The process of stretching double-knit fabrics beyond their limits for the production of lightweight clothing, using yarns with varying raw material compositions and spinning processes

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Professional paper**

The design, production, and analysis of seven samples of plain double-knit fabrics, tailored for underwear and lightweight garments, employing 20 tex yarns were studied. The primary yarn is made of cotton that was spun using the ring spinning process. Three viscose yarn samples were created, along with three modal yarn samples, using ring spinning, rotor spinning, and air-jet spinning processes. The basic characteristics of the tensile properties of yarns and the parameters of the knitted fabric structure that are significant for the tensile properties of knitted fabrics are listed. Samples of strip knit fabric were elongated until they broke along the courses and wales. The force-stretch diagram highlights four key points that are essential for the partial analysis of the tensile properties of knitted fabrics, which include: 1. end of elastic deformation of the knitted fabric, 2. vertex of the curve, 3. beginning of plastic deformation of the knitted fabric and 4. point of maximum measured tensile force or break point of the fabric. The calculations for both partial and total work during the stretching of the knitted fabric until its breaking point were conducted based on the aforementioned points..

Keywords: *knitted fabric; weft knitted; double knit fabric; plain; yarn; cotton; viscose; modal; spinning processes; stretching; and work of rupture*

Stručni rad**

Uloženi rad pri istezanju do prekida desno-desnih pletiva lagane odjeće izrađenih pređama različitih sirovinskih sastava i procesa predenja

S pređama finoće 20 tex projektirano je, izrađeno i analizirano sedam uzoraka glatkog kulirnog desno-desnog pletiva namijenjenog rublju i laganoj odjeći. Temeljna pređa je pamučna ispredena u procesu prstenastog predenja. Tri uzorka su izrađena s viskoznim i tri uzorka s modalnim pređama koje su predene pored prstenastog i u procesu rotorskog te aerodimamičkog predenja. Navedene su osnovne značajke vlačnih svojstava pređa te parametri strukture pletiva koji su značajni za vlačna svojstva pletiva. Trakasti uzorci pletiva su istezani do prekida u smjeru redova i nizova očica. U dijagramu sila - istezanje određene su četiri značajne točke za parcijalno izučavanje vlačnih svojstava pletiva, a to su: 1. kraj elastične deformacije pletiva, 2. tjeme krivulje, 3. početak plastične deformacije pletiva i 4. točka najveće izmjerene sile istezanja ili točka prekida pletiva. Pomoću navedenih točaka izračunat je parcijalni i ukupni rad pri istezanju pletiva do trganja.

Ključne riječi: *pletivo; kulirno; desno-desno; glatko; pređa; pamuk; viskoza; modal; postupci predenja; istezanje; rad do prekida*

1. Introduction

Every material, such as textile fibres, possesses unique characteristics that make it suitable for the manufacturing of specific products. The cultivation of natural fibers is a long-term process and is usually related to a one-year period. In numerous countries it is linked to social policy and the customs of daily life in specific areas [1,2]. Artificial or chemical fibers are manufactured according to different criteria, resulting in desired structures that will have pre-defined chemical, physical and mechanical properties [3,4]. The ring spinning process is employed in conventional technological processes to create yarns of varying structures and tensile properties from natural fibers. Natural fibers are non-uniform in length and cross-section, and thus in mass and tensile properties. The irregularity of the fibers during the ring spinning process leads to inconsistencies in the yarn, resulting in significant challenges during subsequent processing due to the presence of thick and thin sections in the yarn, which causes irregular stretching. Frequent neps and knots in the yarn do not allow for the production of high-quality fabrics [5,6].

In today's society, there is a growing intolerance for deviations from established standards, as products are anticipated to exhibit uniformity in design, provide comfort and functionality, possess an appealing appearance, and require minimal care. Chemical fibres are much more uniform, so they can be used to create a more uniform yarn structure, and thus a more uniform fabric (knitted or woven). Fibers produced from natural polymers, including lyocell, viscose, and modal, exhibit considerable resemblance to cotton fibers, which leads to their common use as substitutes. The uniformity of these fibers has led to the evolution of rotor and air-jet spinning methods, which attain production efficiencies that are considerably higher than those achieved through ring spinning. Yarns produced through contemporary spinning techniques exhibit a notably consistent structure, enabling the creation of more uniform knitted and woven fabrics. Synthetic polymer-based chemical fibers, such as polyester (PES), polyamide (PA), and elastane (EL), are frequently utilized in the manufacturing of multifilament yarns. These yarns are essential in creating elastic garments, including women's underwear, active wear, swimwear, and both preventive and therapeutic compression stockings. Elastic knitted fabric is essentially produced by interlacing two threads while creating a course of the knitted material. One variant is primarily a basic multifilament, usually crafted from polyester (PES) or polyamide (PA), and it can sometimes include natural fibers. The other variant is elastane. By combining multifilament yarns made from synthetic polymers like PES, PA, and EL, modern elastic knitted structures are formed. These structures are used to create various garments that feature a light compression fit against the skin, usually up to 15 hPa, making them comfortable for wear.

Using cotton single yarns of fineness 12 to 17 tex, a very fine plain double-knit fabric with a basic weight of 60 to 120 g/m2 is produced. This sort of knitted fabric is commonly used to produce high-quality women's lingerie. Yarns with a fineness ranging from 17 to 22 tex result in a denser knitted fabric, weighing between 100 and 160 g/m^2, commonly utilized in the manufacturing of traditional women's lingerie. Fabrics knitted from yarns with a fineness of 17 to 22 tex yield a denser material, with weights varying from 100 to 160 g/m^2, and are commonly used in the design of conventional women's lingerie. Cotton knits used to make underwear for colder climates are produced as well with single, somewhat coarser yarns with counts ranging from 22 to 28 tex, and in some circumstances up to 36 tex. This type of knitted fabric has a mass per unit area that ranges from 200 to 350 g/m^2. Consequently, the conventional processes for manufacturing lingerie predominantly utilize cotton single yarns with a fineness between 12 and 36 tex, which demonstrate an elongation at break of 4 to 6%. Knitted fabrics suitable for high-quality, lightweight outerwear designed for warmer climates can be produced using cotton plied yarns, such as 10 tex x 2, 12 tex x 2, 14 tex x 2, and 17 tex x 2. The elongation to break of plied yarns is less than that of single yarns. Such knitted materials are appropriate for the sophisticated application of current textile printing technologies, retaining their quality even after multiple wash cycles. The fineness and elongation at break of the yarn are two fundamental criteria used when controlling the machine to create a certain knitting structure. The essential principle of finishing is suitable for all forms of cotton knitted fabric structures. To achieve the desired results, cotton knitted fabrics are finished with particular techniques that align with the specific requirements and purposes of their applications [10,11].

