Analytical Approach of Creep Behavior of Carpet Yarn

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Received 22 December 2010; accepted 13 June 2011
DOI 10.1002/app.35070
Published online 12 October 2011 in Wiley Online Library (wileyonlinelibrary.com).

ABSTRACT: Based on mechanical models, the creep behavior of carpet yarns after dynamic loading was investigated. For prediction the creep elongation, the frequently used mechanical models reported in the literature were analyzed. The mechanical models which were used in this article were: standard linear model, four-element model, two-component Kelvin's model, and Eyring's model. The obtained creep formulas were fitted to experimental creep data, and the parameters of the model can be obtained using the Marquardt algorithm for nonlinear regression. When comparing the experimental creep curve with the fitted curve from the mechanical model, it is clear that the four-element model explain the experimental creep curve better. During tufting machine stops, the carpet yarns were undergone constant load. The confirmed viscoelastic model will be used to calculate total creep elongation during carpet machine stoppage. Thus, the start-up marks which occurred at carpet machine restarts can be exactly eliminated by adjusting the feeding length according to the creep elongation. J Appl Polym Sci 124: 1160–1167, 2012

Key words: creep; mechanical model; nonlinear regression; start-up marks; creep prediction

INTRODUCTION

When tufting machine starts and stops, there is often a start-up marks on the carpet, which are carpet defects as result of irreversible deformation of the creep yarn. Creep is an increased extension with time in viscoelastic materials when constant stress is applied. Yarns undergo repeated load rather than steady load in tufting; however, they are subjected to a constant load when machine stoppage, which resulting in complicated creep behavior. It is note that the yarn creep elongation during tufting stops is one cause of start-up marks when machine restarts.

It was indicated in the study[1] that the irreversible elongation of warp yarn and the cloth during loom stoppage will result in start-up marks when the loom restarting. Chen et al.,[2] also considered that a major cause of start-up marks is the cloth fell creep due to visocelastic properties of warp and cloth during loom stoppages. As the warp and the cloth under tension, their lengths undergo small amount of variation due to this creep, which affects the position of the cloth fell. They took the creep properties of warp and cloth into account using generalized Kelvin model and calculated the cloth's elongation under constant tension force during stoppage. However, whether the mechanical model is suitable for describing mechanical behavior of warp and cloth is not confirmed. Asayesh and Jeddi[3] used the Eyring's model and Kelvin model in series with a spring to describe fabric elongation, to which subjected a constant load.

Other authors believe that the main reason of start-up marks is stress relaxation of warp and fabric when a loom is stopped and restarted. Chen and Wang[4] considered that start-up marks in woven fabric are the result of relaxation of the warp and the fabric when starting up. Vangheluwe et al.,[5,6] also attributed the start-up marks on fabric to yarn relaxation, and developed an extended nonlinear Maxwell model for describing relaxation of fabric and warp yarns. However, the yarn will be stretched under constant load during loom stops, which is a typical viscoelastic creep phenomenon. When a constant load is applied to carpet yarn for a given time, the instantaneous extension is followed by creep. The removal of the load gives rise to an instantaneous recovery, usually equal to the instantaneous extension, followed by a further partial recovery with time, which still leaves some unrecovered extension.

Research about eliminating start-up marks faces the challenges of accurately predicting the yarn elongation after stoppage, as the elongation is affected by many factors such as the yarn property, stoppage time, dynamic force, etc. Islam and Bandara[1] introduced a noncontact laser-based position sensor for

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measuring the creep elongation. Under controlled conditions, the measurement permits correction of cloth fell position to minimize start-up marks.

