Analysis of Elongation until the Break of the Plain Weft-Knitted and Double-Faced Fabrics

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From a technical standpoint, force-elongation diagrams of plain knitted fabric and double-faced knitted fabric made of 20 tex cotton yarns were examined. Strip samples were cut in the direction of courses and wales which were extended until the break using the computer-controlled tensile strength tester. During the stretching process, the computer records the force-elongation values of the knitted fabric. The numerical data from the computer's tensile strength tester are uploaded to certain computer programs, which define the mathematical shape of the stretching curve. The force-elongation curve can be divided into four basic parts: 1. from the start of stretching to the end of elastic deformation of the fabric; 2. from the end of elastic deformation to the vertex of the curve; 3. from the vertex of the curve to the start of plastic deformation; and 4. from the start of plastic deformation to the knitted fabric break. For several of the mentioned sections, the amount of work required to stretch the knitted fabric till it breaks was calculated.

Key words*: knitted fabric; jersey; double faced fabric; cotton; force-elongation diagram; analysis*

Izvorni znanstveni rad

S tehnološkog gledišta analizirani su dijagrami sila/istezanje glatkog kulirnog desno-lijevog i desno-desnog pletiva koja su izrađena pamučnim pređama finoće 20 tex. Iz pletiva su izrezani trakasti uzorci u smjeru redova i nizova očica koji su na dinamometru upravljanim računalom istezani do prekida. Pri istezanju pletiva računalo registrira vrijednosti sile i istezanja pletiva. Brojčani zapisi iz računala dinamometra se prenose u određene računalne programe pri čemu se određuje matematički oblik krivulje istezanja. Krivulja sila/istezanje je podijeljena u četiri osnovna dijela: 1. od početka istezanja do kraja elastične deformacije pletiva, 2. od kraja elastične deformacije do tjemena krivulje, 3. od tjemena krivulje do početka plastične deformacije i 4. od početka plastične deformacije do prekida pletiva. U pojedinim navedenim dijelovima izračunao se iznos uloženog rada pri istezanju pletiva do prekida.

Ključne riječi: *pletivo; kulirno; desno-lijevo; desno-desno; pamuk; dijagram sila/istezanje; analiza*

1. Introduction

During use, parts of clothing stretch variably longitudinally, transversely, or at an angle in relation to the direction of the tensile force. Classic fabrics used in garment manufacturing have an elongation until the break of up to 20%, making them appropriate for the production of clothing that casually fits the body [1,2]. Depending on the cut of the garment and the ease allowance factor, different types of clothes stretch most when put on and taken off, causing significant strain while worn. When subjected to such stresses, the seam frequently deforms or ruptures first, followed by the fabric. Knitted fabrics have a much higher elasticity than woven fabrics, which means that they can now be used in various areas. The simplest cotton jersey, which is used in the production of light summer T-shirts, has an elongation in the direction of the courses or transversally about 150% and in the direction of the wales or longitudinally half less or about 70%. Double face fabrics, produced from the same yarns as the preceding knitted fabric, have nearly twice the elongation at break (around 250% in the course direction) and half the elongation (120%) in the wale direction. Such knits are appropriate for women's clothing that fits closely to the body or for stouter persons [3-5]. In usage, this knitted fabric expands differently on different places of the body, giving the appearance of a comfortable fit. The most basic structure of exquisite women's stockings produced from multifilament PA yarns (nylon stockings) stretches far more than earlier knitted constructions. In the ankle area it stretches by 50%, in the calf area by 100%, in the thigh area by 200% and under the groin by up to 800%. When a correctly designed and manufactured stocking is worn on the legs and body, it is comfortable to wear [6-8].

The usage of closefitting and compressive clothes has risen during the previous 10 years. Several parameters are decisive for these garments, including wearing comfort, pressure on the body, repetitive use and functional care. Many garments for recreational or professional athletes that lie directly on the body have a mild compressive impact on the body, with a pressure of 7 to 13 hPa (5 to 10 mmHg). People who work in a standing position, such as dentists, business people, letter carriers, mountaineers, foresters, etc., use so-called preventive compression stockings, which exert increased pressure on the leg and achieve a compression of 8 to 24 hPa (6 to 18 mmHg) on the leg [9,10]. People with chronic venous insufficiency or lymphedema, on the other hand, wear compression stockings of varying degrees of compression for therapeutic purposes throughout the disease progression. Such stockings are recommended for therapeutic purposes by medical specialists who continuously monitor the effect of the therapy [11].

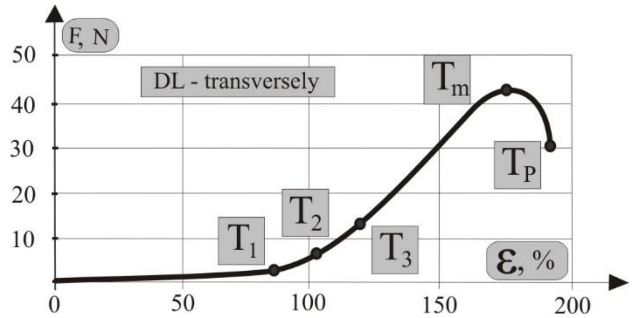
Technologists must carefully balance three key characteristics while creating unique articles of clothing for domains that require the use of knits with a compressive impact on the body. 1. the amount of elongation of the knitted fabric, 2. the force at the given elongation of the knitted fabric and 3. the amount of compression achieved at the given elongation. Many clothing products in current technology procedures are designed to be individualized based on the user's preferences. As a result, it is required to study changes in the fabric structure in specific stretching areas, typically until the fabric begins to deform permanently and, in some cases, until the fabric breaks [12,13].

2. Force-elongation diagram of the knitted fabric

Textile processing laboratories and technological procedures utilize many ways, both standard and non-standard, to stretch and break textiles [14, 15]. In addition to the methods mentioned earlier, some knitted fabric makers utilize internal methods to stretch their fabric without breaking it. This provides valuable data on the material deformation, which is useful for garment production and cutting. In technical research, the narrowing of a knitted fabric in one direction (e.g. transverse) while extending in the other direction (e.g. longitudinal) is significant. When stretching the knitted fabric until it breaks, the strip method is usually used, whereby the tensile tester registers force and elongation in pairs and stores them in the working memory as a numerical record and finally as a visual record in the form of a force-elongation diagram (Fig.1). Depending on the structure of the knitted fabric and the measuring method, different forms of diagrams are obtained, which show several characteristic areas mar-ked with the corresponding points [16].

The first part of the diagram is linear and extends from the start of the section (point 0) to point T_1. From a technical point of view, this region (from point 0 to T_1) contains the elastic deformation of the fabric. A great elongation is achieved with a small increase in force. The fabric is elastic (Hooke's law) because it returns to its original position at the end of the stretching range with no lasting distortion. This elongation range is ideal for producing traditional clothing that do not compress the human body.

The force grows greater than the elongation when the knitted fabric is stretched after the elastic deformation (point T_1).