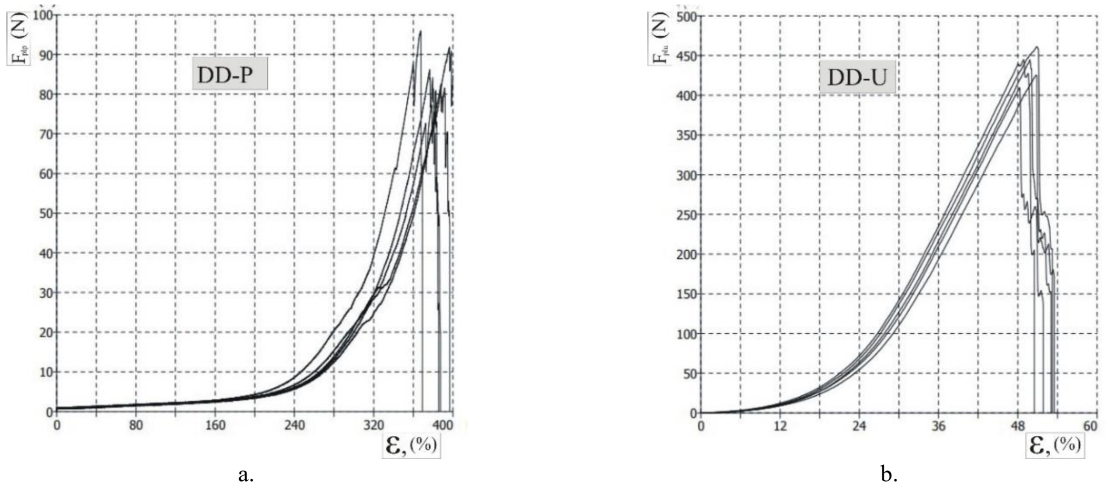
Because of the rising challenges and expense of cultivating and producing cotton fibers, artificial fibers produced from natural polymers have increasingly replaced or substituted cotton fibers for several decades. Alongside the introduction of new fibers, contemporary yarn manufacturing techniques are being implemented, including rotor and air-jet spinning methods. New spinning techniques are employed in modern processes, which significantly alter the structures and tensile properties of the yarns when compared to those produced by the traditional ring spinning processes. Yarns produced from synthetic fibers derived from natural polymers through rotor and air-jet spinning exhibit greater elongation at break and, in numerous instances, enhanced stiffness compared to cotton yarns. These two elements play a crucial role in determining the structure of the knitted fabric when working with these yarns. Based on the conducted research and practical experience, it is not possible to obtain the same knitted structure with the aforementioned yarns of the same fineness [12-14]. Differences in structures increase even after the knitting process. This article aims to investigate the tensile properties of plain double-knit fabric textiles produced using yarns made from diverse raw material compositions and spinning methods. The primary focus of the analysis is on quantifying the work involved in stretching specific important segments of the knitted fabric until it reaches its breaking point.

2. Tensile properties of fine double weft knit fabrics

Fine double weft knit fabrics, characterized by a mass per unit area of 150 to 250 g/m^2, and are often used in the production of men's underwear and lightweight outerwear for women and children, making them suitable for warmer weather. In most cases, they are made from cotton yarns with a fineness of 20 tex, with a mass per unit area of around 170 g/m^2. The yarns were made in the process of ring spinning and have an elongation at break of about 5%. The elongation of knitted fabrics to break in the transverse direction or in the course direction is about 400%, and in the longitudinal direction or in the wale direction is significantly lower and amounts to about 50%, Fig.1. [11,15].

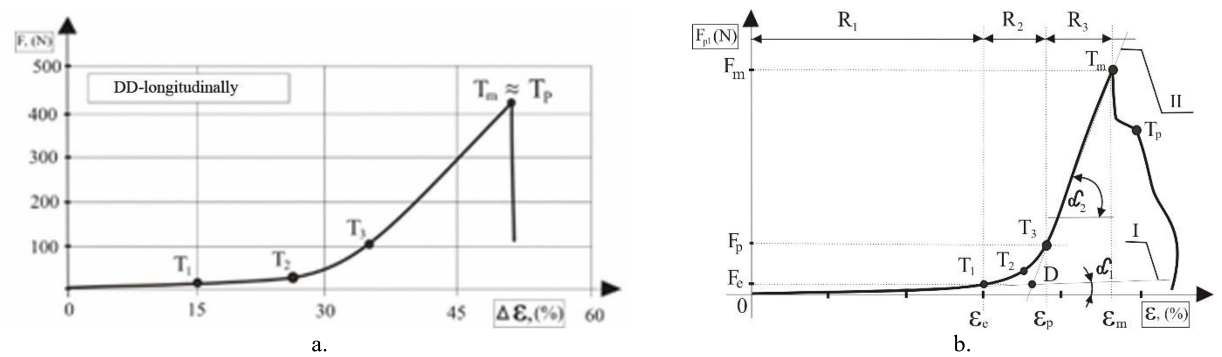
The production of knitted fabrics utilizing yarns created through rotor or air-jet spinning methods, combined with lyocell, viscose, modal, or other chemical fibers derived from natural polymers, results in the formation of similar yet often unique structures, along with varying tensile properties of the fabrics. An examination of the force-elongation diagrams for the various samples of the knits reveals distinct regions that can be further analyzed in relation to the intended use of the product, as illustrated in Fig.2 [16]. The primary region commences at the beginning of elongation and terminates at the end of the linear section of the diagram, which is designated as point T$_1$. In this region, with a small increase in force, a large elongation is achieved, especially in the course direction. The first portion of the diagram is generally viewed as representing the elastic deformation of the knitted fabric, signifying that upon relaxation, the fabric returns to its original configuration, as described by Hook's law. Beyond this region, the curve begins to round slightly, resulting in a rise in force and a reduction in the intensity of stretching (the interval from point T$_1$ to point T$_3$). This is an elasto-plastic region [17,18]. It is assumed that in this region the elongation of knitted fabrics and yarns occurs in their elastic deformation. Between point T$_3$ and the maximum force observed during the stretching process, the relationship between force and elongation continues to be linear. However, the force increases at a greater rate than the elongation, leading to a steeper slope than that of the first line illustrating the elastic deformation of the knitted fabric (Fig.1). It is assumed that permanent deformation of the knitted fabric begins at point T$_3$.

