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Friction Properties of Elastomer Threads

Abstract
This paper presents the estimation of the apparent friction coefficient values of elastomer threads with a linear density of 169 dtex from the Italian enterprise Fillattice-Linel. The tests were carried out on circular friction barriers with diameters from 0.1 mm to 10 mm, and within a preliminary tension range of 4 to 45 cN. A special measuring stand for on-line measurements was designed and constructed. The stand included rotary tensiometric force gauges and a recording system which also analysed the test results obtained. The interpretation of the research results was performed on the basis of a mathematical model, which considers the friction properties according to the generalised friction law, as well as the thread's rheological properties. Furthermore, a comparative analysis of the friction coefficients for elastomer and cotton threads was carried out. The investigations carried out prove that the optimum curvature radius of the friction barrier, at which the resistance of pulling the elastomer thread over the barrier is the smallest, is about 0.25 mm, which means that it is ten times smaller than for cotton yarns. We stated that the variability character of the apparent friction coefficient for elastomer threads, in dependence on the friction barrier's diameter, is determined by the generalised friction law $T = a N^n$. The influence of the thread's rheological properties on the value of the friction coefficient μ is essentially smaller for elastomer threads when compared with cotton yarn, especially for barrier diameters commensurable with the diameters of the elastomer threads.

Key words: *elastomer threads, cotton yarn, friction barriers, modelling, experimental research, friction, rheological properties.*

Introduction

Knitted fabrics with a content of elastomer threads are more and more often produced by knitting machines, mainly rib-knitting machines, with the aim of improving the geometrical stability of knitted fabrics.

Elastomer threads are characterised by great extensibility, which can reach even up to several hundred per cent of relative elongation. This feature causes elastomer threads to require knitting-in conditions on knitting machines which differ from those for classical yarns. The investigations of threads drawn through friction barriers which had hitherto been carried out mainly considered yarns manufactured from natural fibres (cotton and wool), as well as synthetic filaments, but all of them with a relatively small elongation. However, there is a lack of investigations into the knitting-in conditions of elastomer threads. Only general technological recommendations concerning the knitting-in of elastomer threads formulated by the individual producers are available. They come down to the statement that the unwinding, guiding, and knitting-in of elastomer threads should be characterised by small variations of the forces generated in threads under the conditions of an exactly defined draw ratio. No documented scientific knowledge exists which concerns the conditions of knitting-in elastomers, or their influence on the structure and properties of knitted fabrics.

The elastomer threads are knitted-in together with other threads, mainly of cotton. This is why the research results obtained for the friction coefficient of elastomer threads will be compared with those for cotton yarns.

Model of the process of drawing elastomer threads through friction barriers

The results of the process of drawing elastomer threads through friction barriers will be interpreted on the basis of a mathematical model [1, 2] which also considers the rheological properties of the threads. The model was elaborated on the basis of the following assumptions:

- Friction is described by the generalised friction law $T = a N^n$.
- The thread is considered as a material of visco-elastic properties, where the relation between the relative elongation ε, the stretching force F, and the time t over which this force acts is described by the rheological three-element Zener model (Figure 1), according to Equation (1)

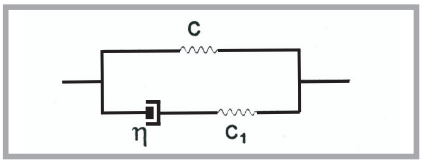

Figure 1. *Zener model; c, c_1 – relative elasticity coefficients, in cN, η - relative dynamic viscosity, in cN s.*

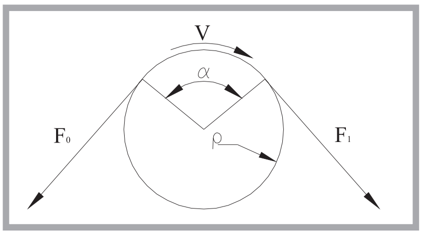

***Figure 2.** Scheme of drawing the thread through a circular friction barrier; F_0, F_1 - forces in the thread before and after the barrier respectively, α - angle of contact, ρ - radius.*

$$F + \frac{\eta}{C_1}\frac{dF}{dt} = c\varepsilon + (c + c_1)\frac{\eta}{c_1}\frac{d\varepsilon}{dt} \qquad (1)$$

where:

c, c_1 – relative elasticity coefficients, in cN, and

η – relative dynamic viscosity, in cN s.