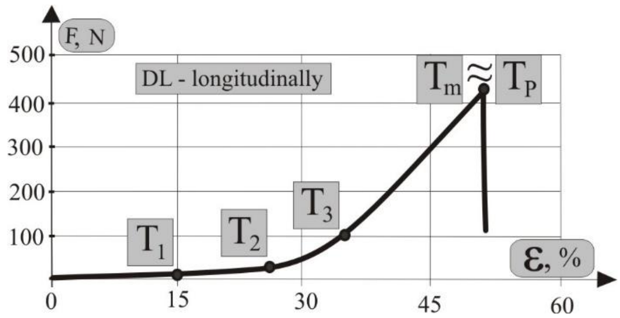


Fig.1 Classical force-elongation diagrams until the break of plain jersey fabrics [3,14]: a) transversely – course direction, b) longitudinally – wale direction; F - force, N, Ɛ - elongation, %, T_1 – presumed end of elastic deformation, T_2 - curve vertex, T_3 – presumed onset of plastic deformation, T_m – highest force, T_p – breaking point of the material

This second area can be considered from the end of the elastic deformation to the apex of the force-elongation curve, i.e. from point T_1 to point T_2. In practical applications, this region is crucial when fabrics are stretched during the garment manufacture that exerts a little pressure on the human body.

Further elongation after the apex of the force-elongation curve (point T_2) results in an even higher rise in force than with elongation. At one point, the connection between force and elongation becomes proportionate, and the curve takes on a largely linear shape, as seen in the first part of the diagram. The material's permanent deformation is thought to start at point T_3, which is the start of this second linear portion of the diagram. The ascent angle in the second linear segment of the diagram is significantly greater than in the first. In practical use, the part of the force-elongation diagram from point T_2 to T_3 is important when compression stockings with a higher degree of compression or various corsets and orthoses are made. The area between the end of elastic deformation of the knitted fabric and the onset of plastic deformation (from point T_1 to T_3) is theoretically referred to as elastoplastic, and this is where a portion of the knitted fabric structure is destroyed. The highest force measured when the material is elongated to break (point T_m) is recorded at the end of the second linear part of the force-elongation diagram, and it is the most commonly used when interpreting the results according to the standard. After the highest measured force during elongation of the knitted fabric (point T_m), the material is permanently destroyed, first by breaking individual yarns and then by the entire knitted fabric sample (point T_p). The highest force recorded during the elongation of the knitted fabric (point T_m) and the breaking force of the knitted fabric (point T_p) differ significantly when stretching individual samples, depending on the structure, the direction of elongation, the shape of the knitted fabric sample, the operation of the devices, etc. (course direction – transverse, wale direction – longitudinal, at some angle in relation to the direction of force). The amount of the difference in the specified forces refers to the analysis of the criteria set for recording the breaking force of the knitted fabric. Technological examination of the force-elongation diagram of simpler knitting structures utilized in garment manufacturing is more appropriate up to the maximal elongation force, however for more complicated knitting structures, the diagram should be analysed up to the breaking point of the knitted fabric. This recommenddation is especially interesting and useful for individual knitted fabrics made from three different types of yarn (leisure wear, three different yarns in one course) with varying elongation at break, such as cotton single yarn (elongation at break 4 to 7%), polyamide multifilament yarn (elongation 20 to 30%), and elastane yarn (elongation over 200%). When analysing the force-elongation diagram of the knitted fabric, it is advisable to always specify the criteria according to which the diagram was analysed. The deformation of knitted fabric for clothing production is interesting up to the start of permanent deformation, sometimes up to the point of greatest stress, and very rarely up to the breaking of the knitted fabric. When producing various corsets, orthoses, and technical aids for the disabled, it is important to analyse to the diagram up to the maximum load force, or until the material breaks. Because of the various areas of use for the individual knitted fabrics, certain research and analytical objectives are established, resulting in the division of the force-elongation diagram into distinct components [17].

3. Experimental part

The force-elongation diagrams of the finished jersey fabric and the unfinished double face fabric loaded in two directions: courses or transversely and wales or longitudinally, were analysed in the experimental section from a technological standpoint. The goal of the research is to divide the force-elongation diagram into individual significant sections, which are identified by the five points mentioned above: 0, T_1, T_2, T_3, and T_m. Pairs of force-elongation and their respective proportions to the maximum force and elongation were identified for the examined samples and the indicated points. These points aim to evaluate the workload in specific sections by stretching the knitted fabric until it breaks. The amounts of invested work are ranked and compared in the various directions of elongation of the knitted fabric.

The two basic structures of weft knitted fabrics were analysed using standard methods [18,19]. The first knitted fabric sample was made using a 20 tex single cotton yarn spun on the ring spinning machine. It is important to note that summer T-shirts were produced exclusively from a lightweight knitted fabric with a simple structure. The weft knitted fabric has a mass per unit area of 140 g/m^2 and a volume mass of 0.34 g/cm^3 and is used to make summer T-shirt. The second sample is also made with 20 tex fineness single cotton yarn, which is made on a ring spinning wheel. The fabric has a volume weight of 0.25 g/cm^3 and a mass per unit area of 170 g/m^2 due to its plain weft-knitted construction. Winter undershirts for men were made from knitted fabric.

The test samples are 50 mm wide and 350 mm long and are elongated on a tensile strength testing machine with flat clamps until they break. The clamps were positioned 200 mm apart and the jersey fabric was stretched at a speed of 100 mm per minute. The distance between the clamps of the tensile stress tester was set to 100 mm as the double-face fabric elongates significantly more in the course direction. The elongation speed was kept the same as for the previous sample. The tensile stress tester takes precise measurements during fabric elongation by capturing 10-20 measurements/mm of stretching, which produces 800 to 5000 accurate force:elongation records [14, 15]. In order to carry out diagram analysis effectively, it is imperative to use numerical data to calculate the total and partial input effort involved in stretching knitted fabric to its maximum force or until it breaks.

4. Results and discussion

Each studied sample has its own set of measurement and analysis data. First, the force-elongation diagrams generated by the computer of the tensile stress tenser are presented.

The numerical data from the tensile stress test machine's control program was converted into a mathematical program for analysis and processing.

The computer software was used to find a mathematical function that explains the change in elongation of the knitted fabric as the force increased. The force-elongation curve discovered in these studies can be described by a third or fourth degree polynomial equation suitable for practical application, depending on the analysis criteria and the accuracy of the results.

Such knitted fabrics stretch more in the course direction, so their change is typically described by a fourth-degree equation, whereas elongation in the wale direction is conveniently described by a third-degree equation [20]. The samples to be stretched with the tensile stress tester were cut from the fabrics by the meter. When stretching the knitted fabric, the threads on the edge of the sample are gradually pulled out of the edge stitches, resulting in significant variations in the elongation force and a large deviation from the mean value, particularly in the first section of the diagram, from point 0 to T_1. To determine the consistency of a force-elongation change in a single section, define the criteria for the practically permissible deviation and divide the curve into individual elongation sections as needed. After dividing the curve into individual sections (points from 0 to T_m), the percentage of work required to elongate the knitted fabric in each section is calculated [21,22].

4.1. Result analysis of elongating the plain weft-knitted cotton fabric

The first sample shown and analysed was cut from a plain weft-knitted fabric that was used for the production of summer T-shirts for women. As mentioned, the knitted fabric was made from a 20 tex single cotton yarn which was spun on a ring spinning machine. Three test samples were used to stretch the knitted fabric to break in the transverse or course direction, while four test samples were used for testing in the wale or longitudinal direction. The elongation of the knitted fabric was performed without preload, therefore all force and elongation measurement data begin at zero. The reason for this type of measurement is the desire to find out the individual parts in the diagram and to calculate the work during elongation, which is important for analysing the influence of the amount of elongation and the force during compression of the knitted fabric on the human body. An average force/elongation diagram was created for the fabric, based on individual measurements. The elongation to break was found to be around 155% in the course direction and 82% in the wale direction, which is half as much (Fig.2).