When dealing with plain knitted fabrics, significant breaking typically happens at the maximum measured elongation force, which contributes to the complexity of the standard's requirements [19]. There are situations where, after reaching the maximum measured force, the stretching continues to progress while the force diminishes gradually. Consequently, this results in a difference between the maximum measured force and the breaking force of the knitted fabric. These diagrams are typical of plated knitted fabrics, where the courses are created using two yarns with varying



a. b.

Fig.1 Force diagrams recorded from the tensile strength tester - elongation at break of the unfinished plain double weft knit fabric, a) transversely - course direction, b) longitudinally - wale direction; F - force, N - elongation, %.



a. b.

Fig.2 Force diagrams – elongation of the fabric until breaking: a) characteristic points in the diagram, b) difference between the maximum measured force and the breaking force of the fabric; F - force, N, Ɛ - elongation, % ; T_1 – end of plastic deformation, T_2 – point of the curve vertex, T_3 – onset of plastic deformation, I – first straight line passes through points 0 and T_1, II – second straight line passes through points T_3 and T_m

with differing raw material compositions and varying elongation properties that lead to breaking. The figure features two lines connected by a curved segment (extending from point T_1 to point T_3), which illustrates the elastoplastic deformation of the knitted fabric. Between these two points, i.e. the end of elastic deformation of the knitted fabric (point T_1) and the beginning of plastic deformation of the knit (point T_3), there is the vertex of the curve (point T_2).

In the case of specific knitted structures or more complex analyses, the diagram is segmented into two sections. The initial section begins at the start of elongation and concludes at the vertex of the curve, covering the interval from point 0 to T_2. The following section runs from the vertex of the curve to the maximum force recorded during the stretching or breaking of the knitted fabric which is from T_2 to T_m. In the production of traditional clothing that falls casually down the body or has a somewhat compressive fit, the initial half of the figure, from the start of the elongation to the curve vertex, is interesting. In a more comprehensive study, the figure is broken into four sections. The first part focuses on the elastic deformation of the fabric, specifically from 0 to T_1. The second section represents the initial segment of the elastoplastic region, specifically from point T_1 to T_2. The third section ranges between points T_2 and T_3, incorporating the latter half of the elastoplastic region. The fourth region encompasses the elongation of the knit from the beginning of permanent deformation to the highest force registered during stretching or breaking the knitted fabric, i.e. from point T_3 to T_m. The various points on the force-elongation diagram can be identified through multiple methods and criteria, which will vary based on the research objectives and the intended use of the product. The aforementioned points delineate the boundary regions within which the applied work is assessed during the failure stretching of the knitted fabric [20-22]. Analyzing the work performed in various sections of knitted fabric produced from yarns spinning techniques yields valuable insights into how these factors affect the tensile properties of the fabric, which are crucial for determining product quality.

3. Experimental part

Yarns of the same fineness and different structures, and thus tensile properties, were selected for experimental research. The chosen yarns were used to manufacture samples of plain double weft knitted fabrics. In this kind of fabric, a single thread is responsible for forming a course of stitches. All samples were knitted under the same conditions, i.e. the machine was not regulated when knitting with individual yarns. Each yarn was used to knit about 10 meters of fabric. All assessments and measurements were conducted on a relaxed, unfinished fabric. The purpose of this research was to analyze the effect of yarn characteristics, which are uniform in fineness yet distinct in structure, on the tensile properties of knitted fabrics. The purpose of this research was to analyze the effect of yarn characteristics, which are uniform in fineness yet distinct in structure, on the tensile properties of knitted fabrics. The study particularly concentrated on the work required in individual sections when the knitted fabric is stretched to failure.

3.1. Yarn properties

For this study, three types of fibers were chosen: viscose, modal, and cotton, and single yarns with a nominal fineness of 20 tex were spun using three different processes: ring, rotor, and air-jet. All yarns are meant for the manufacturing of weft knitted fabric, which is used to make lightweight knitted garments. The basic yarn used was cotton, made only in the ring spinning (R-P) process. The breaking force of this yarn was 302 cN, with an elongation at break of 3.7% (Tab.1).

Tab.1 Tensile characteristics of yarns with a nominal fineness of 20 tex produced by different spinning processes

Yarn	Breaking force, *cN*	Elongation at break, *%*	Breaking strength, *cN/tex*	Rupture work, *cN·cm*
V-R	312±5	13.8±0.3	15.6±0.5	1379±49
V-OE	267±9	10.5±0.3	13.4±0.4	919±50
V-AJ	286±9	12.3±0.4	14.3±0.5	1075±59
M-R	487±10	10.2±0.2	24.3±0.5	1436±47
M-OE	325±9	7.2±0.2	16.3±0.5	738±32
M-AJ	406±10	9.0±0.2	20.3±0.5	1067±42
P-R	302±5	3.7±0.1	15.1±0.3	301±10

V – viscose, M – modal, P – cotton,
R – ring spinning process, OE – OE rotor spinning process,
AJ – air-jet spinning process

Viscose and modal yarns were produced in all three procedures. When analyzing the basic parameters of yarn elongation at break, it is noticeable that all yarns differ from each other. The breaking force for viscose yarn produced by the rotor spinning process (V-OE) is the lowest at 267 cN, while the highest breaking force, measured at 487 cN, is attributed to yarn made from modal fibres using the ring spinning process (M-R). The minimum elongation at break recorded is 3.7%, observed in cotton yarn (P-R), while the maximum elongation at break is 13.8%, noted in viscose yarn (V-R). Both types of yarn are produced using the ring spinning method. A breaking strength of 13.4 cN/tex represents the lowest measurement, identified in viscose yarn spun using the rotor spinning process (V-OE). On the other hand, the highest breaking strength, which is almost twice that amount at 24.3 cN/tex, was recorded in modal yarn spun through the ring spinning process (M-R). Cotton yarn has the lowest work to rupture at 301 cN/cm, indicating minimal elongation at break and breaking force. The rupture work of cotton yarn is recorded at 301 cN/cm, which reflects its minimal elongation at break and a lower breaking force. The highest measured rupture work is 1436 cN/cm and was registered with the modal yarn spun in the rotor spinning process, where this yarn also had the highest breaking force, and the elongation was over 10%.

