They are similar	0

5.5 Conclusion

In this chapter, a prototype brushing device has been investigated. It is found that the device is able to accelerate the fuzz generation as effectively as brushing by human hands. In addition, the device is even more efficient as more amount of fuzz is generated with the same period of brushing time.

The evaluation on the treated fabrics, which brushed by brushing device and shaved by a lint shaver, concludes that the proposed attrition treatment does not affect the thermal insulation, bursting strength and colour of the treated fabric. On the other hand, the treated fabric has much better pilling resistance that the untreated fabric. In the subjective evaluation in the wear trial of a treated sweater, all the evaluators agreed that the pilling tendency of the treated parts of garment was much lower than the untreated parts. The treated parts also gave better comfort, softness and smoothness than the untreated parts.

To sum up, the brushing device is effective in acceleration of fuzz generation, the proposed anti-pilling treatment has little side-effect on the fabric properties, and it can be applied on the finished garments available in the market.

Chapter 6 Conclusion and Recommendations for Future Work

6.1 Conclusion

Review of the literature concerning the pilling problem of fabrics reveals that the anti-pilling treatments used nowadays can not satisfy the requirements of consumers as they may adversely affect the other desirable physical properties of the fabrics, or may produce chemicals and wastewater. The treatments are also costly or too complicated for industrial mass production. Many chemical treatments are fibre specific thus difficult to be applied in fibre blends.

The mechanism of pilling has been studied in depth. The formation of fuzz is the very beginning of the formation of pills. The fuzz, which may form pills, comes from the broken fibres and those migrated from inside to the surface of fabric, and in many cases, with smaller diameters. Accelerating the fibre migration, that is fuzz generation and subsequently removing this pillable fuzz seems to be a key to significantly reduce the pilling of fabrics.

Pilling behaviour of the Nu-Torque^{TM} and conventional worsted knitted fabric has been studied by Random Tumble Pilling test. The results demonstrated that the rate of pills formation exceeds that of wear-off at the beginning and vice versa after it reaches the peak. This implies that the amount of pillable fuzz of the fabric is limited in supply.

Earlier work by others suggested that shearing fuzz in the early stage of abrasion may be an efficacious method of pilling control. Although the amount of pillable fuzz was found to be limited in supply, the suggestion of shearing fuzz in the early stage is not as effective as expected. This is due to the fact that there is still much potential pillable fibres in the fabrics, which will migrate out under a long duration of abrasion action and form pills finally. Therefore, pillable fuzz should be firstly generated out of the fabrics before shearing process to remove the fuzz on the fabric surface.

Physical treatments including acceleration of fuzz generation and fuzz removal have been investigated as potential anti-pilling treatments. The effectiveness of the proposed treatments on worsted knitted fabric has been examined through experiments and the results have been discussed in detail. The experimental results demonstrate that both fabrics made from Nu-Torque™ and conventional yarns after the treatment have much better pilling resistance than those without treatment. The treatment is effective for both types of worsted knitted fabric.

Methods of acceleration of fuzz generation, including tumbling action, flat abrasion action and brushing action, have been investigated. All of them were found to be effective in acceleration of fuzz generation. Among all of them, brushing action seems to be the one with the mildest action and lest problem of wearing-out of material. As a result, brushing action was chosen as the method of acceleration of fuzz generation for the proposed anti-pilling treatment.

Two approaches were studied to remove the fuzz from fabric surface: laser ablation and mechanical shaving. The use of laser for fuzz removal process is more suitable for mass production; however, there are still many technical problems to be solved. In contrast, although using a shaver requires a lot of man power and time, it has many advantages over using laser: it is easier to be controlled; the fabric is less likely to be damaged with care; and the capital cost is also lower than that of using laser. As a result, the lint shaver has been selected for the fuzz removal process of the proposed anti-pilling treatment.

A prototype brushing device was developed and used. The suitable parameters of the device were determined. It has been found that the device is able to accelerate the fuzz generation as effectively as using human hands, and the device is even more efficient as a shorter period of time is required.

The treatment does not affect the thermal insulation, bursting strength and colour of the treated fabric. The treated fabric has much better pilling resistance that the untreated fabric. A wear trial of treated sweater, which is a finished garment available in the market, was conducted. All the evaluators agreed the pilling tendency of the treated parts of garment was much smaller than the untreated parts. The treated parts also gave better comfort, softness and smoothness than the untreated parts.

For both fabrics and garments, the experimental results show that the proposed anti-pilling treatment can reduce significantly the pilling tendency. It confirms that reducing the amount of pillable fuzz in the fabric can reduce the pilling tendency of fabrics.

In conclusion, the objectives of this project as outlined in chapter 1 have been achieved. An effective anti-pilling treatment by acceleration fuzzing and attrition methods, which is free of chemicals and wastewater, has been identified and investigated. The treatment can be applied on fabric and finished garments.

6.2 Recommendations for future work

Due to limited time, there are many unsolved problems. The following are some suggestions for future work.

1. Further investigation of the laser ablation for fuzz removal

In the laser singeing and cutting process, fabrics are discolored by the high laser energy. As the yellowing decreases with the reduction of energy level of laser beam, fine adjustment of the laser energy may solve the problem. It was found that the energy of CO_2 laser become unstable with a lower energy level. A continuous wave laser, which is more stable and evenly distributed, should be used in the future work, instead of a pulsed laser.

2. Further development of acceleration device

Although the prototype of the brushing device is effective in acceleration of fuzz generation, its size is too small to brush a whole garment. The distance between the rotatable brush and the fabric can only change very limitedly. The distance seems too short for thick fabric and a thorough optimization for different type of fabric cannot be conducted. The clips and metal plates which are used for holding the fabric on the two ends seem not fitting for fabric with irregular shape. Clearing system for the brush should also be installed as the fibres trapped in the brush after brushing process. Problems would be found when different colored materials are brushed with the same brush.

The brushing device used in the experiments is only a prototype, further development of the device is recommended. The size of the device should be large enough for garment processing. A better holding device should be designed. The distance between the brush and the fabric should be adjustable with a larger range. Clearing system for the brush should also be installed as the fibres trapped in the brush after brushing process.

3. Development of attrition device

Using lint shaver with human hands is high in consumption of men power and time. Automatic shaving device should be developed. It could be combined with the brushing device in order to provide the proposed anti-pilling treatment efficiently.

4. Investigation on model of amount of pillable fuzz

The amount of pillable fuzz in a fabric is related to the fibre, yarn and fabric structure and properties. At this stage, the amount of pillable fuzz in a fabric can only be found by try and error. With the increased computer power nowadays, mathematical models of amount of pillable fuzz are possible to be established. This would help to estimate the amount of pillable fuzz in a particular fabric in order to control the fabric quality by selecting suitable spinning, weaving or knitting parameters; on the other hand, the parameters in the attrition treatment can be selected more easily with reference to the amount of pillable fuzz provided by the models.

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