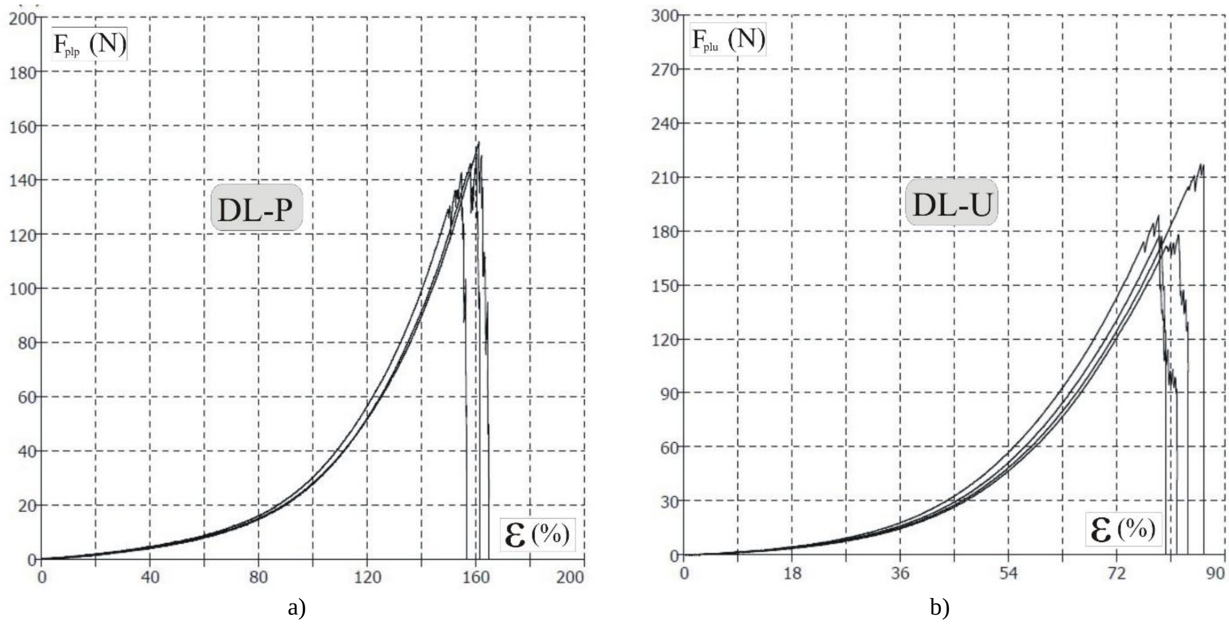


Fig.2 The force-elongation diagram recorded by the computer of the tensile stress tester until the finished plain knitted fabric breaks, a) transversely – course direction, b) longitudinally – wale direction; F – force, N, Ɛ - elongation, %

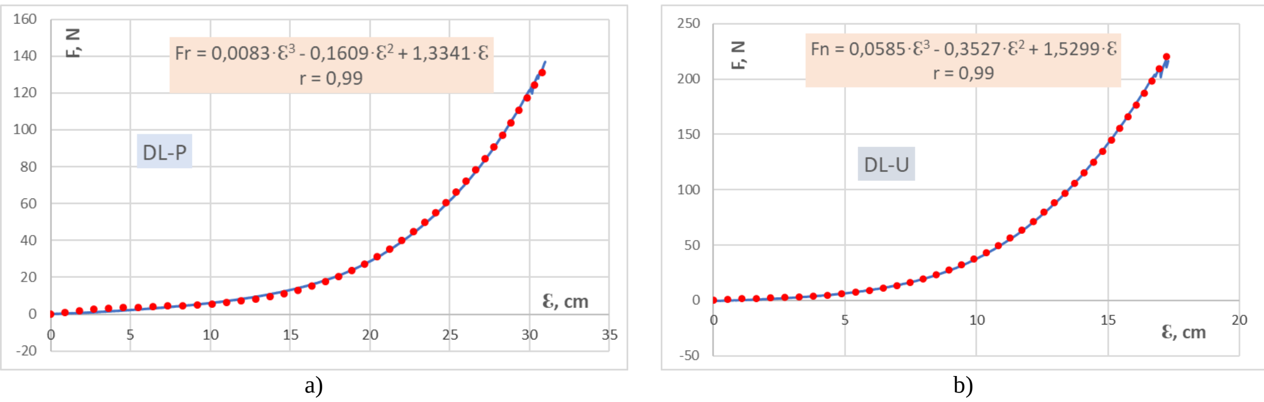


Fig.3 Measurement results of force/elongation till break of a plain weft-knitted fabric, processed using computer software. a) transversely - course direction; b) longitudinally - wale direction; F - force, N; Ɛ - elongation, cm; solid curve - obtained by measuring; dotted curve - obtained by mathematical interpolation.

After downloading and processing numerical data from the tensile tester's computer, which has registered the individual force-elongation measurement points, a mathematical regularity is revealed by a third-degree polynomial function that describes the change in force and elongation of the knitted fabric until breakage (Fig.3). The equations have the following forms, where the elongation Ɛ is expressed in cm.

For the course direction:

$$F_r = 0.0083 \cdot \varepsilon^3 - 0.1609 \cdot \varepsilon^2 + 1.3341 \cdot \varepsilon; \quad r = 0.99$$

For the wale direction:

$$F_n = 0.0585 \cdot \varepsilon^3 - 0.3527 \cdot \varepsilon^2 + 1.5299 \cdot \varepsilon; \quad r = 0.99$$

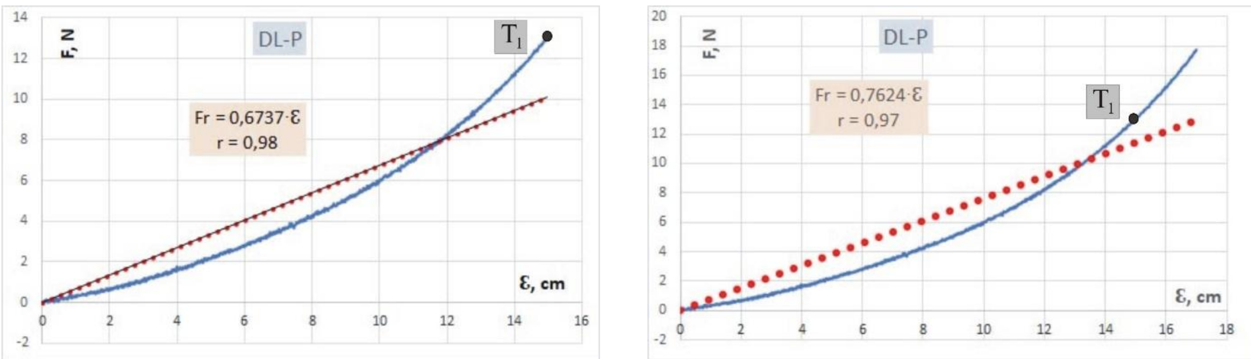
From the diagrams created from the computer recordings during the operation of the tensile stress tester (Fig.2), it can be seen that the highest force measured during the elongation of the knitted fabric corresponds approximately to the breaking force ($T_m \approx T_p$). At this point, the knitted fabric breaks instantly, as indicated by the diagram's sudden drop in force, and the majority of the curve runs parallel to the ordinate. Stretching the knitted fabric in the course direction (Fig.2a) results in an average maximum force of 137 N, which is the same as the breaking force of the knitted fabric, whereas stretching in the wale direction produces a significantly higher force of 190 N. The average shape of both curves is very well represented by a third-degree polynomial function, as evidenced by the high Pearson's correlation coefficient (r=0.99), with an average deviation of less than 5% between the theoretical and the measured data.