3.2. Properties of knitted fabrics

The knitting machine was prepared and regulated in accordance with the qualities of the cotton yarn, and this procedure was followed for all samples. All knitted fabrics were produced on a circular double bed knitting machine featuring an E17 gauge, utilizing 8 knitting systems and 432 x 2 needles, operating at a needle rotation speed of 45/min. At the point of entry into the knitting system, the yarn exhibited a tensile force of 3±1 cN. Four structural parameters are outlined that characterize the resulting knitted fabric and are significant for the assessment of tensile characteristics. The primary and most critical parameter is the mass per unit area of the unfinished knitted fabric, which for the produced samples ranges from 127 to 165 g/m^2, as shown in Tab.2. The first crucial aspect to note is that yarns spun in the ring spinning process create the maximum mass per unit area of knitted fabric, regardless of fibre origin. The yarns produced via the rotor and air-jet spinning processes achieve a similar outcome, although they exhibit a considerably lower mass per unit area. The yarns produced using the rotor and air-jet spinning techniques yield a greater mass per unit area, which is accompanied by an increase in the shrinkage of the knitted fabric. This effect is particularly pronounced in the course direction of the stitches, following the removal of the fabric from the knitting machine and its subsequent relaxation. Yarn stiffness is the primary source of variable shrinkage of knitted fabrics after removing from the machine and relaxing, which results in varying widths of knitted fabrics produced on the same machine.

Tab.2 Structure parameters of plain double weft knitted fabrics made from yarns of nominal fineness 20 tex spun using different types of tensile properties and spinning processes

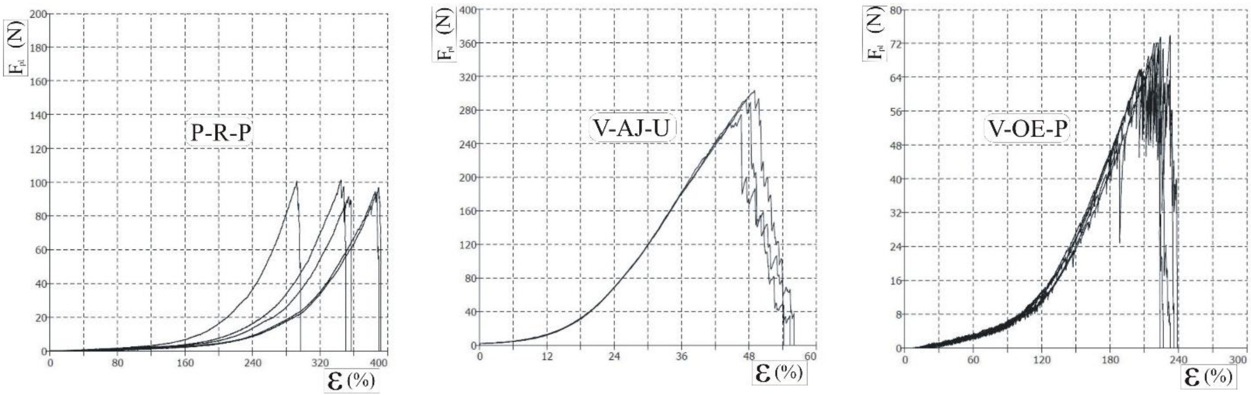
Yarn	Mass per unit area, *g/m^2*	Volumetric mass, *g/cm^3*	Thickness of knitted fabric, *mm*	Thread consumption in a stitch, *mm*
V-R	165±5	0.26±0.01	0.63±0.02	3.12±0.02
V-OE	131±3	0.22±0.02	0.59±0.01	3.10±0.01
V-AJ	127±3	0.22±0.02	0.58±0.02	3.16±0.02
M-R	155±5	0.27±0.03	0.58±0.02	3.13±0.01
M-OE	128±3	0.21±0.02	0.61±0.01	3.14±0.01
M-AJ	131±4	0.22±0.02	0.60±0.01	3.13±0.02
P-R	157±4	0.25±0.02	0.64±0.02	3.15±0.02

V – viscose, M – modal, P – cotton,
R – ring spinning process, OE – OE rotor spinning process,
AJ – air-jet spinning process

The volumetric mass is between 0.22 and 0.27 g/cm^3, and it is associated with the mass per unit area and the thickness of the knitted fabric. Typically, as the mass per unit area rises, the thickness of the knitted fabric also rises. This suggests that knitted fabrics created from yarns spun using ring spinning machines are generally thicker. The yarn consumption in the loop is in the range of 3.10 to 3.16 mm and has no significant relationship with any of the previously mentioned parameters of the knitted fabric structure.

