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Research on Mechanism Analysis and Elimination Method for the Tufted Carpet Stop Mark

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Abstract
The tufted carpet stop mark is an important factor affecting carpet final quality. It is closely related to the change in yarn tension caused by the tufting machine being improperly stopped and the yarn creep properties. The purpose of this paper is to develop a reasonable approach to eliminate the tufted carpet stop mark. Focusing on a typical tufting machine, the tufting equipment system and basic working principle of tufted carpet are briefly described. A yarn path flexing model which integrates yarn feeding parts, yarn guiders and the tufting needle for a typical tufting process is constructed. The yarn tension change is analysed along with the change in the yarn path. A Polypropylene yarn four-component model is used for analysing the relationship between tension and yarn creep properties. The creep property of polypropylene yarn under a certain tension is verified by experiments. According to the yarn tension change in different running positions of the tufting needle, a reasonable method of eliminating the stop mark which stops and restarts the machine in the highest position is put forward. Finally the experimental results prove that the method is effective and feasible.

Key words: *creep property, stop mark, tufted carpet, yarn path, yarn tension.*

Introduction

Carpets are tufted, woven, knotted and needled from man-made fibres, wool, haircords, silk and cotton [1, 2]. Tufted carpet is rich in colour, pattern and variety, which accounts for 80% of the total carpet market [3]. Factory-finished tufted carpet, which can be used as both floor covering and wall covering, offers not only comfort but also considerable advantages in terms of insulation and the heat balance in buildings. Now all-over sculptured-style jacquard carpet is internationally accepted as the most advanced tufted carpet product. ***Figure 1.a*** shows a sculptured-style jacquard carpet with five kinds of pile height. ***Figure 1.b*** shows a sculptured-style jacquard carpet with eight kinds of pile height.

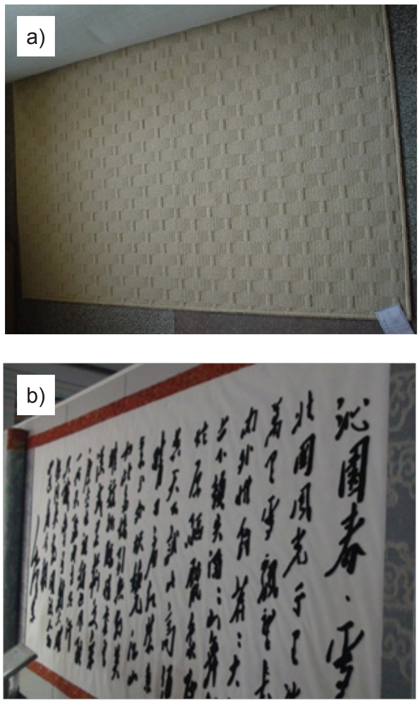

Figure 1. *Sculptured-style jacquard carpet; a) five kinds of pile height, b) eight kinds of pile height.*

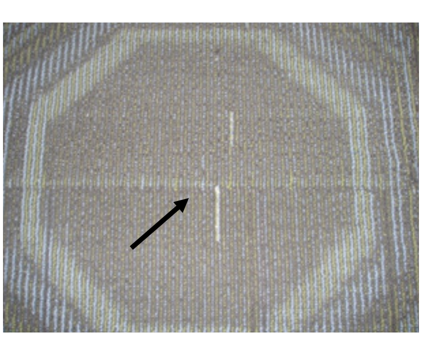

Figure 2. *Stop marks of tufted carpet specimens.*

Yet there are many strict requirements for assessing the quality level of tufted carpet. If tufted carpet is slightly flawed, its rank will be reduced, or it may be discarded as waste. The stop mark is a very important factor affecting the quality of tufted carpet. In a typical tufting process, due to the presence of working procedures such as replacing yarns and making up broken ones, stopping and restarting the tufting machine is inevitable, which makes the original pile yarn work in a non-normal state and produce the uneven-loop phenomenon. Tufted carpet produces stop marks or a low-loop at the stop position is pulled out, or a whole row, even multi-rows of loops are pulled out, which greatly affect the quality of the carpet [4, 5]. ***Figure 2***