- The deformation ε of the thread on the friction barrier is the result of the action of the friction forces T.
- The velocity of the increase in the thread's relative deformations $d\varepsilon/dt = V_\varepsilon$ on the friction barrier is constant for the given velocity v of drawing the thread through the barrier.
- The relaxation of the preliminary forces F_0 on the barrier is negligible.

Considering the assumptions mentioned above, the force value in the thread after leaving the friction barrier is:

$$F_1 = F_0 + c \cdot v_\varepsilon \cdot t + \eta \cdot v_\varepsilon \left(1 - e^{\frac{-tc_1}{\eta}}\right)$$

where:

v_ε is the velocity of the increase in the thread's relative deformations on the friction barrier, in s^{-1}, and

t is the time of passing the thread over the friction barrier, in s.

The value of the static expression ($c\, v_\varepsilon\, t$) is related to the action of friction forces T, whereas the second expression is the dynamic component which results from the relative deformations of a medium with visco-elastic properties, such as the thread being considered, and describes the relations between the parameters in the Maxwell link of the standard Zener model (Figure 2).

The friction coefficient μ is not directly present in the model interpretation, as the generalised friction law $T = a\,N^n$ was accepted. After introducing equation (2) into the dependence (3) instead of F_1, the apparent friction coefficient μ for cylindrical friction barriers can be determined as:

$$\mu = 1/\,a \ln (F_1/\,F_0) \qquad (3)$$

and by extension:

$$\mu = \frac{1}{\alpha} ln \frac{F_0 + c \cdot v_\varepsilon \cdot t + \eta \cdot v_\varepsilon \left(1 - e^{\frac{-tc_1}{\eta}}\right)}{F_0} \qquad (4)$$

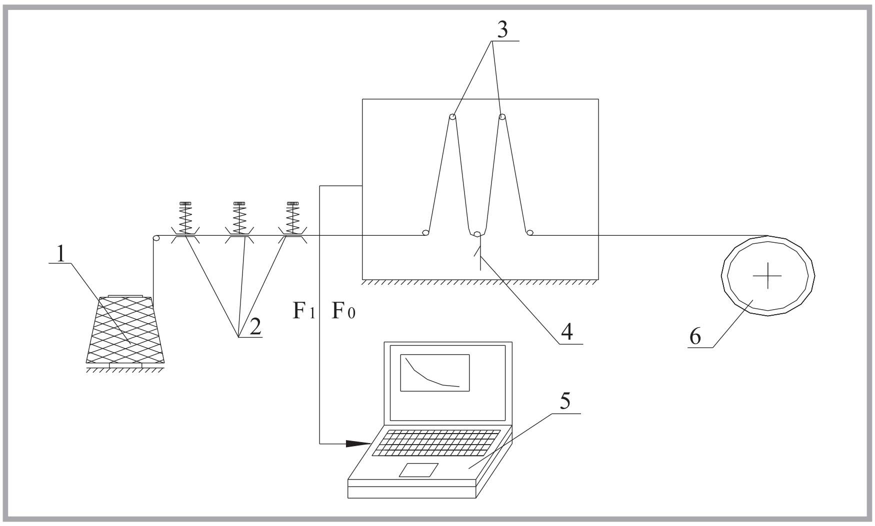

***Figure 3.** Measuring stand for determination of the classical friction coefficient; 1 – yarn package, 2- disk tensioners, 3 – measuring gauges, 4 – friction barrier, 5 – computer, 6 – yarn take-up roller.*

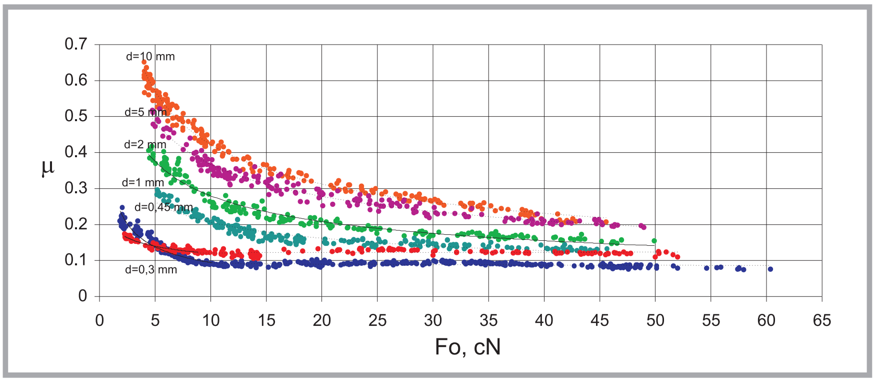

***Figure 4.** Friction coefficients μ of elastomer yarn as a function of F_0 for various diameters d of the friction barrier, measured under the following conditions: thread velocity of v=1 m/s, angel of contact $\alpha = 169^o$ (2.9406 rad).*