4. Results and discussion

Each basic knitted sample of the unfinished fabric yielded five test specimens in the course direction and five in the wale direction, which were utilized to evaluate the tensile properties of the fabric. The test specimen measured 50 mm in width and 300 mm in length, with a grip distance of 100 mm on the tensile strength tester, and an elongation rate of 100 mm/min. The knitted materials were subjected to stretching until they broke without any pre-existing load, with the aim of determining the work done across a range of elongation from the lowest to the highest levels. Key characteristics were noted during the elongation of the knitted fabric, as illustrated in Fig.3 and detailed in Tab.3. The elongation of the knitted fabric in the course direction or transversely is 220 to 354% and is significantly greater than the elongation in the wale direction, which is 33.5 to 62%, or the elongation in the course direction is 5.7 to 7.2 times greater than in the wale direction. According to some assumptions, this ratio is substantially less and equals 1:4 [23]. Cotton yarn produced using a ring spinning machine (P-R) exhibits the lowest elongation at break, measuring 3.7%. In contrast, knitted fabric that is stretched in the course direction demonstrates the highest elongation values and shows significant force-elongation distribution results (Fig.3a). The data from the measurements show that the knitted fabric experiences a break at a specific moment, coinciding with the highest elongation force applied. The tensile properties of knitted fabrics created from viscose yarns using the air-jet spinning technique (V-AJ) differ significantly. This knitted structure exhibits a high degree of uniformity, which is evident when five test specimens are stretched in the wale direction, as illustrated in Fig.3b.



a) b) c)

Fig.3 Force diagrams – elongation of the double weft knit fabric; a) cotton, in the course direction – transversely (P-R-P), b) viscose, in the wale direction - longitudinally, (V-AJ-U), c) viscose, in the course direction - transversely (V-OE-P)

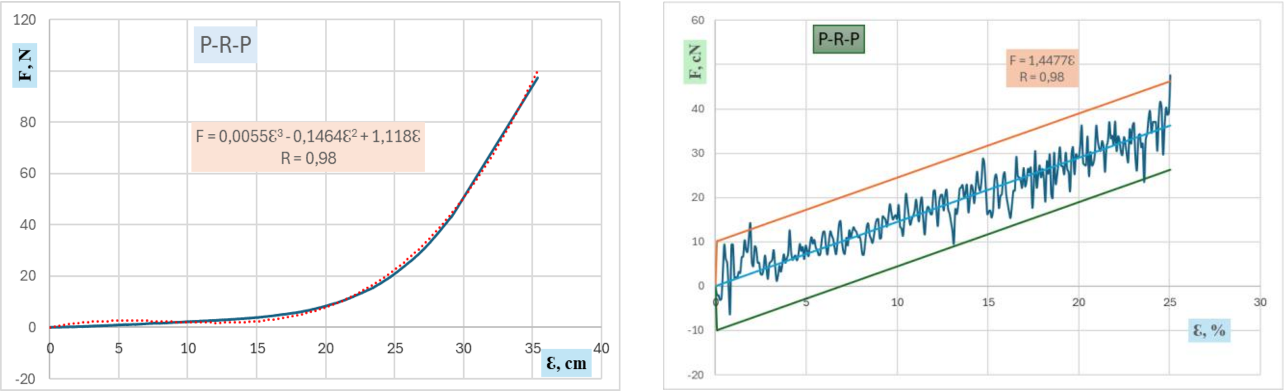
Tab.3 The values of important parameters for the elongation of knitted fabric samples to breaking and the calculations for both partial and total work under the force-elongation curve

Sample	**T₁**				**T₂**				**T₃**				**Tm**				**Wu, N·cm**
	Ɛ, %	**Ɛ,** cm	**F,** N	**W,** N·cm	**Ɛ,** %	**Ɛ,** cm	**F,** N	**W,** N·cm	**Ɛ,** %	**Ɛ,** cm	**F,** N	**W,** N·cm	**Ɛ,** %	**Ɛ,** cm	**F,** N	**W,** N·cm	
Elongation of the fabric in the course direction or transversely - P																	
V-R	165	16.5	3.6	20	168	16.8	3.8	1	170	17	3.9	1	339	33.9	73	521	543
V-OE					113	11.3	10.9	43					220	22	72	399	445
V-AJ					130	13.0	4.4	21					277	27.7	74.8	455	476
M-R					170	17	4.9	29					310	31	84.2	473	502
M-OE	100	10	4.7	17	110	11	6.2	5	120	12	7	6	255	25.5	88.4	504	532
M-AJ					145	14.5	8.8	*45*					249	24.9	74.5	357	402
P-R	190	19	7	45	200	20	8.4	8	210	21	10	9	354	35.4	97	625	687
Elongation of the fabric in the wale direction or longitudinally - U																	
V-R					10	1	10.1	4					47.8	4.8	367	649	653
V-OE					7.5	0.8	20.9	6					33.5	3.4	229	311	317
V-AJ					7	0.7	3.9	1					47.5	4.8	291	460	461
M-R	5	0.5	1	0	7.5	0.8	2.3	0	10	1	4.5	1	46.3	4.6	407	570	571
M-OE					10	1	6	2					45.2	4.5	267	377	379
M-AJ					5	0.5	7.3	1					34.4	3.4	278	351	352
P-R	15	1.5	7.7	4	17.5	1.8	10.6	2	20	2	14.3	3	62	6.2	335	561	571

T_1, T_2, T_3, T_m - significant points on the force-elongation diagram – elongation of the fabric, Ɛ - elongation of the fabric in a specific section, % and cm, F – amount of elongation force in the region of boundary points, N, W – work under (part) of the force/elongation diagram, N·cm, W_u - total work during the elongation of the fabric until breaking, N·cm, P – transversely , U – longitudinally

The rupture in the knitted fabric occurs gradually rather than abruptly, as seen with cotton. Initially, when the first section is torn, the stretching persists, leading to a progressive alternation between stretching and tearing. In this case, the maximum force during stretching differs from the force required to break the knitted fabric. When calculating the work required in stretching the knitted fabric till breaking in separate sections, it is important to specify which region of the force diagram - elongation the work is calculated for. Yarns produced through the rotor spinning method exhibit a distinct structure compared to those created using ring and air-jet spinning techniques. Consequently, the force-elongation diagram of the knitted fabric varies from the earlier diagrams, as illustrated in Fig.3c. This diagram shows that the curve generally adopts a saw-like configuration, which is a result of the discontinuous plastic deformation occurring in the yarn as it stretches within the knitted fabric. The three primary observations about the elongation of knitted fabrics up to their break point indicate a pressing need for improved attention in the creation of lightweight knitwear, especially when using yarns produced through different spinning processes. In a broad investigation of a knitted fabric's force-elongation diagram designed for compression garments, the four previously stated characteristic points are frequently determined: T_1, T_2, T_3, and T_m. The effort applied to each segment of the knitted fabric is assessed by measuring the extent to which it stretches before reaching its breaking point. The compression value of the fabric on the human body is determined by the measurements of the body and the necessary elongation length of the knitted material. To analyze knitwear that exerts minimal pressure on the human body, a simpler diagrammatic approach is utilized. The opening section extends from the commencement of stretching to the vertex of the force-elongation curve and illustrates the fabric's elastic deformation (from 0 to T_2).