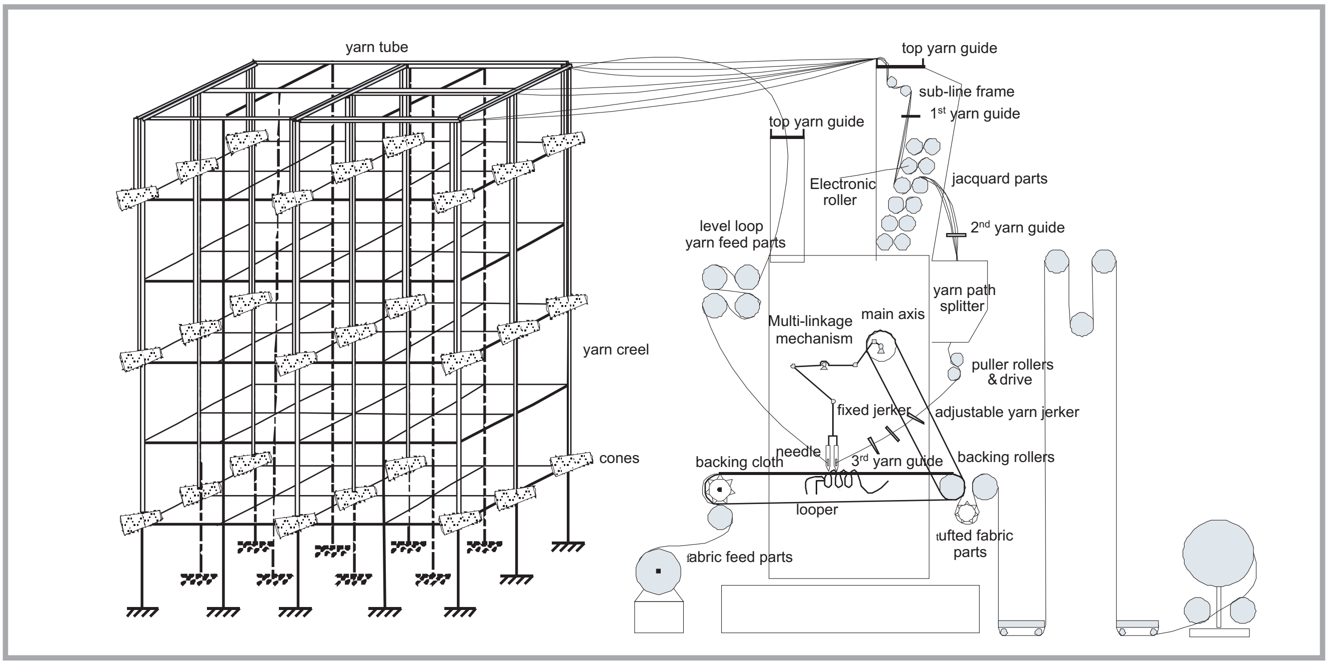

Figure 3. Typical carpet tufting equipment.

shows tufted carpet samples with stop marks. ***Figure 2*** shows tufted carpet after stopping the tufting machine for about seven hours. From ***Figure 2***, it is noted that the pile height of the stop mark is significantly inconsistent with that when the tufting machine is running smoothly. Because of the stop marks, these tufted carpets will be lower in grade or be rejected. Therefore finding the causes of the tufted carpet stop mark and developing a reasonable approach to eliminate it are absolutely necessary.

Over the past decade, various approaches have been suggested in an attempt to overcome the problem of strop marks. Most of these devices are based on engineering applications which lack theoretical analysis detail. For example, Jackson [6] disclosed a device to relax tufting yarns and vary the tension in each cycle. When the needles are in the raised position, the yarns are relaxed so that the machine may be stopped to reduce the height of the last row of tufts formed. Colbert [7] disclosed an auxiliary drive means whereby the puller rolls may be driven independently. During periods of machine stoppage, it keeps the yarn under tension to avoid withdrawal or retraction. Jackson [8] addressed the problem of stop marks by making the loopers clear the pile loops during stoppage so as to relieve yarn tension. Long [9] devised a soft start-up mechanism for a tufting machine so as to avoid the creation of stop marks. Cooper [10] researched an auxiliary drive apparatus which is actuated in response to the stoppage of the machine for immediately providing a positive feed of the tufting yarns. This paper proposes to eliminate the tufted carpet stop mark by focusing on its mechanism analysis.

Carpet tufting equipment system

A typical tufting equipment system is shown in ***Figure 3***. This assembly mainly consists of fabric feed parts, tufted fabric parts, level loop yarn feed parts, jacquard parts, tufting needles and loopers.

Pile yarn has a long path before threading the tufting needle. The pile yarn starts from the cones and threads through the creel tube, the sub-line frame and the first yarn guide. Then the pile yarn enters into the level loop yarn feed system and jacquard system, respectively. After moving out from the second yarn guide and yarn path splitter, pile yarn threads through the jacquard system and puller rollers. Finally the pile yarn is threaded by the tufting needle along a complicated path.