Analysis of the elongation results of the knitted fabric in the course direction

There are a variety of mathematical methods that can be utilized to identify the most crucial points on the force-elongation plot, specifically T_1, T_2, T_3, T_m, and T_p. Depending on the analysis criteria, these points can be interpreted either numerically or directly from the diagram. The diagram shows the elongation of the knitted fabric from the start to point T_1, with the first half being linear and illustrating the elastic deformation of the fabric when stretched in the course or transverse direction (Hook's law), as seen in Figs.2a and 3a. In order to stretch the knitted fabric within this range, a force of up to 10% of the maximum force is needed. The minimum acceptable Pearson correlation coefficient for this relationship between force and elongation is 0.98. This means that a certain degree of calculation error can be tolerated. The form of the first linear part of the curve, which describes the elastic deformation up to an elongation of 75%, or 15 cm, was revealed by mathematical analysis of the data in the first part of the diagram (Fig.4a). That is, the point T_1 has the coordinates $T_1(15; 13.2)$: 15 cm elongation and 13.2 N force amount. For example, if the elongation increases to 85 %, or 17 cm (Fig.4b) the correlation coefficient drops to less than 0.98, and the permissible error range increase, so that the range is discarded as unacceptable for the given criteria.

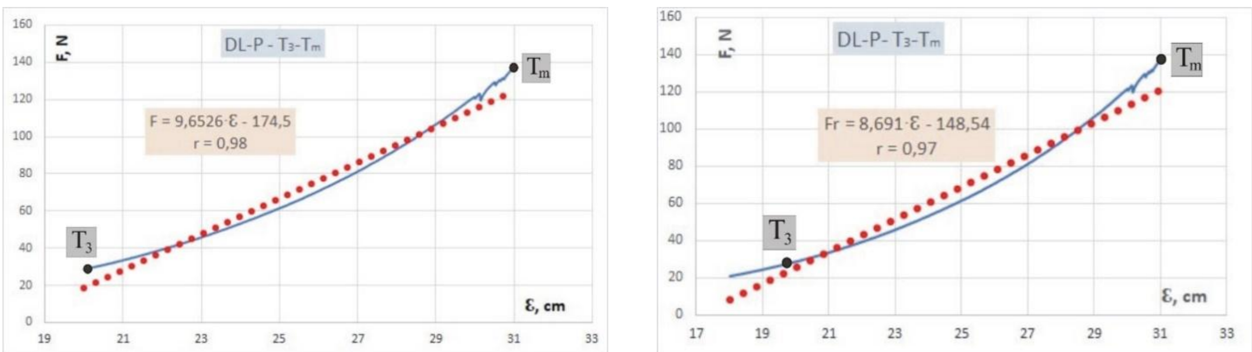
To determine the point at which permanent deformation begins during the uniaxial elongation of fabric, simply identify the point T_3. This can be done by fixing the point of the greatest observed force during elongation (T_m), which can be read from the force-elongation numerical record. The second curve line, which goes from point T_3 to point T_m, passes through this point. With a correlation coefficient greater than 0.98, point T_3 is reached when the knitted fabric is stretched by 20 cm, or 100% of the initial elongation length (Fig.5a). Below this limit, the correlation coefficient falls, and the lower limit is discarded (Fig.5b).

The coordinates of the most significant points in this investigation were determined by means of numerical



a) b)

Fig.4 Mathematical determination of the elastic deformation area (Hook's law – from point 0 to T_1) a) as it elongates in the course direction; a) the linear range extends up to an elongation of 15 cm or 75 % with a correlation coefficient of more than 0.98, b) for an elongation of the knitted fabric of more than 15 cm or 75 %, the correlation coefficient is less than 0.98; F - force, N, Ɛ - elongation, cm



a) b)

Fig.5 Mathematically determined region of plastic deformation of the knitted fabric (from T_3 to T_m) during elongation in the course direction; a) the linear range extends from 20 cm elongation or 100 % to the highest force when elongating or breaking the fabric with a correlation coefficient of over 0.98, b) if the knitted fabric is elongated by 18 cm or 85 %, the correlation coefficient is less than 0.98; F - force, N, Ɛ - elongation, cm records, diagrams, and correlation calculations:

T_i (elongation, cm; force, N): T_1 (15; 13.2), T_2 (17; 17.8), T_3 (20; 28.7) and T_m (31; 137).

T_i (elongation, %; force, N): T_1 (75; 13.2), T_2 (85; 17.8), T_3 (100; 28.7) and T_m (155; 137).

The correlation method was used to calculate the points T_1 and T_3, the point T_m was read from the numerical recording, and the point T_2 was estimated from the diagram based on the orientation of the points T_1 and T_3. All points could be calculated using an appropriate computer program, which should include criteria for calculation accuracy, i.e. the acceptable practical error, or estimated from the force-elongation diagram with specific errors.

In accordance with the objective of these investigations, the points determined in the force-elongation diagram of the knitted fabric are the basic determinants for calculating the partial and total work under the force-elongation curve, Table 1.

The length of the knitted fabric to be elongated between the clamps is 20 cm, while the sample is 5 cm wide. After 15 cm of elongation (or 75% or a relative elongation of 0.75), the fabric elastic deformation finishes at point T_1. A force of 13.2 N is required to stretch the knitted fabric to the end of the elastic deformation, which corresponds to around 10 % of the breaking force of the knitted fabric of 137 N. The work done during stretching a knitted fabric until the end of elastic deformation is 71 N·cm, which represents only 7% of the total work done before the fabric breaks (Fig.6).

After the end of the elastic deformation of the fabric, the elongation is continued by a further 2 cm or 10 % until the peak of the force-elongation curve is reached. At the apex of the curve, the total elongation of the knitted fabric is 85%, where a force of 17.8 N or about 13% of the breaking force of the knitted fabric was required. The section of the diagram between the end of the elastic deformation and the apex of the curve represents just 4% of the total work applied in stretching the fabric to breaking, which is equal to 31 N·cm.

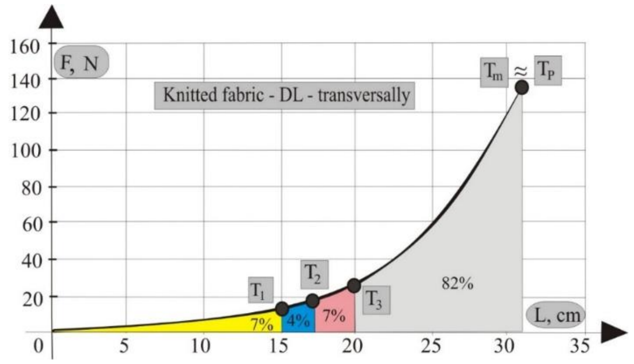


Fig.6 Percentage of the work done in certain parts of stretching the weft-knitted fabric until the break in the course direction or transversely; F - force, N, ε -elongation of the fabric, cm, T_1 - presumed end of elastic deformation, T_2 - vertex of the curve, T_3 - presumed onset of plastic deformation, T_m - maximum force, T_P - breaking point of the knitted fabric (material)

When the knitted fabric is stretched to its maximum elasticity, the yarn is pulled from the sides of the stitches and into the upper and lower curves of the stitch. At the highest point of the curve, the yarn is deemed to begin stretching structurally. By further stretching the knitted fabric by 3 cm or 15 %, point T_3 is reached, from which the plastic deformation of the knitted fabric begins. Before plastic deformation, the knitted fabric was stretched to 100% with a force of 28.7 N, which is 21% of the breaking force.