The amount of elongation in the knitted fabric in this initial segment is often vital for enabling easy wear and removal of the garment, as well as for achieving a suitable fit to the contours of the human body. The second section of the diagram encompasses the region extending from the curve's vertex to the maximum force recorded during the stretching process or the breaking point of the knitted fabric (from T_2 to T_m). During the development of the aforementioned garments, the second segment of the diagram is deemed unimportant and is not explored in detail. In double knit fabrics, the elongation in the course direction significantly exceeds that in the wale direction, often being effectively represented by a third-degree polynomial equation, as illustrated in Fig.4a. A more comprehensive mathematical analysis of the diagram reveals that several regions are defined by the four points previously mentioned. The location of the points in the diagram is defined according to established criteria. The opening portion of the diagram, from the commencement of stretching to point T_1, shows an average linear pattern and is defined by a linear equation that starts at the zero point. The point T_1, marking the conclusion of the presumed elastic deformation, is identified using the criterion that stipulates a minimum Pearson correlation coefficient of 0.98. In this section of the diagram, tensile forces typically account for less than 5% of the breaking force, occasionally reaching up to 10%, and are seldom higher. However, the fluctuations in force can be significant, with variations of ± 50%, as illustrated in Fig.4b. It is essential to align the interpretation of force variation with the correlation coefficient. The diagrams of all five stretched knitted test samples in this initial section is nearly indistinguishable from one another, indicating the consistency of the knitted structure. The onset of the anticipated permanent deformation (point T_3) can be calculated in multiple ways, depending on the structure of the fabric. In the case of a traditional plain knitted fabric structure, per-



a) b)

Fig.4 Force diagrams - elongation of the knitted fabric in the course direction - transversely, (P-R-P): a) measurement diagram - solid line, mathematical interpolation diagram described by a polynomial equation - dotted line, b) force variations from the beginning of stretching to a length of 25%, (2.5 cm) manent deformation initiates with the second direction of the force diagram—elongation. This process frequently culminates in the maximum force recorded during elongation or the breaking force of the knitted fabric, referred to as point T_m. The basic point on this line can be taken as the value of the greatest recorded force, and the point of the beginning of permanent deformation (T_3) is calculated by evaluating the line pointing towards the end of elastic deformation, using the criterion of the minimum Pearson coefficient of 0.98. As a result, the endpoint of elastic deformation (T_1) and the onset of plastic deformation (T_3) were determined. The vertex point of the curve (T_2) is obtained by combining points T_1 and T_3 and intersecting the two resultant lines (Fig.2b). The deformation of knitted fabrics, created from yarns of a specific structure or with multiple yarns interlaced together, varies when they are stretched. Individual yarns begin to fracture when permanent deformation initiates, resulting in the appearance of distinct teeth within the diagram. This leads to the creation of a saw tooth diagram, with its onset commonly indicating the point of permanent deformation, known as point T_3. Once permanent deformation occurs, the elongation of the knit fabric loses significance due to the presence of visible cracks and holes, making it inappropriate for typical use. The segment of the curve between points T_1 and T_3 (end of elastic and beginning of plastic deformation of knitted fabric) is of relevance for application and analysis. The elastoplastic region has been largely overlooked in the field of knitted fabric research. It is especially useful in the manufacture of elastic clothing that compresses the human body (preventive compression stockings, therapeutic compression stockings, swimwear, women's bodysuits, recreational clothing, etc.).

For the purposes of these investigations, knitted textiles were created using cotton, viscose, and modal yarns spun in various spinning methods. All yarns have distinct tensile characteristics. Knitted fabrics are used to make both lightweight knitted clothing and leisure clothing that fits the human body in a somewhat compressive manner. During the analysis of the force-elongation diagram in various samples, points T_1, T_2, and T_3 were determined according to the criteria outlined earlier. However, due to the structure of the yarns, and thus the knitted fabric, the tensile qualities of certain samples varied, therefore the three indicated points could not be evaluated using the prior criteria. To be precise, the two lines that represent the essential aspects of the force-elongation diagram coincide at their limit values for permissible deviation, causing the three identified points to be lost. In this situation, the first line joins the second line's corridor via its permissible deviation, and the second line enters the first line's corridor. The overlapping corridors present three focal points for analysis. In this example, the intersection of these two lines determined the curve vertex (T_2), which was kept as the transition point between elastic and plastic deformation of the knitted fabric, hence points T_1 and T_3 were omitted. In the samples where points T_1, T_2, and T_3 are recognized, the distance between each point is minimal. Consequently, it is occasionally feasible to conduct a more straightforward, somewhat less precise, analysis of the diagram that excludes points T_1 and T_3.

The fabric, knitted from cotton yarns that are spun using the ring spinning process, demonstrates elongation in the course direction (P-R-P). It reaches the limit of elastic deformation at 190% elongation, achieves the curve vertex at 200%, and begins to exhibit permanent deformation at 210%, as indicated in tab.3. Knitted fabrics produced from modal yarns spun in the rotor spinning method (M-OE-P) exhibit much reduced elongation in the course direction, with 100% at the end of elastic deformation, 110% at the curve vertex, and 120% at the start of permanent deformation. The typical elongation points of viscose knitted fabrics in the course direction (V-R-P) are between those of cotton and modal knitted fabrics, but closer to those of cotton knitted fabrics. Regarding other knitted fabric samples, the permissible deviation corridors for the assessed points coincide, allowing for the determination of solely the vertex point of the curve, namely T_2.