The basic working principle of carpet tufting is shown as follows. Thousands of tufting needles are driven by the main axis system to move downward and embed the yarn into the backing. When the tufting needles move downward to the lowest position, loopers under the backing hook the yarn, which coordinate with the tufting needle movement precisely. After the tufting needles are driven by the main axis system to move up and off the backing, the loopers make yarns from the loops on the rear of the backing. When the tufting needles move up to the highest position, the loopers exit the pile loop formed. Before the tufting needles move downward again, the yarns' spring-back process is over. Here a whole pile loop in the tufting process is finished. Generally a pile-loop is formed when the main axis rotates one circle, therefore tufting needles will continue to move up and down reciprocally, repeating this process.

Different pile heights can be obtained by controlling the yarn-feeding. Through the horizontal movement of the hackle, a variety of carpet patterns can be realised. The jacquard effect of tufted carpet can be achieved by compounding the horizontal and vertical movement of the hackle [11].

Yarn flexing and yarn tension in the yarn path

In a typical tufting process, with the distance periodic changes between the tufting needle and the backing, yarn flexing in the yarn path shows a periodic change. ***Figure 4*** (see page 68) shows a schematic diagram of path flexing in the yarn path.

In ***Figure 4***, the symbol A represents puller-rollers. B the fixed yarn guider, and C and D are, respectively, adjust-