The work required to stretch the fabric from the apex of the curve to the onset of plastic deformation is 68 N·cm or 7% of the total work required to break the fabric. The stretch section of knitted fabric from the end of the elastic to the onset of plastic deformation is of interest for the production of garments with a compressive effect on the body. It is essential to compare the amount of stretch in knitted fabric, the elongation force, and the work done until plastic deformation begins. The knitted fabric can stretch up to 100%, with an elongation force of 21% of its breaking force. The work done is 18% of the total work. It is essential to note that the elongation part of knitted fabric from point T_3 to the break (point T_m) is often overlooked in garment manufacturing, and it is

Tab.1 The values of relevant parameters while stretching the weft-knitted fabric in the course direction to calculate the partial and total work under the force/elongation curve

Section	ε		ε_r	F_i, N	F_{ui}, %	W, N·cm	W_u, %
	%	cm					
0 - T_1	75	15	0.75	13.2	10	71	7
T_1 - T_2	10; (85)	2; (17)	0.85	17.8	13	31	4
T_2 - T_3	15; (100)	3; (20)	1	28.7	21	68	7
T_3 - T_m	55; (155)	11; (31)	1.55	137	100	785	82
Total						955	100

T_1, T_2, T_3, T_m - significant points in the force-elongation diagram of the knitted fabric, ε -elongation of the knitted fabric in the course direction, % and cm, ε_r - relative elongation of the knitted fabric, F_i - percentage of elongation force in the area of the boundary points, N, F_{ui} – percentage of elongation force in the area of the boundary points, %, W - work under (part of) the force-elongation diagram, N·cm, W_u - percentage of work in a specific section of the diagram, %

not taken into consideration in detail. However, it should be emphasized that if the knitted fabric is stretched further from point T_3, individual threads in the knitted structure begin to break, creating holes in the knitted fabric which represent a visible permanent deformation of the material. The overall elongation length of the knitted fabric in the course or transverse direction is 31 cm (155%), with a breaking force of 137 N. The work required to stretch the fabric in the region of permanent deformation (from point T_3 to T_m) is 785 N·cm or 82% of the total work required to break the fabric, which is 955 N·cm.

Analysis of the elongation results of the knitted fabric in the course direction

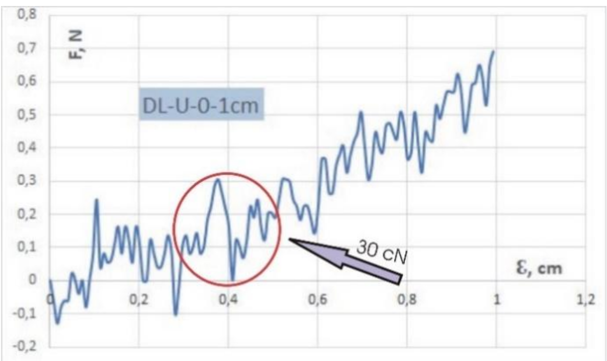
The knitted fabric was stretched until it broke in the course direction or along the fabric using the coordinates obtained as described above. The mentioned points for a sample of the elongation of the fabric have the following coordinate values:

T_i (elongation, cm; force, N): T_1 (4; 4.7), T_2 (7; 14.7), T_3 (10; 39.8) and T_m (16; 190).

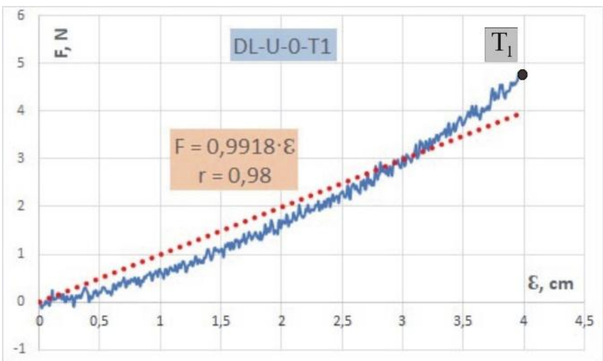
T_i (elongation, %; force, N): T_1 (20; 4.7), T_2 (35; 14.7), T_3 (50; 39,.8) and T_m (82; 190).

The samples to be elongated in the wale direction or along the knitted fabric had the same measurements as the samples to be stretched in the course direction. Observing the knitted fabric, it can be seen that it stretches 82% in the wale direction up to the maximum load force, which is much less than its elongation in the course direction (155%, elongation ratio: 1:1.89). When stretched in the wale direction, the fabric had a higher force of 190 N compared to 137 N in the course direction (force ratio: 1:1.39). When creating knitted outerwear that drapes freely over the body, the relationship between force and elongation in the fabric must be considered. The knitted fabric with a slightly denser structure is ideal for making light-weight clothing with pockets. The user can keep the essentials in the pockets without the material becoming severely deformed. It is very challenging to cut knitted fabric samples precisely between two wales on both sides without any interruption over the full length in the wale direction. If the stitch tightness in a wale is 14/cm, there are 280 threads that make up the same number of courses at a 20 cm distance between the stress tensile tester clamps. During the initial stretching of the knitted fabric, first the individual threads are pulled out from the edge stitches on both sides by a jerky motion, resulting in vibrations in the knitted fabric. These vibrations are recorded as sudden increases or decreases in force during the measurement (Fig.7a). Especially in this first part of the elongation of the knitted fabric, the fluctuations in relation to the amount of elongation force are large, so that they sometimes cause problems in determining the permissible error in the computer processing of the measurement data. After only 4 mm of stretching, Fig.7a displays a force variation of 0.3 N in the area. The region of elastic deformation, from 0 to point T_1, is also where these variations may be seen in Fig.7b. If the length of the elongation increases, the force of the elongation also increases, so that the registered change decreases. However, when the elongation length grows, so does the elongation force, therefore the variation detected for it decreases.