In this article, carpet yarn is a slightly twisted continuous filament yarn which is composed of viscoelastic fibers. So, we will exactly calculate the creep elongation with the help of yarn mechanical model. The model parameters could be obtained by fitting the experimental data of creep test to creep formulas of mechanical models. Virginijus et al.,[7] investigated creep and creep recovery behavior of fabrics under different constant loads. He considered that the generalized Voigt element could be used to analyze the creep and creep recovery of fabric. Manich et al.[8] analyzed the stress-strain behavior of cotton, acrylic, and polyester yarns by viscoelastic models. For simplification, they took the potential model and the modified Maxwell model to fit yarn stress-strain behavior. As far as Maxwell model is concerned, however, the creep compliance equals to $\varepsilon(t)/\sigma_c = 1/E + t/\eta$. With the increase of time to infinity, the deformation will be infinity and unrecovered under constant stress. So, the Maxwell model has viscous fluid-like behavior in nature and could not describe yarn creep behavior.

Also, other researchers considered that the time-dependent deformation is nonlinear. Gupta and Kumar[9] studied the creep behavior of nylon filament using a nonlinear viscoelastic model. They concluded that the nonlinear model gives better fit than the linear model.

Previous works[2,3,7,8] used theoretical and mechanical models to describe the creep behavior of textiles materials, but only a few discuss carpet yarn, which is high denier yarn.

In this article, we present theoretical and experimental investigations of the creep deformation of carpet yarn after dynamic loading. Based on the well-known four mechanical models, the main purpose is to confirm whether the proposed mechanical models can represent the creep behavior of carpet yarns using semiempirical methods. Then, compare these theoretical models with experimental results to suggest better model to explain the yarn's creep behavior. The result shows that the four-element model could be used to calculate total creep elongation during carpet machine stoppage, for it has comparative high coefficient and low residual sum of squares. Thus, the start-up marks which occurred at carpet machine restarts can be eliminated by adjusting the feeding length according to the calculated elongation.

THEORETICAL ANALYSIS

Naturally, yarn is a viscoelastic material. They will show time-dependent elongation when stress is applied to viscoelastic materials and will not fully recover when stress is removed. The elongation and recovery curves of carpet yarn are shown in Figure 1, which is known as creep and creep recovery.[10]

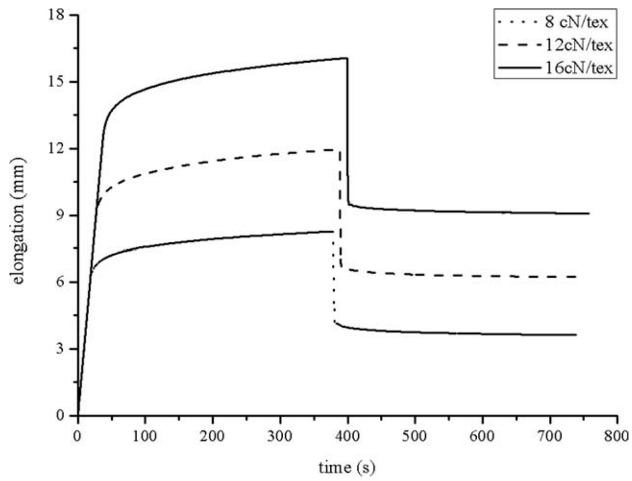

Figure 1 Creep and creep recovery curve for three applied stress levels.

It shows the typical curve for the application of three constant loads (16 cN tex^{-1}, 12 cN tex^{-1}, 8 cN tex^{-1}) to a carpet yarn for a given time (6 min) and then removing the load. It is clear known that the creep rate is nonlinear with the applied stress. In addition, a permanent plastic strain is observed even at low load. With respect to Northolt et al.,[11] the irreversible strain mainly results from the orientation of crystallites and rearrangement of entanglements. The total elongation is assumed to be comprised of elastic, viscoelastic, instantaneous reversible, and irreversible component. The instantaneous extension was followed by creep. The removal of the load gave rise to an instantaneous recovery, followed by a further partial recovery with time and still left some unrecovered extension.

One can found that the carpet yarn has viscoelasticity when subjected dynamic loading. The term viscoelastic is here restricted to designate those mechanical behavior can be represented by a model constructed from elements which obey Hooke's elastic law and elements which obey Newton's viscosity law. We expect that the creep properties under constant load may be explained by the viscoelastic model.