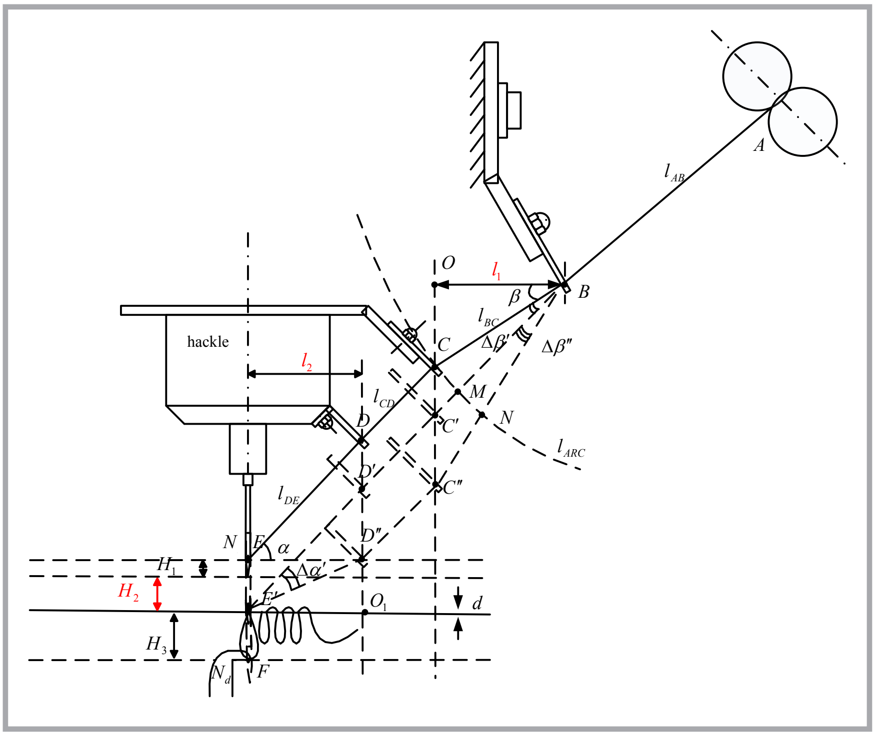

***Figure 4.** Yarn flexing in the yarn path.*

able yarn guiders, which are with a fixed pitch and move along with the hackle. N_d is the looper and N_e the tufting needle. l_{AB} is the distance between the puller-roller A and fixed yarn guider B. l_{BC} is the distance between the fixed yarn guider B and adjustable yarn guider C. l_{CD} is the distance between the adjustable yarn guider C and D. l_{DE} is the distance between the adjustable yarn guider D and tufting needle N_e. l_1 is the distance between the fixed yarn guider B and adjustable yarn guider C in the horizontal direction. l_2 is the distance between adjustable yarn guider D and tufting needle N_e in the horizontal direction. E is the highest position of the tufting needle and F the lowest. E' is the contact point with the backing. C' is the position of adjustable yarn guider C when the tufting needle moves downward to the contact point E'. D' is the position of adjustable yarn guider D when the tufting needle moves downward to the contact point E'. C'' is the position of adjustable yarn guider C when the tufting needle moves downward to the lowest position F. D'' is the position of adjustable yarn guider D when the tufting needle moves downward to the lowest position F. $l_{BC'}$ is the distance between the fixed yarn guider B and adjustable yarn guider C when the tufting needle moves downward to the contact point E'. $l_{C'D'}$ is the distance between adjustable yarn guiders C and D when the tufting needle moves downward to the contact point E'. $l_{D'E'}$ is the distance between the adjustable yarn guider D and tufting needle N_e when the tufting needle moves downward to the contact point E'. $l_{BC''}$ is the distance between the fixed yarn guider B and adjustable yarn guider C when the tufting needle moves downward to the lowest position F. $l_{C''D''}$ is the distance between adjustable yarn guiders C and D when the tufting needle moves downward to the lowest position F. $l_{D''E'}$ is the distance between the adjustable yarn guider D and contact point E' when the tufting needle moves downward to the lowest position F. H_1 is the distance between the tufting needle hole and needlepoint. H_2 is the distance between the needlepoint and backing. H_3 is the sum of the loop-height and spring back of the yarn. d is the backing thickness. α is the angle between line l_{DE} and horizontal line. β is the angle between line l_{BC} and horizontal line. $\Delta\alpha'$ is an angle variation of α when the tufting needle moves downward. $\Delta\beta'$ is the angle variation of β when the tufting needle moves downward to the contact point E'. $\Delta\beta''$ is angle variation of β when the tufting needle moves downward to the lowest position F. l_{ARC} is an arc with B as the center and l_{BC} as the radius. M is the intersection of l_{BC} and l_{ARC} when the tufting needle moves downward to the contact point E'. N is the intersection of l_{BC} and l_{ARC} when the tufting needle moves downward to the lowest position F. O is the intersection of $l_{CC''}$ and l_1. O_1 is the intersection of $l_{DD''}$ and the backing.

According to the tufting process, the yarn path and tension can be analysed through two parts:

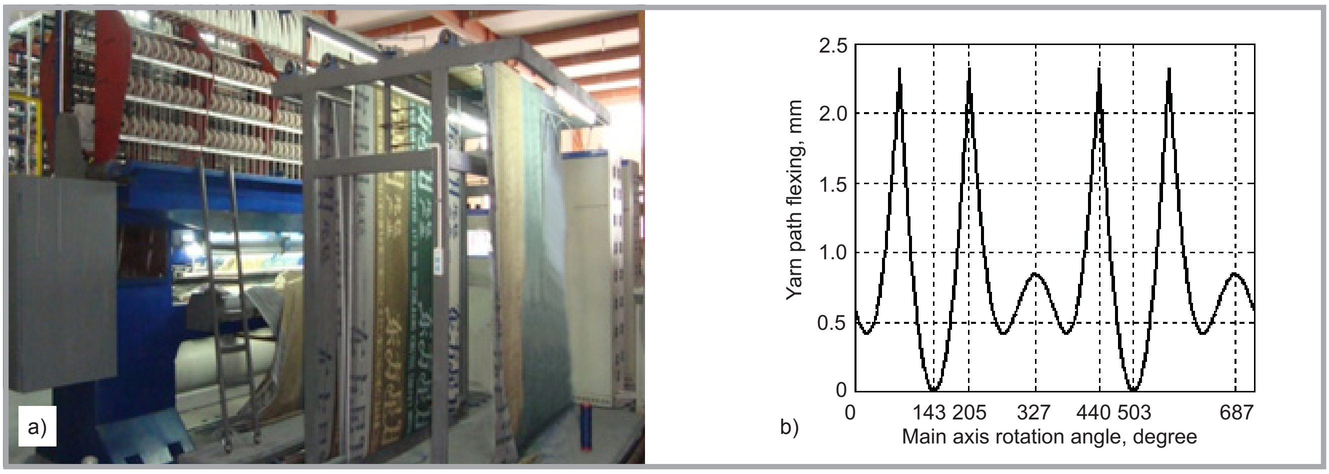

***Figure 5.** Periodic yarn path flexing: a) Tufted carpet machine b) Yarn flexing in the yarn path.*

Yarn path and tension before the tufting needle enters the backing

When the tufting needle is in the highest position, the yarn path length is defined as L_1. When the tufting needle moves downward to the contact point *E'*, the yarn path length is defined as L_2.