When stretching the knitted fabric in the wale direction, the elastic deformation ends after 4 cm (20%) stretching (Fig.7b, tab.2). This elongation requires only 4.7 N of force, which is approximately 2% of the maximum force produced during stretching. This elongation requires only 1% of the total work needed to break the knitted fabric, which corresponds to 7 N·cm of force. The vertex of the curve is reached when the fabric is stretched by a further 3 cm or 15%. In this scenario, the vertex of the curve is achieved at 7 cm (35% of elongation) with an applied force of 14.7 N, which is only 7% of the maximum force for stretching the knitted fabric. The work necessary to stretch the fabric from the end of



a)



b)

Fig.7 Force variations throughout the elongation of the knitted fabric in the region of elastic deformation: a) at initial stretching from 0 to 1 cm, b) in the region from point 0 to T_1

Tab.2 Values of significant parameters when stretching plain knitted fabric in the wale direction to calculate the partial and total work under the force-elongation curve

Section	ε		ε_r	F_i, N	F_{ri}, %	W, N·cm	W_u, %
	%	cm					
0 - T_1	20	4	0,2	4,7	2	7	1
T_1 - T_2	15; (35)	3; (7)	0,35	14,7	7	27	4
T_2 - T_3	15; (50)	3; (10)	0,5	39,8	21	76	9
T_3 - T_m	32; (82)	6; (16)	0,82	190	100	652	86
Total						762	100

T_1, T_2, T_3, T_m - significant points in the force:elongation diagram of the knitted fabric , ε - elongation of the knitted fabric in the wale direction, % in cm, ε_r - relative elongation of the fabric , F_i - value of elongation force in the region of boundary points, N, F_{ui} - value of the percentage of elongation force in the region of the boundary points, %, W - work under (part) of the force:elongation diagram, N·cm, W_u - percentage of work in an individual section of the diagram, %

the elastic deformation to the vertex of the curve is 27 N·cm, which is just 4% of the work required if the fabric is stretched to its maximum force. This guideline of 5% (1+4) produces close-fitting clothes with a low pressure impact (to 24 hPa or 18 mmHg). If the knitted fabric is stretched by a further 3 cm or a total of 10 cm (50%) from the start of elongation, plastic deformation of the knitted fabric begins. A force of 39.8 N is required to stretch the knitted fabric from the vertex of the curve to the start of plastic deformation, i.e. the work required is 76 N·cm, which is only 9% of the total work required to stretch the knitted fabric. Initially, the material deforms and individual threads break, resulting in a tensile force of 190 N and elongation of 82%.

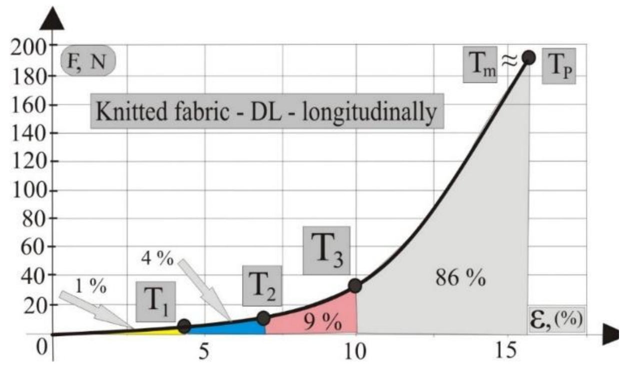


Fig.8 Percentage of the work done in certain parts of stretching the weft-knitted fabric until the break in the wale direction or longitudinally; F - force, N, ε -elongation of the fabric, cm, T_1 - presumed end of elastic deformation, T_2 - vertex of the curve, T_3 - presumed onset of plastic deformation, T_m - maximum force, T_p - breaking point of the knitted fabric

According to Fig.8, the maximum recorded force during the elongation process was 762 N·cm. Out of this value, 86% of the force was used to cause permanent deformation, while only 14% was used to deform the knitted fabric permanently.

4.3. Analysis of the elongation results of plain double-faced cotton fabric

An unfinished double-faced knitted fabric was chosen for the analysis, which was also knitted from a 20 tex single cotton yarn. The knitted fabric has a mass per unit area of 170 g/m^2 and a volume mass of 0.25 g/cm^3 and is used to make winter undershirts for men and sometimes summer T-shirts for women. The basic principles of analysing the structure and elon-gation of the knitted fabric on the tensile stress tester until breakage are the same as for weft knitted fabrics. The basic principles of analysing the structure and elon-gation of a knitted fabric using a tensile stress tester till breaking are the same as for weft knitted fabrics. This sort of double-faced knitted fabric has a much higher elongation to break in the course direction than jersey. Therefore, the distance between the clamps of the tensile testing machine during stretching was 10 cm, so that the initial length of the sample to be elongated was 10 cm. The maximum force recorded by stretching the knitted fabric until it breaks in the course direction is 95 N, but in the wale direction, it is substantially greater at 444 N. When stretched to its maximum force or until it begins to break, the knitted fabric stretches up to 370% in the course direction, whereas it only stretches up to 50% in the wale direction (Fig. 9).

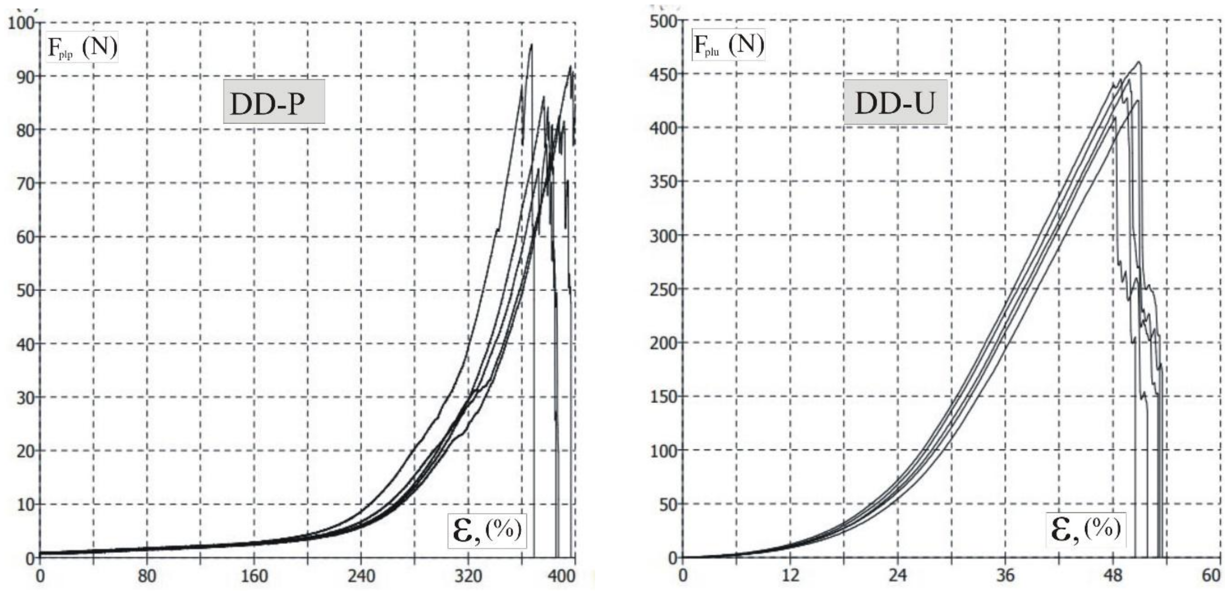
As in the previous example, by downloading the numerical recordings from the computer that regis-tered the individual points of the force:elongation measurement and processing them mathematically, a mathematical regularity is obtained that is described by a third and fourth degree polynomial function that describes the change in the force and elongation of the knitted fabric up to the highest load point at which the knitted fabric breaks, Fig.10.