The corresponding diagram of tensile creep and creep recovery test is presented in Figure 2. The model is loaded, and creep process at constant load σ during the time period $(t_1 - t_2)$ is occurred. Elongation, which upstarts during the time period $(0 - t_1)$, is conventionally named as elastic elongation (ε_1).

At the end of creep process (when $t_2 - t_1 = \theta_1$), the model elongation reaches value ε_a, which is

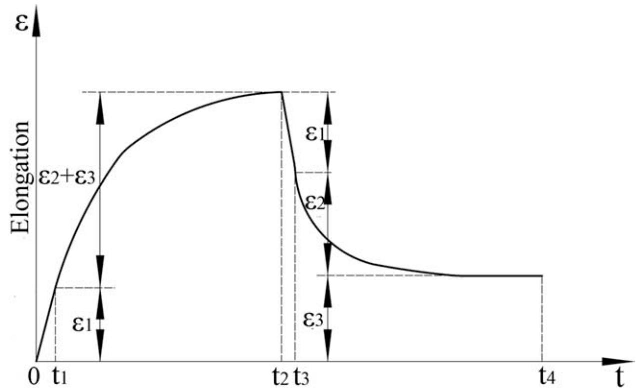

Figure 2 Diagram of creep and creep recovery curve.

considered as total elongation ($\varepsilon_a = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$), where $\varepsilon_2 + \varepsilon_3$ is the creep amount during the loading period θ_1. As soon as the load is removed, elastic elongation (ε_1) immediately vanish as well, and which is followed by creep recovery. Elongation at the end of creep recovery process ($t_4 - t_3 = \theta_2$) is assumed to be irreversible elongation (ε_3), and elongation contracted during the time θ_2 is supposed to be viscoelastic elongation (ε_2). In Figure 2, elastic deformation is a completely recoverable after loading; furthermore, viscoelastic deformation is a time-dependent and reversible deformation, and plastic deformation is unrecoverable.

The creep and creep recovery behavior of carpet yarn may be interpreted qualitatively by the four-element viscoelastic model as shown in Figure 3. The assumption is made that the regularity of viscoelastic elongation during creep process is identical with the regularity of its decrease during creep recovery. The immediate reversible deformation is represented by Hookean spring, the elasticity constant of which is E_2. The delayed reversible (viscoelastic) deformation is represented by Voigt model, and its elasticity and viscosity constants are, respectively, E_1 and η_1. The instantaneous irreversible deformation is represented by the Newtonian piston, the viscosity constant is η_2.

In such way, the variation of yarn strain during creep and creep recovery process can be interpreted as the resultant process of the development of both viscoelastic and plastic elongations.

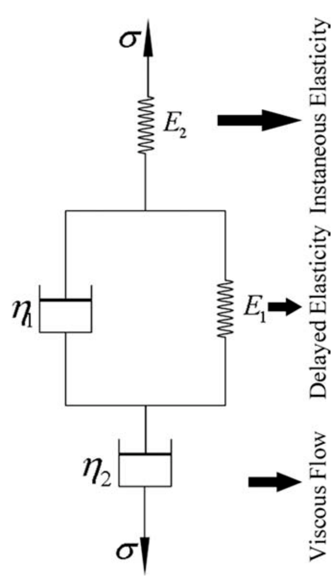

Figure 3 Viscoelastic model for explaining yarn deformation.

MATERIALS AND EXPERIMENT

Materials

Polypropylene carpet yarn (PP), polyamide yarn (PE), polypropylene network-combination yarn and polyamide network-combination yarn, as same linear density of 1288D were selected for study.