As shown in ***Figure 4***, L_1 can be expressed as

$$L_1 = L_{AB} + L_{BC} + L_{CD} + L_{DE} \quad (1)$$

and L_2 as

$$L_2 = L_{AB} + L_{BC'} + L_{C'D'} + L_{D'E'} \quad (2)$$

where $L_{CD} = L_{C'D'}$, $L_{C'D'} = L_{C''D''}$, $L_{ED} = L_{D'E'}$.

thus when the yarn path changed from L_1 to L_2, yarn variation Δs_1 can be expressed as

$$\Delta s_1 = l_1\left(\frac{1}{\cos(\beta+\Delta\beta')} - \frac{1}{\cos\beta}\right) = C'M \quad (3)$$

Analysing ***Equation 3***, it can be obtained that when the yarn path changes from L_1 to L_2, the yarn path gets longer. Due to the constant yarn feeding in a unit of time, the yarn is stretched when the yarn path changes from L_1 to L_2. Thus it is known that yarn tension in yarn path L_2 is greater than that in yarn path from L_1.

Yarn path and tension after the tufting needle penetrates the backing

When the tufting needle penetrates the backing, the yarn path length is defined as L_3.

L_3 can be expressed as

$$L_3 = L_{AB} + L_{BC'} + L_{C'D'} + L_{D'E'} + 2(H_3 + d) \quad (4)$$

Comparing L_3 and L_1, yarn variation Δs_2 can be expressed as follows

$$\Delta s_2 = l_1\left(\frac{1}{\cos(\beta+\Delta\beta'+\Delta\beta'')} - \frac{1}{\cos\beta}\right) + l_2\left(\frac{1}{\cos(\alpha-\Delta\alpha')} - \frac{1}{\cos\alpha}\right) + 2(H_3+d) \quad (5)$$

Because the loop-height and spring back of yarn cannot be specified, here $2(H_3 + d)$ is ignored. Measuring the actual data of the tufted carpet machine, shown in ***Figure 5.a***, it is noted that l_1 = 120 mm, l_2 = 108 mm, l_{CO} = 28 mm, $l_{DD'}$ = 65 mm, d = 0.35 mm, $\alpha \approx 31°$ and $\beta \approx 13.1°$. Combined with the yarn path variations Δs_1 and Δs_2, the relationship between the main axis rotation angle and distance between the tufting needle and backing is obtained by analysing the multi-linkage mechanism motion i.e. periodic yarn path flexing with the main axis rotation angle, shown in ***Figure 5.b***.

From ***Figure 5.b***, it is clear that when the tufting needle is in the highest position, yarn path flexing is zero and the main axis rotation angle is about 143°. When the tufting needle moves downward to the backing, the main axis rotation angle is about 205° and yarn path flexing 2.32 mm. When the tufting needle moves downward from the backing to the lowest position, the main axis rotation angle is about 327° and yarn path flexing 0.84 mm.

Generally the range of pile height is from 1 mm to 16 mm; thus even if the loop-height is 1 mm,

$$2(H_3 + d) + 0.84 > 2.32 \text{ mm.}$$

Therefore yarn path L_3 is the longest in the tufting process. When the yarn path changes from L_2 to L_3, the yarn continue to be stretched and yarn tension also becomes greater.

Analysing ***Figure 5.b***, it is known that the yarn path is always positive in the tufting process, greater than the initial value. The yarn path flexing shows a periodic change corresponding with the periodic change of the loop process formed.

Yarn creep characteristic

Tufting is the dominant production technique for factory-manufactured carpets, the use of man-made fibres and, in particular, polypropylene yarns, nylon yarns and staple fibre yarns. Various yarn materials basically differ from one another in their characteristics and cannot be regenerated with one another. Using different pile material or using the same kind of pile material but having a different stopping machine time for carpet tufting, the stop mark caused will be different. Polypropylene yarn, which is often used for tufting carpet, is a kind of viscoelastic material and its fibres have both elastic and viscous characteristics. Generally its yarn model, comprising massless Hookean springs and Newtonian dashpots, is widely used to represent its viscoelastic behaviour [12, 13].

Standard linear solid model of yarn

The four-component model is shown schematically in ***Figure 6*** [14]. The model has a spring with elastic constant E_2 in parallel with a dashpot with viscosity coefficient η_2. At the same time, a spring with elastic constant E_1 and a strong dashpot with viscosity coefficient η_3 are in series with it.