Materials and research programme

An elastomer thread of a linear density of 168 dtex from the Fillattice-Linel company (Italy) was used for this investigation. The measurements of the friction coefficient were carried out within a wide range of preliminary tensions (from 4 cN to 45 cN), as different values of tension exist in the threads before each barrier, while the threads are guided, and in the knitting zone. The preliminary tension was changed while pulling the thread through the barrier. The friction coefficient was measured for cylindrical friction barriers with a diameter within the range of d = 0.1 to 10 mm.

Research method

Investigations of the friction coefficient were carried out with the use of a measuring system integrated with a computer, and presented in Figure 3. The thread unwrapped from the yarn package (1) was directed over a set of disk tensioners (2), and pulled over a friction barrier (4). Forces in the threads were measured before and after the friction barrier with the use of rotary force-measuring tensometric gauges (3). The computer program we devised enabled us, every time after averaging the force values in the threads before and after the friction barrier for the succeeding working points, to calculate the value of the friction coefficient

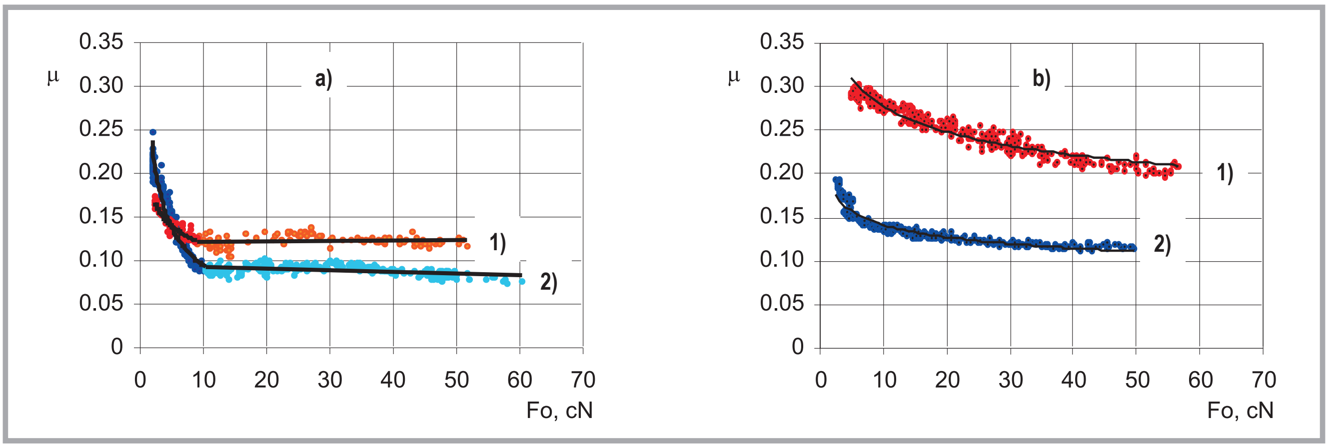

Figure 5. *Friction coefficient μ as a function of the preliminary tension F_0 for: a) elastomer yarn, b) cotton yarn with 20 tex; measured under the following conditions: thread velocity of v = 1 m/s, angel of contact α = 169⁰ (2.9406 rad), radius of curvature ρ of the friction barrier for sinker ρ = 0.05 mm (1) and for needle ρ = 0.225 mm (2).*