The equations are next:

For the course direction:

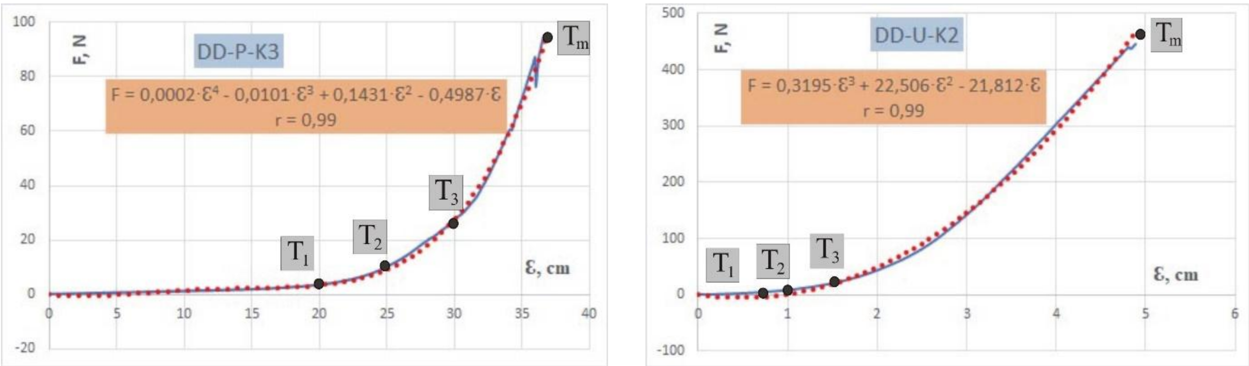
$$F_r = 0.0002\cdot\varepsilon^4 - 0.0101\cdot\varepsilon^3 + 0.1431\cdot\varepsilon^2 + 0.4987\cdot\varepsilon;$$

r = 0.99



a) b)

Fig.9 Force-elongation diagram recorded by the computer of the tensile stress tester until the break of the unfinished double-faced weft knitted fabric, a) transversely - course direction, b) longitudinally - wale direction; Ɛ - elongation of the fabric, %, F - elongation force of the fabric, N



a) b)

Fig.10 Results of measurement of force/elongation until the break of a plain double-faced weft-knitted fabric, processed in a computer program: a) transverse - course direction, b) longitudinal - wale direction; Ɛ - elongation of the knitted fabric, cm, F - force, N; solid curve - obtained by measurement, dotted curve - obtained by mathematical interpolation

For the wale direction:

$$F_n = 0.3195 \cdot \varepsilon^3 + 22.506 \cdot \varepsilon^2 - 21.812 \cdot \varepsilon; \quad r = 0.99$$

The equations appear difficult at first glance. However, they are simple and acceptable to modern technologists who use computer processing, especially when analysing similar knitting structures and then designing new structures based on the criteria provided. The elongation of the knitted fabric in the course or transverse direction is significantly greater than in the wale direction, so it is better described by a fourth-degree polynomial equation, whereas the elongation of the knitted fabric in the wale direction or along the knitted fabric is lower, so it is described by a third-degree equation.

After analysing the numerical data, diagram, and correlation calculations, the most important coordinates for stretching the double-faced knitted fabric in the course direction are:

T_i (elongation, cm; force, N): T_1 (20; 3.5), T_2 (25; 10.1), T_3 (30; 27.2) and T_m (37; 95).

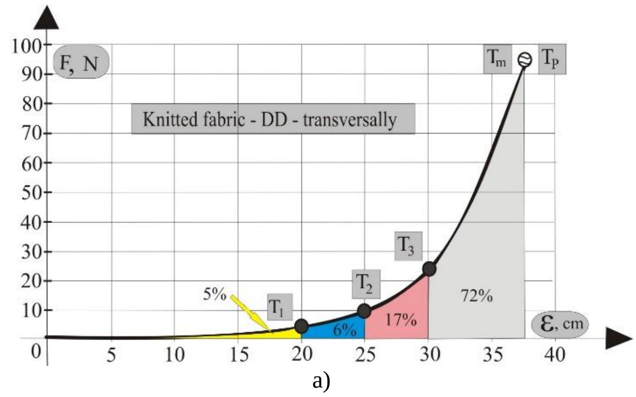
T_i (elongation, cm; force, N): T_1 (200; 3.5), T_2 (250; 10.1), T_3 (300; 27.2) and T_m (370; 95).

When a plain double-faced weft-knitted fabric is stretched in the course direction, it exhibits high elongation until it reaches its elastic limit and breaks (Tab.3, Fig.11). The investigation was conducted on a knitted fabric sample that closely resembled this type of structure produced from a 20 tex cotton yarn. The elongation from the beginning to the end of the elastic deformation is 200% or 54% of the total elongation, requiring a force of only 3.5 N, which corresponds to about 4% of the highest force registered when stretching the knitted fabric (95 N).

Tab.3 Values of significant parameters when stretching double-faced knitted fabric in the course direction to calculate the partial and total work under the force-elongation curve

Section	Ɛ		$Ɛ_r$	F_i, N	F_{ui}, %	W, N·cm	W_u, %
	%	cm					
0 - T_1	200	20	2.0	3.5	4	26	5
T_1 - T_2	50; (250)	5; (25)	2.5	10.1	11	30	6
T_2 - T_3	50; (300)	5; (30)	3.0	27.2	28	90	17
T_3 - T_m	70; (370)	7; (37)	3.7	95	100	370	72
Total						516	100

T_1, T_2, T_3, T_m - significant points in the force-elongation diagram of the knitted fabric , Ɛ - elongation of the knitted fabric in the course direction, % and in cm, $Ɛ_r$ – relative elongation of the fabric , F_i - value of elongation force in the region of boundary points, N, F_{ui} - value of the percentage of elongation force in the region of the boundary points, %, W - work under (part) of the force-elongation diagram, N·cm, W_u - percentage of work in an individual section of the diagram, %



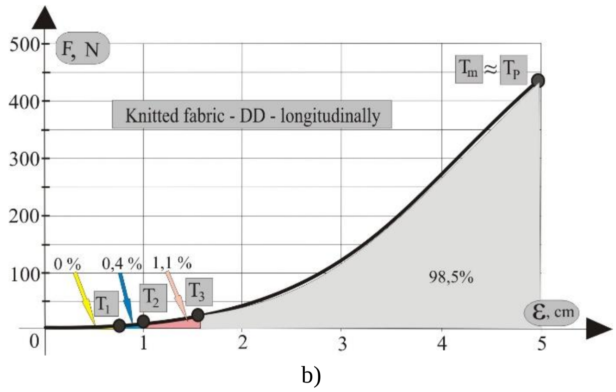


Fig.11 Percentage of the work done in certain parts of stretching the double faced fabric until the break; a) in the course direction or transversally, b) in the wale direction or longitudinally; F - force, N, Ɛ -elongation of the fabric, cm, T_1 - presumed end of elastic deformation, T_2 - vertex of the curve, T_3 - presumed onset of plastic deformation, T_m - maximum force, T_p - breaking point of the knitted fabric

The elongation of the knitted fabric in the course direction with modest force is suitable for making comfortable clothing for stouter people, such as undershirts, panties, pyjamas, and nightgowns. The work invested in this first part of stretching the knitted fabric, i.e. from point 0 to T_1, is 26 N·cm, which is only 5% of the total work needed to tear this kind of knit (516 N·cm), Fig. 11a. With further loading, the force increased to 10.1 N, stretching the fabric by 50% (5 cm) to reach the vertex point of the force/elongation curve (T_2). The work from T_1 to T_2 is 30 N·cm and accounts for 6 % of the total work. When the force is increased to 27.2 N, the fabric stretches 50% (or 5 cm) and permanent defor-mation occurs (point T_3). To overcome the resistance of the fabric stretching from the curve vertex to the onset of permanent deforma-tion (from point T_2 to T_3), 90 N·cm of work was done, which is 17% of the total work. The knitted fabric was stretched three times, from point 0 to T_3, up to 300% of its original length until it reached a point of permanent deformation. It required a total work investment of 146 N·cm, which accounts for 28% of the total work required to break such knitted fabric. Similarly, the force applied during this process was 27.2 N, which makes up 28% of the total force required to break the fabric. After being stretched with additional force, the knitted fabric elongated by a total of 370% before breaking. The greatest amount of force recorded during the process was 516 N·cm. It is advisable that this sort of the knitted fabric, designed for corpulent and physically powerful individuals as underwear, should not be produced using yarns finer than 20 tex. This is because using finer yarns could lead to tearing of the fabric during dressing and undressing. It is recommended to use coarser yarns like 22, 25 or 28 tex to produce knitted underwear for corpulent persons.