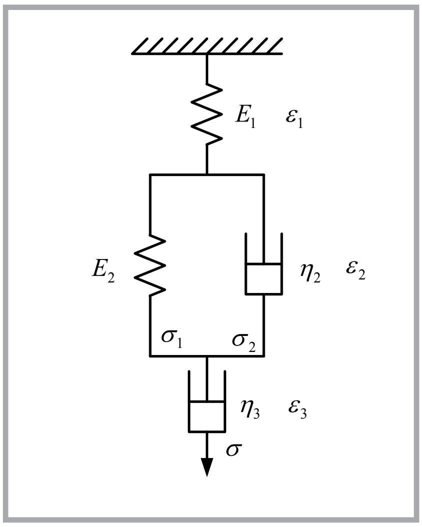

Figure 6. *Four-component model.*

A mechanical model of the yarn can be expressed as

$$\begin{cases} \sigma = \sigma_1 + \sigma_2 \\ \dot\varepsilon = \dot\varepsilon_1 + \dot\varepsilon_2 + \dot\varepsilon_3 \end{cases} \quad (6)$$

$$\begin{aligned} &E_1\ddot\varepsilon + \frac{E_1E_2}{\eta_2}\dot\varepsilon = \\ &= \ddot\sigma + \frac{E_1}{\eta_2}\left(1 + \frac{E_2}{E_1} + \frac{\eta_2}{\eta_3}\right)\dot\sigma + \frac{E_1E_2}{\eta_2\eta_3}\sigma \end{aligned} \quad (7)$$

Assuming $\sigma = \sigma_c$ and transforming ***Equations 6*** and *7*, the following equation can be obtained by

$$\tau_k\ddot\varepsilon + \dot\varepsilon = \frac{\sigma_c}{\eta_3} \quad (8)$$

$$\tau_k = \eta_2/E_2 \quad (9)$$

According to the initial condition $t = 0$, $\varepsilon(0) = \frac{\sigma_c}{E_2}$ & $\dot\varepsilon(0) = \sigma_c\left(\frac{1}{\eta_2} + \frac{1}{\eta_3}\right)$, yarn deformation $\varepsilon(t)$ can be obtained as follows.

$$\varepsilon(t) = \frac{\sigma_c}{E_1} + \frac{\sigma_c}{E_2}(1 - e^{-t/\tau_k}) + \frac{\sigma_c}{\eta_3}t \quad (10)$$

Analysing ***Equation 10***, it is known that yarn deformation $\varepsilon(t)$ under a certain loading consists of three parts:

- transient elastic deformation σ_c/E_1
- delayed elastic deformation $\sigma_c(1 - e^{-t/\tau_k})/E_2$,
- irreversible plastic deformation $\sigma_c t/\eta_3$.

Therefore under a certain loading the yarn material has creep behaviour. Yarn deformation will also gradually increase, which is time-dependent [14,

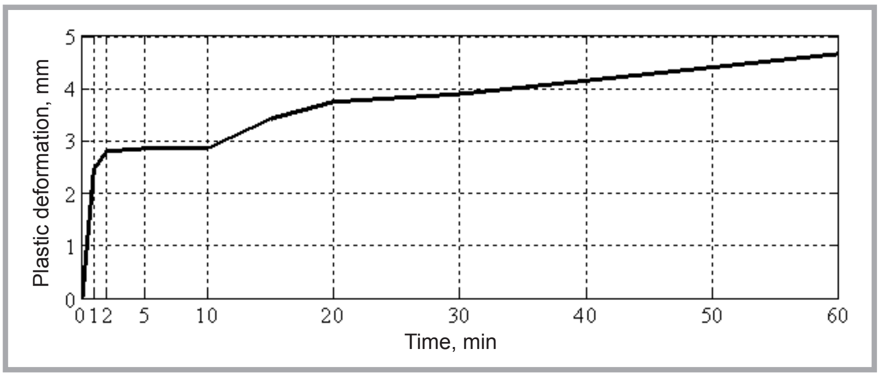

Figure 7. *Yarn plastic deformation curve.*

Table 1. *Plastic deformation rate and elastic recovery ratio of polypropylene yarn.*

Time, min	1	2	5	10	15	20	30	60
Plastic deformation ratio, %	0.99	1.12	1.14	1.14	1.37	1.49	1.56	1.86
Elastic recovery ratio, %	31.58	83.65	200.0	114.3	18.18	17.02	16.33	12.00

15]. If the yarn is working in a stress state when the tufting machine is suddenly stopped and restarted, the tufted carpet will produce a stop mark due to yarn creep properties.