Experiments

The tensile creep of carpet yarns after subjected to cyclic loading were studied. During tufting, the carpet yarns are subjected to dynamic loading followed by creep elongation under constant load during machine stoppage. In this article, yarn loading conditions were selected to simulate those occurring on the yarn during tufting. Vangheluwe[5] designed a test method for simulating the relaxation behavior of warp yarns during loom stopping, and tested relaxation after dynamic loading of the yarn. In this article, the same method is adopted to simulate the creep behavior of carpet yarns during tufted machine stops. A control program was written for the INSTRON tensile tester to perform dynamic loading of the yarn between two force levels (see Fig. 4). Two force levels were chosen, as the carpet yarn tension will be peak value when the needle carrying yarn

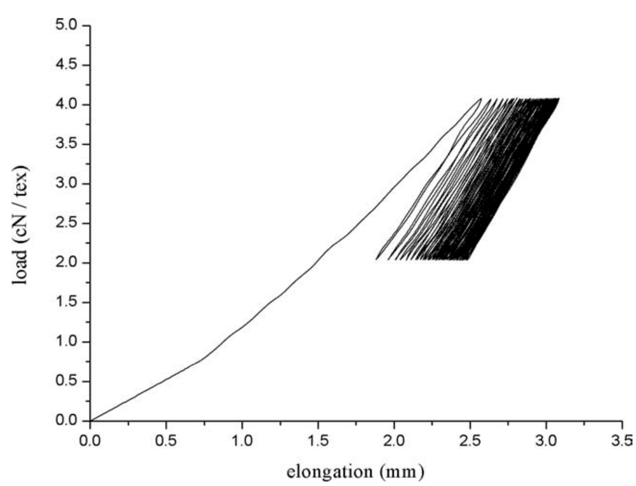

Figure 4 Dynamic loading between two force levels.

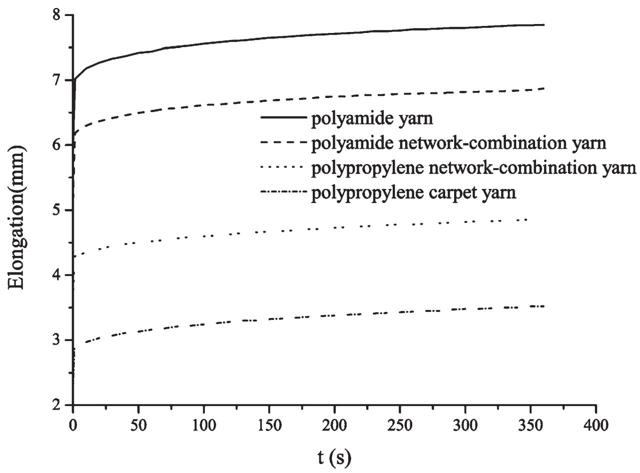

Figure 5 Experimental creep curves of four yarns (upper level).

penetrates the backing fabric in tufting. However, it will be least value when the needle withdraws from the backing fabric. After finishing a predetermined number of load cycles, the stress acted on the yarn is kept constant during the machine stops.

There were 50 cycles of dynamic loading of the sample between two levels for the force (from 2.0 to 4.0 cN tex^{-1}, respectively), followed by creep measurement during 360 s. Yarn tensile tests were performed with 100 mm clamp distance at a speed of 40 mm min^{-1}. Creep tests were executed in which creep measurement started from the upper level of the dynamic loading. The creep property of yarn was tested using INSTRON Universal Testing Machine under standard laboratory conditions (20°C, 65% relative humidity).

The average experimental creep curves of different carpet yarn have been shown graphically in Figure 5.

Creep curves illustrate that yarns deform initially giving high instantaneous elongation but thereafter the rate of elongation decreases. The first stage, where the elongation occurs instantaneously, is due to filament movement in the yarn accompanied with filament decrimping. The second stage is the region where the filament elongation occurs.

MODELS

Due to the typical viscoelastic behavior of material under dynamic loading, the creep behavior of carpet yarn can be described by mechanical models, which consist of the basic elements, namely the spring and the dashpot. The spring describes the elastic property of Hooke's spring, whereas the dashpot represents the viscous properties of Newton's liquid. With different combinations of these elements, we can get a number of viscoelastic mechanical models.

It is the purpose of this article to examine these models and acquire the suitable model for describing the creep elongation of carpet yarn after dynamic loading.