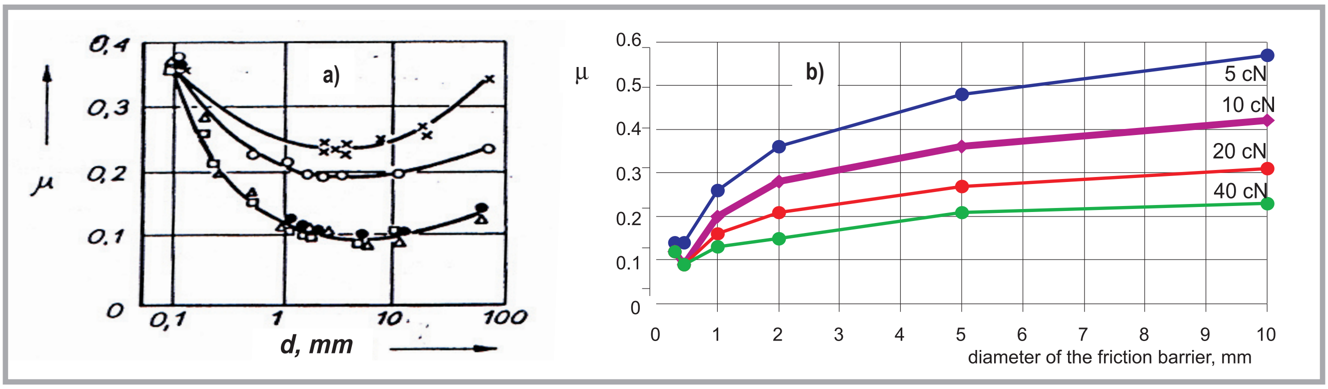

Figure 6. *a) Dependence of the apparent friction coefficient of cotton yarn on the diameter d of the friction barrier [3], test conditions: cotton 20 tex, steel, α = 180⁰, v = 3.3 m/s, F_0 = 5 cN, × - yarn not treated with paraffin, o – yarn insufficiently treated with paraffin, Δ - yarn treated optimally with paraffin, □ - yarn treated excessively with paraffin; b) the same dependence as a) but for elastomer threads.*

and plot it in the diagram of μ - F_0 coordinates (see Figure 4)

Analysis of research results

In Figure 4, it is clearly visible that with the increase in tension of the elastomer thread before the tension barrier, the value of the apparent friction coefficient μ decreases degressively. Furthermore, if the diameter of the cylindrical friction barrier increases, the intensity of the influence of the preliminary tension F_0 on the value of the friction coefficient μ is greater, which testifies to the existence of different values of the factor n in the generalised friction law.

In order to identify the conditions of the knitting process, knowledge of the behaviour of elastomer threads on friction barriers of the knitting zone, i.e. on needles and sinkers, is indispensable; these are the only barriers which are not rotational through the way of feeding and knitting-in the elastomer threads. Within the friction barrier diameter's range of d = 0.1 to 10 mm, the smallest values of the coefficient μ occur precisely for these friction barriers. It should also be mentioned that under these conditions, for greater values of the preliminary forces (F_0>5 cN), the value of the coefficient μ for the friction pair needle hook/thread is smaller than for the friction pair sinker/thread (see Figure 5.a). The second characteristic feature of the dependency μ = f(F_0) is the insignificant influence of the preliminary tension F_0 on the value of coefficient μ for the values of preliminary tension F_0>10 cN (Figure 5a).

By comparing the test results obtained for elastomer threads with the results for cotton yarn with 20 tex (Figure 5b), it may be stated that considerably greater differences in the values of the friction coefficient on the needle, as well as on the sinker, occur for cotton yarn. The experimental investigations into the friction coefficient of cotton yarn which have been carried out hitherto demonstrated that the maximum values of the friction coefficient μ occur for barriers of dimensions which are commensurable with the thread diameter [1, 2]. Furthermore, it has been experimentally proved [3] that an optimum range of friction barrier diameters exists, for which the resistance values of pulling through the threads are minimal (see Figure 6a).

The results of modelling the apparent friction coefficient for cotton yarn and elastomer threads are presented in Figure 7. The procedure of determining the rheological parameters on the basis of dynamically drawing the threads and force relaxation therein is described in detail in the literature [1, 2]. It should be emphasised that a significant differentiation of the coefficients a and n in dependence on the value of the friction barrier diameter was obtained for elastomer threads. This is caused by the substantial influence of longitudinal forces on the real contact surface.

In model interpretations concerning the rheological context [1, 2], the influence