As with the previous examples, the most significant points when stretching the double-faced weft-knitted fabric in the wale direction can be determined through a numerical record, a diagram taken from the computer of the tensile stress tester, and correlation calculations. These points can be identified by their respective coordinates:

T_i (elongation, cm; force, N): T_1 (0.7; 4.2), T_2 (1; 8.4), T_3 (1.5; 20.4) and T_m (5; 444).

T_i (elongation, cm; force, N): T_1 (7; 4.2), T_2 (10; 8.4), T_3 (15; 20.4) and T_m (50; 444).

This knitted fabric sample is unique due to its elongation in both course and wale directions (Tab.4).

Tab.4 Values of significant parameters when stretching double-faced knitted fabric in the wale direction to calculate the partial and total work under the force-elongation curve

Section	ε		ε_r	F_i, N	F_{ui}, %	W, N·cm	W_u, %
	%	cm					
0 - T_1	7	0.7	0.07	4.2	0.9	0	0
T_1 - T_2	3; (10)	0.3; (1)	0.1	8.4	1.8	2	0.4
T_2 - T_3	5; (15)	0.5;(1.5)	0.15	20.4	4.5	7	1.1
T_3 - T_m	35; (50)	3.5; (5)	0.5	444	100	655	98.5
Total						665	100

T_1, T_2, T_3, T_m - significant points in the force-elongation diagram of the knitted fabric, ε - elongation of the knitted fabric in the wale direction, % and in cm, ε_r – relative elongation of the fabric, F_i - value of elongation force in the region of boundary points, N, F_{ui} - value of the percentage of elongation force in the region of the boundary points, %, W - work under (part) of the force-elongation diagram, N·cm, W_u - percentage of work in an individual section of the diagram, %

The plain knitted fabric can elongate up to 155% in the course direction and 82% in the wale direction. The ratio of elongation in the wale and course direction is 1:1.89. However, in practice, it has been found that this type of knitted fabric can be stretched twice as much in the wale direction. This feature makes it suitable for the production of short-sleeved summer T-shirts for warmer weather. The elongation to breakage in the course direction of this knitted fabric is 370%, whereas in the wale direction it is only 50%. The ratio of elongation in the wale to course directions is 1:7.4. Although it is often said that the elongation of this fabric type is four times greater in the course direction than in the wale direction. When a double-faced knitted fabric is stretched in the wale direction, the fabric structure resists tensile force, indicating that the elastic deformation area of the fabric stops after just 7% stretching. A force of 4.2 N is required for this amount of stretching, but the work involved is negligible. Therefore, it is classified as insignificant (amount 0). When the tensile force is increased to 8.4 N, the knitted fabric stretches by an additional 3%, reaching point T_2 on the vertex of the curve. However, only 0.4% of the total work involved in stretching the knitted fabric until it breaks comes from this part, which requires only 2 N·cm of work. If the knitted fabric is stretched by a further 5%, plastic deformation of the knitted fabric begins. Currently, the tensile force exerted on the knitted fabric is 20.4 N, which is only 4.5% of the maximum force required to break it. The amount of work involved in this process is 7 N·cm, which represents only 1.1% of the total work required to break the fabric. Thus, the work required to stretch the knitted fabric to the point of elastic deformation is negligible. On the other hand, the work needed to stretch the fabric to the point of permanent deformation is 7 N·cm, which is only 1.5% of the total work required to break the fabric. If the tensile force is increased further, the knitted fabric will stretch by 35% (or 3.5 cm) at break, with a maximum force of 444 N, 50% elongation, and a total work of 665 N·cm. It is important to note the unique properties of a knitted fabric. Specifically, the amount of work required to stretch the fabric to its elastic limit (from point 0 to T_1) is negligible. The work required in the elastoplastic range (from point T_1 to T_3) is also minimal, comprising only 1.5% of the total work. However, the work required to stretch the knitted fabric in the plastic deformation region is significant, amounting to 655 N·cm or 98.5% of the total work required to break the fabric in the wale direction. This information is significant in concluding that the knitted fabric will stretch considerably in the course direction during use but will not shorten significantly in the wale direction. This suggests that the knitted fabric is well-suited for making underwear or similar products for more corpulent individuals, as mentioned earlier. Recently, rotor and aerodynamic yarn technologies have become popular due to their unique structure and resulting tensile and other qualities, which differ from standard yarns spun on ring spinning machines. When producing knitted fabrics for specific garments, it is crucial to choose the right type of yarn. The selection of yarn plays a significant role in determining the tensile strength of the fabric, which in turn affects its performance characteristics. Thus, careful consideration must be given to the choice of yarn to ensure optimal results.

5. Conclusion

In current technological processes, the design of a knitted fabric is no longer exclusively based on the basic characteristics of the yarn and the knitted fabric breaking or stretching strength, but also on additional criteria such as the work required in stretching and breaking the knitted fabric. Not only does the overall amount of work necessary to break the knitted fabric matter but so does the work on individual stretching zones, especially when the cloth starts to deform permanently. The quantity of work required is frequently less when producing traditional clothing that falls down the body or fits loosely than when producing clothing that fits the body compressively. For this reason, the above-mentioned research is very often used in the manufacture of leisure clothing, preventive compression clothing (elastic women's underwear, especially for fuller people, stockings) and therapeutic compression clothing (compression stockings, corsets, orthoses, elastic clothing for the disabled). The analysis of the elongation of finished plain knitted fabrics and double-faced knitted fabrics made from 20 tex cotton yarns was conducted for the purposes of this study. In the wale direction, the elongation till break of plain weft-knitted fabric measured 82%, while in the course direction or transversely, it reached 155%, resulting in an elongation ratio of 1:1.89 in both directions. During the process of stretching the knitted fabric along the course direction towards the curve's vertex 11% of the work was involved, while the remaining 89% of the work occurred from the curve's vertex until the fabric ultimately broke.

Plain double-faced knitted fabrics exhibited substantially distinct tensile features from plain weft-knitted fabrics. The elongation of the knitted fabric in the course direction until the break was as much as 370%, and in the wale direction 50%, where the elongation ratio in the wale direction was 1:7.4; the elongation of the double-faced fabric in the wale direction was 2.4 times greater than that of the weft-knitted fabric, and the elongation in the wale direction was 39% lower. It is worth noting that the percentage of work necessary to stretch the double-faced fabric in the course direction up to the vertex of the curve was 11%, much like the weft-knitted fabric, although it was lower for the double-faced fabrics.

The data gathered on the elongation characteristics of knitted fabrics have a significant impact on their application in the production of certain knitted items. The degree of elongation in the knitted fabric may be modified during finishing. The new techniques for developing the structures of knitted fabrics and garments attempt to combine more influencing aspects that impact the high-quality practical application of the finished products, with the approach focused on generating personalized clothing.

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