Models for describing creep strain

To eliminate start-up marks during tufting stops, the creep behavior of a single yarn after 50 cycles of dynamic loading is considered. Chen and Wang[4] described qualitatively the time-dependent deformation of the fabric and warp in response to different loading during loom stoppage by a Kelvin model in series with a spring. Vangheluwe and Kiekens[12] proposed a nonlinear spring in parallel with Maxwell elements for description yarn relaxation curves. The obtained formula is fitted very well with experimental relaxation curves using least squares fitting. Manich et al.,[8] studied the stress-strain behavior of cotton, acrylic, and polyester yarns by using modified Maxwell model, which the deformation of spring was replaced by power-law deformation. They considered the modified Maxwell model can best fit the mechanical behavior. Maatoug et al.,[13] investigated the tensile properties of sizing yarn using the Zener's model and fitted the experimental data to model using the nonlinear regression methods.

When the carpet yarns are subjected to constant loading during stoppage, the creep behavior will be occur. Referring to these mechanical models, this article presented four models as a theoretical analysis to predict the creep elongation of carpet yarn, to which subjected constant stress after dynamic loading.

The first model we selected is the standard linear model as shown in Figure 6(a). The second model is four-element model as shown in Figure 6(b). The third model is two-component Kelvin's model as shown in Figure 6(c). The fourth model is the Eyring's model[10] as shown in Figure 6(d).

In Figure 6, E_1, E_2 are the elastic constant of spring (cN tex^{-1}), which is linear with the deformation, and η_1, η_2 are the viscosity of the Newtonian piston (cN s tex^{-1}), and K and α are constants.

1. The standard linear model

   In this model, the immediate reversible (elastic) deformation is represented by Hookian spring, the elastic constant of which is E_2 and the delayed partially reversible (viscoelastic) deformation is represented by Kelvin model, which its elasticity and viscosity constants are, respectively, E_1 and η_1.

   Thus, the relation between stress and deformation presents the differential equation

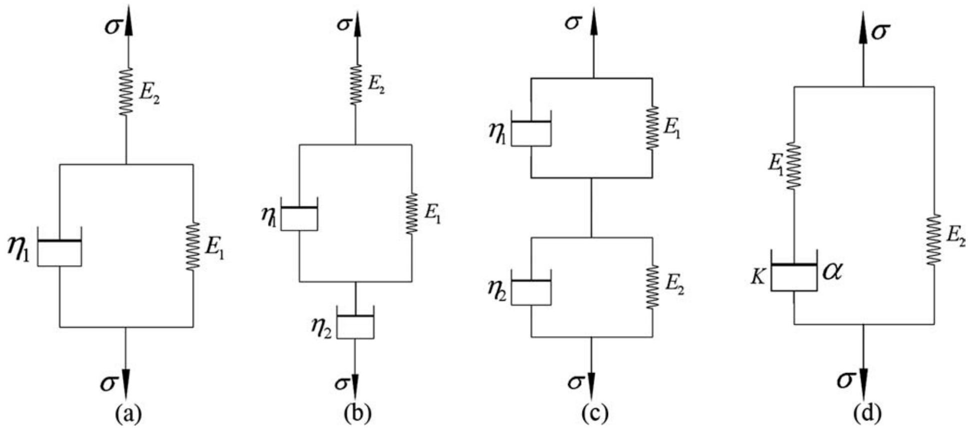

Figure 6 Viscoelastic mechanical model. (a) standard linear model, (b) four-parameter model, (c) two-component Kelvin's model, and (d) Eyring's model.

$$\sigma + \frac{\eta_1}{E_1 + E_2}\dot{\sigma} = \frac{E_1 E_2}{E_1 + E_2}\varepsilon + \frac{E_2 \eta_1}{E_1 + E_2}\dot{\varepsilon} \quad (1)$$

The creep expression for standard linear model under constant stress σ can be written as:

$$\varepsilon(t) = \frac{\sigma_c}{E_2} + \frac{\sigma_c}{E_1}(1 - e^{-t/\tau_1}) \cdot \tau_1 = \eta_1/E_1 \quad (2)$$

2. Four-element model

In this model, the Maxwell model in series with the Kelvin model. The differential Equation (3) governs the constitutive relations between stress σ (cN tex^{-1}) and strain ε (%).