Experiment

To demonstrate the yarn creep characteristics, an experiment was performed on polypropylene yarns (PP). The maximal tension value measured was about 50 cN when the tufting machine was running smoothly, thus tests were carried out applying a 50 cN constant force to polypropylene yarns. The tensile tester used was a Shimadzu AGS-500ND, Japan forcing instrument, with an original yarn length of 250 mm. The polypropylene fabric backing's thickness was 0.35 mm.

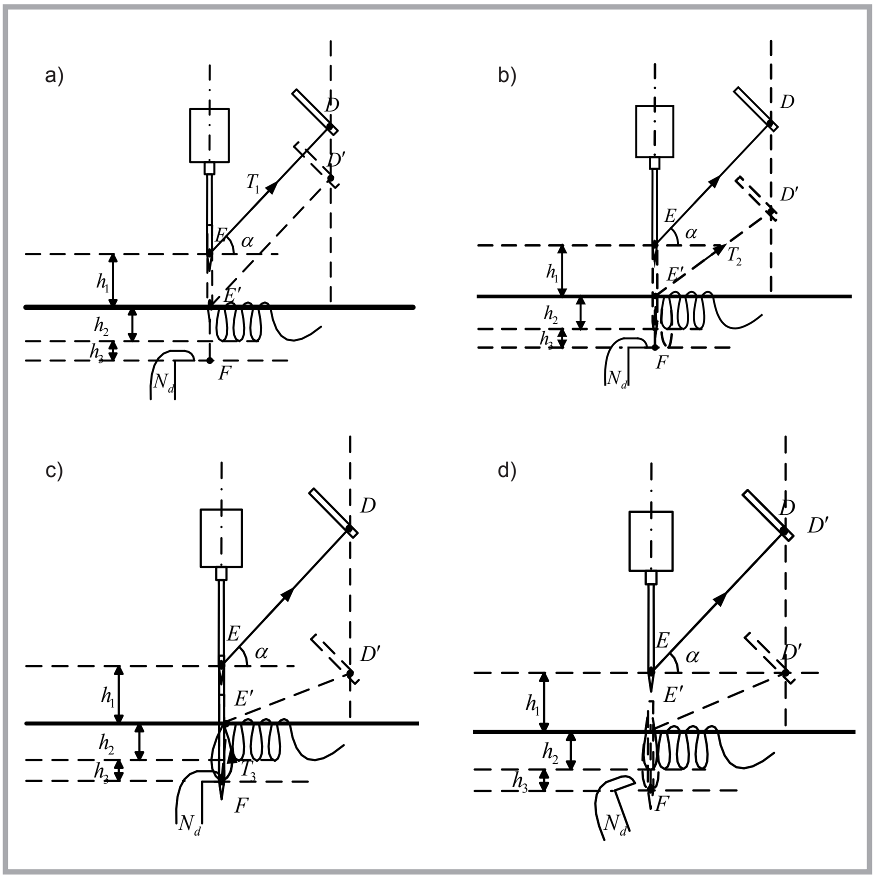

Figure 8. *Analysis diagram of yarn tension; a) yarn tension in h_1, b) yarn tension in h_2, c) yarn tension in h_3 d) yarn tension when needle is in highest position.*

The yarn plastic deformation was obtained as shown in ***Figure*** *7*. The plastic deformation rate and elastic recovery ratio of polypropylene yarn is shown in ***Table 1***.

Analysing ***Figure*** *7* and ***Table 1***, it is clearly shown that the plastic deformation of polypropylene yarn will always be increased with the passage of time. The deformation of polypropylene yarn is not only produced in the transient but also gradually increases with the passage of time. If using polypropylene yarn for tufting carpet, a stop mark will appear at the stopping moment. The yarn creep characteristic influences the loop-height gradually with time .

Discussion of elimination method

By analysing yarn path flexing and yarn characteristic, it is known that different times of stopping the machine and variations in path flexing are factors affecting the size of stop marks. Yarn tension is the real reason for the stop mark. If there is a stop position where the yarn tension can be subjected to zero and the tufting machine be just stopped and restarted in this position, pile yarn will work in a normal state again and a stop mark will not appear in this tufted carpet.

According to the running position of the tufting needle, the yarn tension process can be divided into the following four stages, shown in ***Figure 8***.