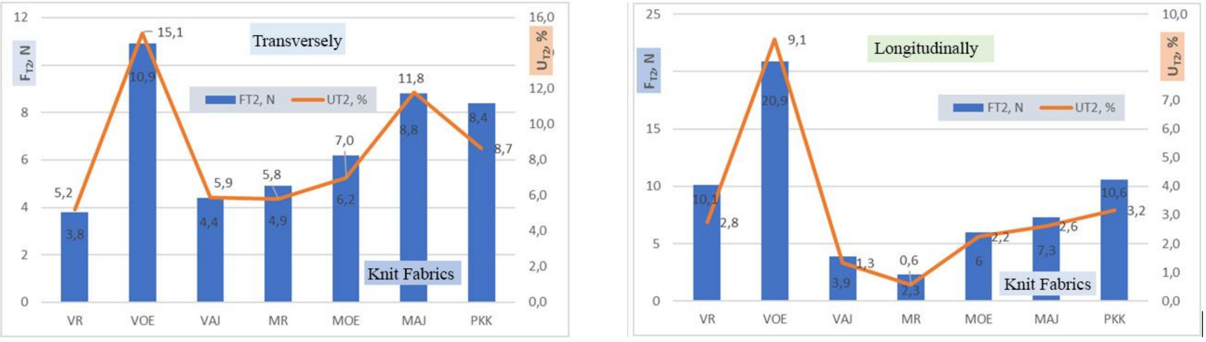
Stretching the knitted fabric longitudinally results in substantially lower amounts. Among the seven samples analyzed, only two exhibited a defined point T_1, indicating the conclusion of elastic deformation. In the cotton knitted fabric (P-R-U), elastic deformation concludes at an elongation of 15%, with the vertex point occurring at 17.5%, and the onset of plastic deformation starting at 20%. In modal knitted fabrics created from yarns spun in the ring spinning process (M-R-U), elastic deformation ends at 5% elongation, the curve's vertex at 7.5%, and permanent deformation begins at 10% elongation. Across other knitted fabric samples and in the context of transverse stretching, the corridors of acceptable deviations for the evaluated points overlap, thereby allowing for the identification of just the vertex of the curve, i.e. T_2.

Stretching the knitted fabric in the course direction reveals that the minimum stretch at the curve vertex is 110%, as determined from a sample of modal yarns spun using the rotor spinning technique (M-OE-P). The maximum stretch, however, reaches 200%, as measured in a cotton knitted fabric (P-R-P). Yarns spun using the ring spinning process (R) result in knitted fabrics that showcase outstanding elongation, with peak elongation rates of 168, 170, and 200% at the curve vertex, and break rates of 310, 339, and

354%. The minimum elongation to the vertex of the curve (110 and 113) was observed in knitted fabrics produced from yarns created through the rotor spinning process (OE). The elongation towards the vertex of the curve, measured in the wale direction or along the knitted fabric, is least pronounced in modal knitted fabrics made via the air-jet spinning method (M-AJ-U), which shows a 5% elongation. On the other hand, cotton knitted fabrics (P-R-U) exhibit the highest elongation at 17.5%. Due to the considerable differences in both transverse and longitudinal stretching, it is crucial to synchronize the stretching of the knitted fabric along the course direction with the wale direction to achieve optimal functionality and comfort in use. This type of analysis benefits from knowing the maximum force observed at the top of the force-elongation curve, as well as the ratio of that force to the tensile strength of the knitted fabric. The force applied when stretching the knitted fabric in the course direction varied between 3.8 and 10.9 N. The minimum force was observed in the viscose knitted fabric produced from yarns spun using the ring spinning method (V-R-P), while the maximum force was recorded in the viscose knitted fabric made from yarns spun through the rotor spinning technique (V-OE-P), as illustrated in Fig.5a. The proportion of this force compared to the breaking force of knitted fabrics is lowest in those made from viscose yarns produced through the ring spinning process (V-R-P), measuring at 5.2%. Contrary, it is highest in viscose knitted fabrics created from yarns spun using the rotor spinning process (V-OE-P), reaching 15.1%. It is noteworthy that the impact of breaking force and elongation on the force required to stretch the knitted fabric to the vertex of the force-elongation curve is minimal. The force exerted when stretching the knitted fabric in the wale direction or along its length is considerably variable, falling within the range of 2.3 to 20.9 N, as shown in Fig.5b. Similarly, the knitted fabric made from viscose yarns processed via rotor spinning (V-OE-U) shows significant strength values. In this case, the knitted fabric created from viscose yarns through the rotor spinning technique (V-OE-U) exhibits strong characteristics. The force percentage is minimal, ranging from 0.6% to 3.2% of the overall breaking force of the knitted fabric, with a single case (V-OE) reaching 9.1%. In the experiment design, yarns exhibiting markedly different structures and tensile properties were intentionally selected, based on the hypothesis that these properties would correlate with those of the knitted fabric. Special attention was given to the relationship between the rupture work of the yarns and that of the knitted fabric. Yarns differ in terms of breaking force, elongation, strength and work to rupture (tab.1). The significant differences in their tensile properties are equally influenced by the raw material composition and the spinning process. Despite extensive analysis and sample sorting, no significant patterns of yarn structure effect on the tensile characteristics of knitted textiles were discovered, either in the course or wale directions.

The first parameter to evaluate is the quantity of work involved in stretching the knitted fabric to the maximum point of elastic deformation, which ranges from 0 to point T_1. In this study, only five out of the fourteen samples were subjected to analysis. When the fabric is elongated in the course direction, the measurement increases; however, it experiences a notable decrease when stretched in the wale direction or along the fabric (tab.3). In other samples, the end of elastic and the beginning of plastic deformation overlap in the allowable deviation corridor and are connected to the curve vertex, i.e. points T_1 and T_3 are joined at point T_2.