$$\sigma + \left(\frac{\eta_1 + \eta_2}{E_1} + \frac{\eta_2}{E_2}\right)\dot{\sigma} + \frac{\eta_1 \eta_2}{E_1 E_2}\ddot{\sigma} = \eta_2 \dot{\varepsilon} + \frac{\eta_1 \eta_2}{E_1}\ddot{\varepsilon} \quad (3)$$

The creep expression for four-element model under constant stress σ can be written as:

$$\varepsilon(t) = \frac{\sigma_c}{E_2} + \frac{t\sigma_c}{\eta_2} + \frac{\sigma_c}{E_1}(1 - e^{-t/\tau_1}) \cdot \tau_1 = \eta_1/E_1 \quad (4)$$

3. Two-component Kelvin's model

The two-component Kelvin's model consist of two series-connect Kelvin's components. In the first Kelvin's component, the strain is marked as ε_1 and the stress as σ_1 and in the second one as ε_2 and σ_2. The total strain is suggested as the sum of the stress of the first and the second Kelvin's component $\varepsilon = \varepsilon_1 + \varepsilon_2$. While the total stress equals to the stress in the first and second Kelvin's component $\sigma = \sigma_1 = \sigma_2$.

The constitutive relations between stresses σ (cN tex^{-1}) and strain ε (%) as follows:

$$\sigma + \frac{\eta_1 + \eta_2}{E_1 + E_2}\dot{\sigma} = \frac{E_1 E_2}{E_1 + E_2}\varepsilon + \frac{\eta_1 E_2 + \eta_2 E_1}{E_1 + E_2}\dot{\varepsilon} + \frac{\eta_1 \eta_2}{E_1 + E_2}\ddot{\varepsilon} \quad (5)$$

The creep constitutive equation of models will be derived as follows by considering stress σ constant.

$$\varepsilon(t) = \frac{E_1 + E_2}{E_1 E_2}\sigma_c - \frac{\sigma_c}{E_1}e^{-t/\tau_1} - \frac{\sigma_c}{E_2}e^{-t/\tau_2} \quad (6)$$

where $\tau_i = \eta_i/E_i$ (i = 1,2) is retardation time.

4. Eyring's model

Regarding the nonlinear creep behavior of the carpet yarn, we suggest using a non-Newtonian element in the considered rheological model as shown in Figure 6(d), the model consists of a Hooke's spring and a non-Newtonian viscosity dashpot. This suggestion is implied from the research work of Ref. [3]. In this model, the springs follow Hook's law, but the dashpot shows non-Newtonian viscosity, its behavior being represented by a hyperbolic-sine law of viscous flow.

$$d\varepsilon/dt = K \sinh \alpha\sigma \quad (7)$$

where $d\varepsilon/dt$ is strain rate, σ is stress, K and α are constants.

This modification means that the strain rate increases more rapidly with stress increase than it would when it were proportional to stress, as in Newton's law.

The constitutive equation of Eyring's model can be derived mathematically

$$\frac{d}{dt}\{(E_1 + E_2)\varepsilon - \sigma\} = E_1 K \sinh \alpha(\sigma - E_2\varepsilon) \quad (8)$$

The creep behavior of the models is described by the following equations:

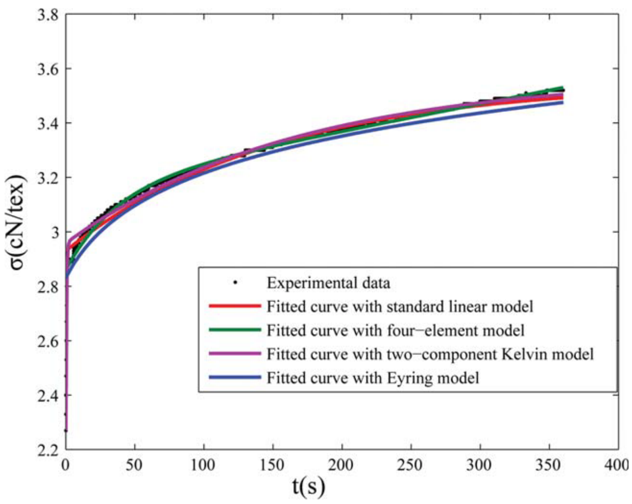

Figure 7 Fitted curves vs. experimental data for yarn creep behavior. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