1. In the first stage, shown in ***Figure 8.a***, the motion range of the tufting needle is from the highest position to the contact point with the backing. The tufting needle is upon the backing and yarn tension is T_1.
2. In the second stage, the motion range of the tufting needle is from the contact point with the backing to the loop-height position, shown in ***Figure 8.b***. The tufting needle is under the backing and the looper just does not work. Yarn tension is T_2, including the friction between the tufting needle and backing; thus $T_2 > T_1$.
3. In the third stage, the tufting needle is under the backing, whose motion range is from the loop-height position to the lowest position, shown in ***Figure 8.c***). When the tufting needle arrives at the lowest position, the looper just hooks the yarn. Yarn tension is T_3, including the friction between the tuft-

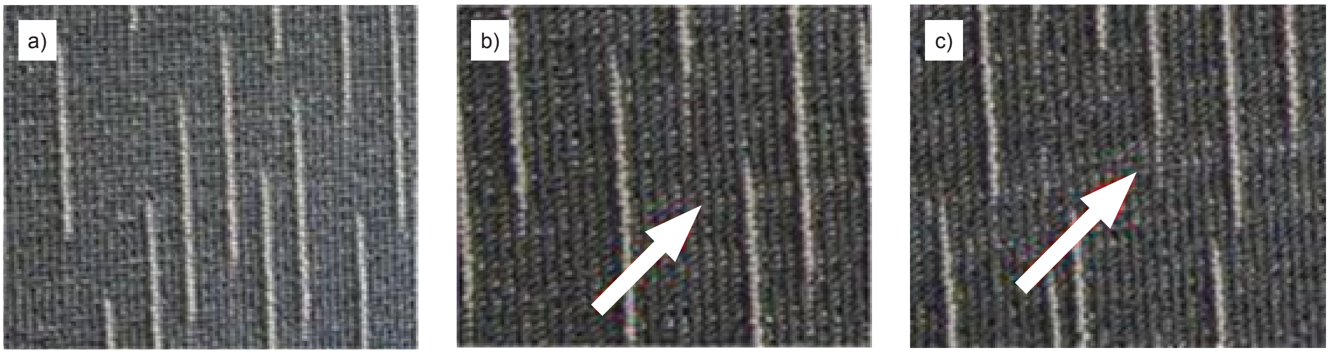

***Figure 9.** Tufted carpet samples with the tufting needle stopped in different positions; a) in the highest position, b) in the other position, c) in the lowest position.*

ing needle and backing as well as the force on the yarn looper; thus $T_3 > T_2$.

4. In the fourth stage, the tufting needle motions upward. When the tufting needle is in the highest position, the looper is simply out of the yarn, shown in ***Figure 8.d***. At this time, the yarn path is the smallest and the yarn is slack, being without any tension. Therefore a stop mark will not appear in the tufted carpet when the tufting machine is stopped and restarted at this moment.

Analysing ***Figure 8***, it is known that the yarn is subjected to tension control in the first three stages. Only when the tufting needle is at the highest point, is the yarn without any tension.

To prove the effectiveness of the method of eliminating stop marks, which stops and restarts the machine in the highest position, experimental validation was performed on a tufting machine, shown in ***Figure 5.a***. Using polypropylene yarns as material for tufting carpet and stopping the machine after about 2 minutes, tufted carpet samples with the tufting machine stopped in different positions were obtained, shown in ***Figure 9***.

Analysing the experiment results, it is clear that no stop mark will appear in the tufted carpet when the tufting machine is suddenly stopped and restarted at the highest position. The stop mark is most obvious when the tufting needle stops at the lowest position. In a typical tufting process, the yarn tension and creep are maximal when the tufting needle moves downward to the lowest position.

Conclusion

In this paper, by analysing the yarn tension of the tufting equipment system and yarn creep characteristic, the conclusion can be drawn that yarn tension is the real reason for the stop mark when the tufting machine is stopped in an improper position. In a typical tufting process, the yarn tension changes with the tufting needle position alternately. When the tufting needle enters the backing and moves downward to the lowest position, the yarn tension is maximal. Theory analysis results show that difference in stopping the machine and variations in the yarn characteristic are factors affecting the loop-height of stop marks. Due to yarn creep properties, a stop mark will be produced by yarn tension at the stopping moment and the stop mark's loop-height will gradually increase with time.

According to the yarn tension and yarn creep characteristic analysis results, the yarn tension will be zero when the tufting needle stops at the highest position. A reasonable method of eliminating the stop mark i.e. stopping and restarting machine at the highest position is put forward. This method is very effective and credible, which is evidenced by the theory analysis and experiment results.

Acknowledgements

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