The second parameter examines the work required from the initial stage of stretching up to the vertex of the force-elongation curve. This parameter is duly noted for all samples. When the knitted fabric is extended in the course direction, its value falls within the range of 21 to 53 N·cm, which constitutes 3.9 to 11.2% of the total effort required to stretch the fabric to its breaking point. The two samples, V-R and



a) b)

Fig.5 Amount of force when stretching the knitted fabric to the vertex of the curve in relation to the breaking force of the knitted fabric: a) when stretching the knitted fabric in the course direction - transversely, b) when stretching the knitted fabric in the wale direction - longitudinally, FT2 - amount of force when stretching the knitted fabric to the vertex of the curve, N, UT2 - percentage of force when stretching the knitted fabric to the vertex of the curve in relation to the breaking force of the knitted fabric, %

V-AJ, have the lowest measurement at 21 N·cm, in contrast to the M-OE sample, which has a slightly greater measurement of 22 N·cm. Three samples (M-R, V-OE, and M-AJ) had much higher values, with cotton knitted fabric having a value of 53 N·cm, a 2.5 times greater than the smallest the amount. The work needed to stretch the knitted fabric to its breaking point in the wale direction is between 0 and 6 N·cm, constituting just up to 1.9% of the total work required for this process. It is less than 1% in five samples, 1.1% in the cotton sample, and 1.9% in the V-OE sample. The considerable differences in the work involved in stretching knitted fabric along the course and wale directions arise from the fabric's structural characteristics. However, the variations that occur when stretching the fabric in one direction cannot be definitively ascribed to the raw material composition or the spinning processes used.

In the third part of the diagram, the focus is on the effort required to stretch the knitted fabric between the vertex of the curve and the breaking point (from T_2 to T_m). In the course direction, the work needed to stretch the knitted fabric, is between 357 and 634 N·cm, accounting for 88.8 to 96.1% of the total work performed. It is the smallest in the knitted fabric made from modal yarns spun in the air-jet spinning process (M-AJ), and the largest in the cotton knitted fabric (P-R). It should be emphasized that the absolute work involved in stretching the knitted fabric in the wale direction is similar to that required in the course direction, with values between 311 and 649 N·cm. Nevertheless, the relative work is notably higher, ranging from 98.1% to 100%. When comparing the tensile properties of yarns (tab.1) with those of the knitted fabric (tab.3), it is clear, as discussed in the previous sections, that it is difficult to conclusively determine which parameters concerning the tensile properties of the yarns and the structure of the knitted fabric have a significant effect on the work required to stretch the fabric from the curve vertex to its breaking point.

Stretching knitted fabric to break requires a total work of 402 to 687 N·cm in the course direction and 317 to 653 N·cm in the wale direction. Only two samples (M-R and V-R) showed a greater measurement when the knitted fabric was stretched in the wale direction. Among the yarn samples, the modal yarn (M-AJ) required the minimal effort to stretch the knitted fabric to its breaking point in the course direction, in contrast to viscose yarns (V-OE), which needed somewhat more work. In analyzing the minimum work required to stretch the knitted fabric in the wale direction, it was found that the effort needed for viscose knitted fabrics (V-OE) was lower than that for modal fabrics (M-AJ) across the two samples. Among the fabrics tested, cotton (P-R) and viscose knitted fabrics (V-R) demanded the greatest amount of work before breaking, employing yarns that were spun using the ring spinning process. When stretching the knitted fabric until it breaks in the wale direction, it is necessary to apply the most work when breaking the knitted fabric made from yarns in the ring spinning process (P-R, V-R and M-R). Within these analyses, it is significant to observe that cotton yarns show the minimum work to break, a slightly increased breaking force, and nearly the highest work necessary for breaking the knitted fabric. Unlike cotton yarns, modal (M-AJ) and viscose yarns (V-OE) exhibit a considerably higher work-to-break ratio, while also requiring less effort to break the fabric. Modal yarn produced through the ring spinning (M-R) process exhibits the greatest breaking strength and work to break, while not experiencing the highest work to break the fabric.

5. Conclusion

A total of seven samples of double weft knitted fabrics were produced using cotton, viscose, and modal yarns, each with a nominal count of 20 tex. These fabrics are intended for the production of underwear and lightweight clothing. The yarns were made through the processes of ring, rotor, and air-jet spinning. A basic knitted fabric sample was constructed with cotton yarn, which will act as a reference point for assessing the properties of different knitted fabrics. Given the significant differences in the tensile properties of yarns, it was reasonable to expect that the tensile properties of knitted fabrics would also vary, especially in particular regions when the fabric is subjected to stretching until it breaks. The research on unfinished knitted fabrics leads to the following conclusions.

- The breaking force of the yarns was observed to be between 267 and 487 cN, with elongation at break percentages ranging from 3.7% to 13.8%. The breaking strength varied from 13.4 to 24.3 cN/tex, and the work at break was recorded between 301 and 1436 cN·cm. The tensile properties of cotton yarn produced by the ring spinning process are significantly distinct from those of other types of yarn.
- All knitted fabric samples were manufactured on a single spinning machine in a double weft knitted structure. The knitting conditions remained uniform across all samples, meaning that the machine operated without any adjustments while using a particular yarn. The unfinished knitted fabric had a mass per unit area of 127 to 165 g/m^2, a volumetric mass of 0.21 to 0.26 g/cm^3, and a yarn consumption per stitch of 3.10 to 3.16 mm.

- The elongation of the knitted fabric to break in the course direction or across ranged from 220 to 354%, and in the wale direction from 33.5 to 62%. In theoretical calculations, plain double weft knitted fabrics stretch four times more in the course direction than in the wale direction. The research demonstrated that the elongation of the knitted fabric in the course direction was significantly higher, reaching up to 7.2 times that of the wale direction.
- The work exerted in stretching the knitted fabric to the vertex of the force-elongation curve in the course direction varies between 21 and 53 N·cm, which constitutes approximately 12 to 21% of the total work required to break the knitted fabric. Stretching the knitted fabric along the wale direction results in a notable decrease in size, with measurements typically ranging from 0 to 6 N·cm.
- The total work required to break the knitted fabric does not differ significantly when stretching the fabric to break in the course and wale direction. The total work required to stretch the knitted fabric in the course direction varied between 402 and 687 N·cm, while in the wale direction, it ranged from 317 to 653 N·cm.
- According to classical knitting principles, the production of knitted fabrics from yarns of uniform fineness, but with diverse raw material compositions and spinning processes, can be accomplished without considerable difficulty. The structure of the knitted fabric reveals significantly different basic parameters, particularly in width and mass per unit area, which greatly affect the tensile properties of the fabric. It is essential to take the aforementioned differences into account during the production of knitted fabrics designed for the same product, particularly given the weak correlation between the tensile properties of yarns and those of the knitted fabrics. The differences identified in the unprocessed knitted materials are likely to be highly complex, making it difficult to effectively compensate for them in the finishing processes of the knitted fabric.

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