$$\varepsilon(t) = \varepsilon_0 + \frac{\varepsilon_\infty}{\alpha\sigma_c}\log(1 + At) \quad (9)$$

where $A = \frac{\alpha K \sigma_c(1-\varepsilon_0/\varepsilon_\infty)}{\varepsilon_\infty \log_e \coth\{\alpha\sigma_c(1-\varepsilon_0/\varepsilon_\infty)/2\}}$, $\varepsilon_0 = \frac{\sigma_c}{E_1+E_2}$ is the initial elongation at $t = 0$ and $\varepsilon_\infty = \frac{\sigma_c}{E_2}$ is the final elongation at $t = \infty$.

Equations (2), (4), (6), and (9) show the theoretical creep behavior of carpet yarn with different model. The creep experimental data of carpet yarn will be fitted to the four equations. The constant values of constitutive equation of any viscoelastic model describing the springs and dashpots of viscoelastic models can be determined semiempirically by nonlinear regression.

RESULTS AND DISCUSSION

Accurate idealization of material response involves selection of an appropriate viscoelastic model and suitable modulus and viscosity values of the respective spring and dashpot components. For extracting the discrete viscoelastic parameters E_1, E_2, η_1, η_2, K, and α, the Marquardt algorithm was used for performing the nonlinear regression of eqs. (2), (4), (6), and (9) to the experimental creep curves by applying nonlinear regression. Theoretical and experimental creep curves of the polypropylene carpet yarn are shown in Figure 7.

Figure 7 shows the experimental results and fitted curves for creep behavior of polypropylene carpet yarn with four viscoelastic models.

The model parameters E_1, E_2, η_1, η_2, K, and α which fitted with experimental data (Fig. 7) were calculated using the iteration procedures included in the nonlinear regression analysis are displayed in Tables I–IV. The parameters of viscoelastic models, which for describing mechanical behavior of other yarns also obtained as shown in Tables I–IV using nonlinear regression.

Tables I–IV give the values of the elastic modulus, the viscous coefficient, and retarding time.

In Table V, the accuracy of the models is given as the residual sum of squares χ^2_{red} [see eq. (10)] and the square of the correlation coefficient R^2 [see eq. (11)].

$$\chi^2_{red} = \sum_{i=1}^{n} (y_i - y_i')^2 \quad (10)$$

where y_1, experimental values; $y_{1'}$, values calculated with the regression analysis; n, number of data points ($n = 360$)

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - y_i')^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \quad (11)$$

In Figure 7, there were reasonably good agreement between the prediction and the experimental data except for Eyring's model. These models can predict the creep behavior of carpet yarn after dynamic loading. With the increase of time to infinity, however, the strain in eq. (6) goes to zero, which is not applicable to the carpet yarn for viscoealstic irreversible deformation. Thus, the two-component model cannot describe the deformation of viscoelastic carpet yarn. With respect to creep curves, the four-element model and standard linear model can describe the creep behavior of carpet yarns.

Fitting aptness is assessed by comparing the coefficient estimation R^2. The higher the coefficient (near to unity), the better the model will be more fitted to the experimental. As the residual sum of squares of four-element model is far less than that of standard

TABLE I
Estimated Strain Creep Parameters of the Standard Linear Model

Yarn	E_1/cN tex^{-1}	E_2/cN tex^{-1}	η_1/cN s tex^{-1}	τ_1/s	R^2
Polypropylene yarn (PP)	6.44	1.37	920.17	142.86	0.945
Polyamide yarn (PE)	5.20	0.57	472.87	90.91	0.897
PP network-combination	6.9	0.93	985.22	142.86	0.938
PE network-combination yarn	6.26	0.65	569.07	90.91	0.874