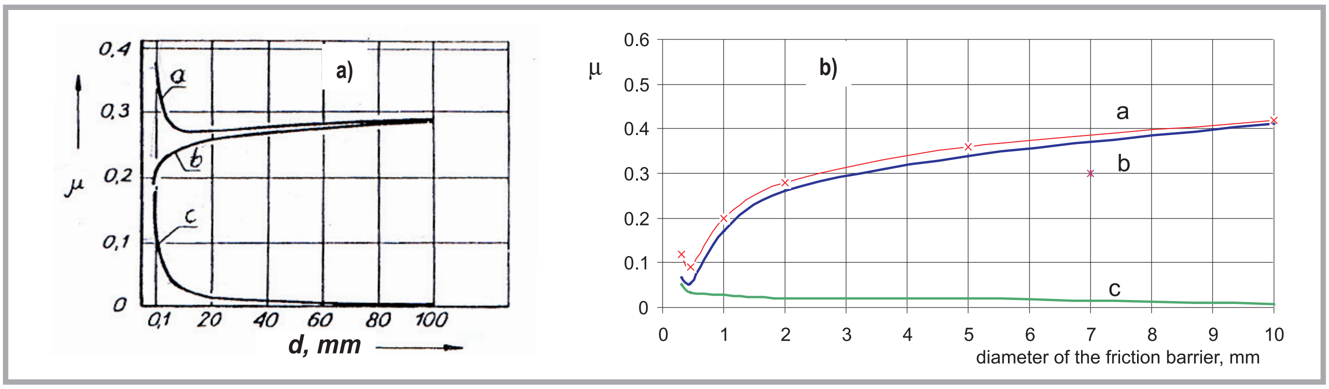

Figure 7. Model interpretation of the apparent friction coefficient concerning the rheological context [2]; a) for cotton yarn (calculation parameters: F_0 =5 cN, v = 2 m/s, a = 0.36, n = 0.93, c = 2500 cN, c_1 = 4500 cN, η = 2 cN s); b) for elastomer threads: (calculation parameters: F_0 =10 cN, v = 1 m/s, n = 0.93, c = 68 cN, c_1 = 128 cN, η = 2 cN s); × - experimental results; the curves (in Figures a) and b)) are marked: a – summarised value of friction coefficient μ, b – the friction process predominant on barriers with relatively large diameters, connected with the generalised friction law, c – the friction process predominant on barriers with diameters commensurable with the thread diameter, considering the influence of the rheological properties of the thread pulled over the barrier.

of friction barriers on the value of the μ coefficient was explained by the superposition of two processes which are mutually opposed regarding the directions of their influence. The first process, which is connected with the real contact surface (curve b, Figure 7), is predominant in barriers with relatively large diameters, and is connected with the action of the generalised friction law, whereas the second process (curve c, Figure 7) reveals its influence and is predominant in barriers with diameters commensurable with the thread diameter. The latter process considers the influence of the rheological properties of the thread pulled over the barrier. The sum of both resistances (visualised by curves a and c) yielded the summarised value of the friction coefficient μ, the changes of which as a function of the barrier diameter are shown by curve a in Figure 7.

The results of investigation into the friction coefficient for elastomer threads presented in Figure 6b and its model interpretation (Figure 7b) indicate the qualitatively similar influence of the friction barrier's diameter on the resistance while pulling the elastomer thread over the friction barrier, and also in the case of cotton yarn. The essential difference comes down to the value of the friction barrier's diameter at which the minimum value of the coefficient μ occurs. For tension values of F_0>5 cN, the minimum value of the friction coefficient μ was obtained for a friction barrier of diameter d = 0.45 mm.

From this it results that the optimal curvature radius of the friction barrier, at which the resistance during pulling the elastomer thread over the barrier is the smallest, equals about 0.25 mm, and is ten times smaller than for cotton yarn.

The variability character of the friction coefficient's value as a function of the friction barrier diameter is similar to the changes in the friction coefficient's value according to curve b (Figures 6b and 7), whose character is determined by the generalised friction law $T = a N^n$. The influence of the elastomer's rheological properties on the value of the friction coefficient for small values of the friction barrier diameter, commensurable with the thread diameter, is significantly smaller than for cotton yarn (curve c; compare Figure 7a and 7.b). As mentioned before, the shape of curve c is connected with the relationship between the speed of increase in the relative deformations of visco-elastic features and the rheological parameters c_1 and η in the Maxwell link of the Zener standard model. According to the accepted model, the investigations and considerations presented above indicate that it is not only the phenomena in the contact range which are decisive about the force values in elastomer threads, but also those phenomena which take place in the thread material.

Conclusions

- Investigations into the process of pulling elastomer threads over friction barriers demonstrated that, within the range of the friction barrier's diameters d = 0.1 to 10 mm, the variability character of the function of the apparent friction coefficient μ in dependence on the barrier's diameter (μ = f(d)) is determined by the generalised friction law $T = a N^n$, and the influence of the thread's rheological properties is significantly smaller than for cotton yarn, especially for barrier diameters commensurable with the diameter of the elastomer thread.
- The optimum curvature radius at which the resistance of the barrier while pulling it over the elastomer thread is the smallest, about 0.25 mm, i.e. ten times smaller than for cotton yarn.

Acknowledgment

This investigation presented herein was carried out as part of project No. T08E 081 27 sponsored by the Polish Ministry of Science and Information Society Technologies.

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Received 21.02.2005 Reviewed 26.07.2005