TABLE II
Estimated Strain Creep Parameters of the Four-Parameter Model

Yarn	E_1/cN tex^{-1}	E_2/cN tex^{-1}	η_1/cN s tex^{-1}	τ_1/s	R^2
Polypropylene yarn (PP)	11.59	1.43	305.11	26.32	0.993
Polyamide yarn (PE)	4.91	0.61	44.22	9.01	0.925
PP network-combination	11.66	0.96	233.24	20.0	0.958
PE network-combination yarn	3.57	0.75	9.10	2.54	0.93

TABLE III
Estimated Strain Creep Parameters of the Two-Component Kelvin's Model

Yarn	E_1/cN tex^{-1}	E_2/cN tex^{-1}	η_1/cN s tex^{-1}	η_2/cN s tex^{-1}	τ_1/s	τ_2/s	R^2
Polypropylene yarn (PP)	6.47	5.82	1078.75	2.82	166.67	0.48	0.961
Polyamide yarn (PE)	5.68	3.40	710.23	4.19	125.0	1.23	0.993
PP network-combination	6.92	5.87	1153.40	3.98	166.67	0.68	0.993
PE network-combination yarn	6.92	3.58	865.05	3.97	125.0	1.11	0.994

TABLE IV
Estimated Strain Creep Parameters of the Eyring's Model

Yarn	E_1/cN tex^{-1}	E_2/cN tex^{-1}	K	α	R^2
Polypropylene yarn (PP)	0.71	0.60	0.003	0.21	0.961
Polyamide yarn (PE)	0.69	0.75	0.05	0.10	0.987
PP network-combination	0.6	0.45	0.01	0.15	0.956
PE network-combination yarn	0.06	0.6	0.05	0.09	0.986

liner model and the corresponding coefficient is near to unity, we can clearly considered that the four-element model will be used to describe the creep behavior of carpet yarn after dynamic loading.

The good correspondence between theoretical and experimental results on creep and the highest coefficient also enables the authors to maintain that the four-element model is appropriate for analysis of the time-dependent creep behavior of the carpet yarn after dynamic loading.

With the help of the theoretical model, the creep elongation of carpet yarns after finite creep time during machine stoppage can be assessed.

The fitted curve for the creep behavior was represented by the following equation:

$$\varepsilon(t) = 2.8 + 0.001t + 0.34(1 - e^{-0.038t}) \qquad (12)$$

CONCLUSION

During tufting machine stoppage, the carpet yarns are subjected to a constant tension, which resulting in complicated creep behavior. The creep behavior of carpet yarns in tufting results in start-up marks on carpet surface when tufting restarts.

In this article, four mechanical models which represent the creep behavior of carpet yarns after dynamic loading were proposed to predict the creep behavior as well as to fit the mechanical data and obtain the model parameters through semiempirical means.

With respect to above analysis, we can conclude that:

Four carpet yarns were subjected to dynamic loading during a number of load cycles, and then followed by creep experiment under constant stress. The measurements of creep elongation were started

TABLE V
Analysis of Variance of Four Models for Polypropylene Carpet Yarn

Model	Source	Sum of squares	d.f.	Mean squares	R squares
Standard linear model	Regression	3974.295	3	1324.765	0.945
	Residual	0.517	357	0.001	
Four-element model	Regression	3974.446	4	993.612	0.993
	Residual	0.064	356	0	
Two-component Kelvin model	Regression	3974.748	5	794.95	0.961
	Residual	0.366	355	0.001	
Eyring's model	Regression	3974.443	3	1324.814	0.961
	Residual	0.369	357	0.001	

from same stress in creep tests. Then compare these theoretical models with experimental results, we obtained that the four-element model is a suitable model to describe the creep behavior during tufting machine stoppage. The parameters of the model can be obtained by fitting the mechanical model with the experimental data using nonlinear regression. The elongation of carpet yarns during carpet machine stoppage under constant stress can be calculated by applying the confirmed model. Thus, the start-up marks when the carpet machine restarts can be eliminated by adjusting the feeding length according to the calculated elongation.

This work was Supported by Innovation Program of Shanghai Municipal Education Commission under grant No. 11ZZ58.

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