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Technology and Properties of Distance Five-layered Double-Weft-Knitted Fabrics with Elastomeric Threads

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Abstract
This paper presents the concept of forming distance weft-knitted fabrics with five knitted layers in their structure. The knitted fabrics developed have a relatively large thickness in relation to the needle pitch and distance between the needle beds of the knitting machine on which they were formed. The effect described was obtained by combining three knitted layers with the use of different reports and the number of monofilament threads knitted-in, and by modifying the knitted layers with elastomer threads. The distance knitted fabrics designed and produced for potential use as preforms for composites and parts protecting against an impact were tested and analysed with respect to their structural parameters.

Key words: *distance weft-knitted fabrics, spacer fabrics, monofilament, elastomeric yarn, knitting algorithm, structural parameters, flat knitting-machine.*

In the simplest case, a distance weft-knitted fabric is composed of two plain warp-knitted fabrics connected with an additional thread which keeps a constant distance between them. The thickness of the distance knitted fabric produced according to the algorithm presented in ***Figure 1*** depends on the diameter and mechanical properties of the thread connecting the layers and on the distance between the needle beds of a knitting machine. A similar principle of regulating the thickness of the distance knitted fabric is described in papers [1, 2] concerning distance warp-knitted fabrics.

The realisation of the algorithm given in ***Figure 1*** requires the use of a knitting-machine, which:

- has a mechanism regulating the distance between the needle beds,
- enables to use an additional component in the knitting zone which allows to hold the connecting monofilament fed on the needles (in system 3).

These requirements are fulfilled by cylindrical knitting machines, which have a mechanism regulating the distance between the disc and the cylinder. The range of this regulation makes it impossible to produce a knitted fabric of great thickness. Flat knitting machines do not have any possibility of regulating the distance between the needle beds.

An attempt to design the algorithm presented without any special elements supporting the monofilament thread (introduced in system 3) in systems 1 and 2, ends with an elevation, along with the needles, of the thread recently introduced connecting the layers. As a result, the stitch is not properly formed, and the process of knitting is disturbed. The use of such an additional element is relatively easy in the case of a cylindrical knitting machine [2], while in the case of a flat knitting machine, the introduction of an additional supporting element into the knitting zone leads to a significant redesigning of the knitting machine.

There is substantial literature on distance knitted fabrics [6 - 13] describing various

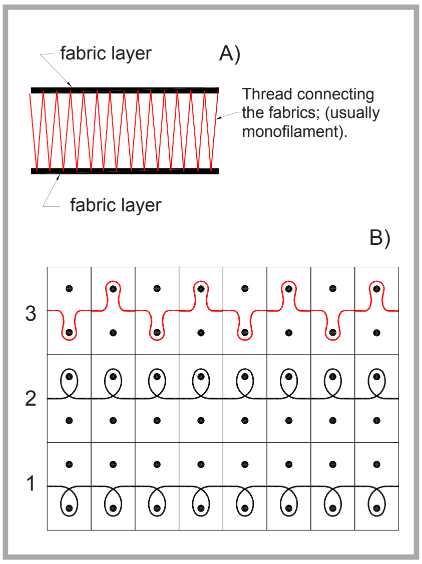

Figure 1. *Idea and algorithm of knitting the distance knitted stitch. A – idea of the stitch, B – basic algorithm of knitting.*

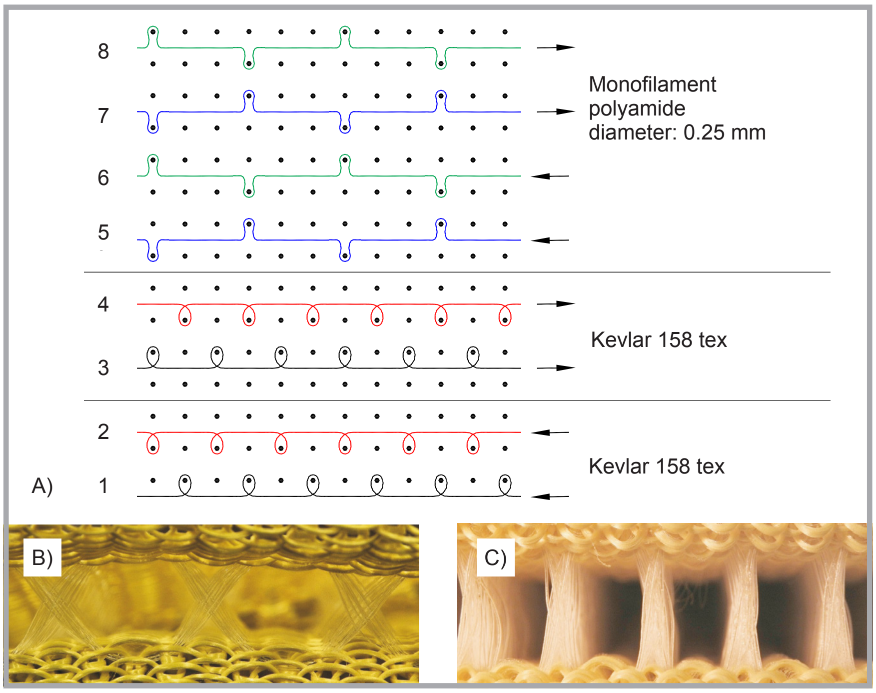

Figure 2. *Example of an algorithm for producing distance weft-knitted fabric of relatively great thickness. A – algorithm of knitting, B – cross-section of a knitted fabric without elastomer thread, C – cross-section of a knitted fabric with elastomer thread; (action repeated multiple times).*

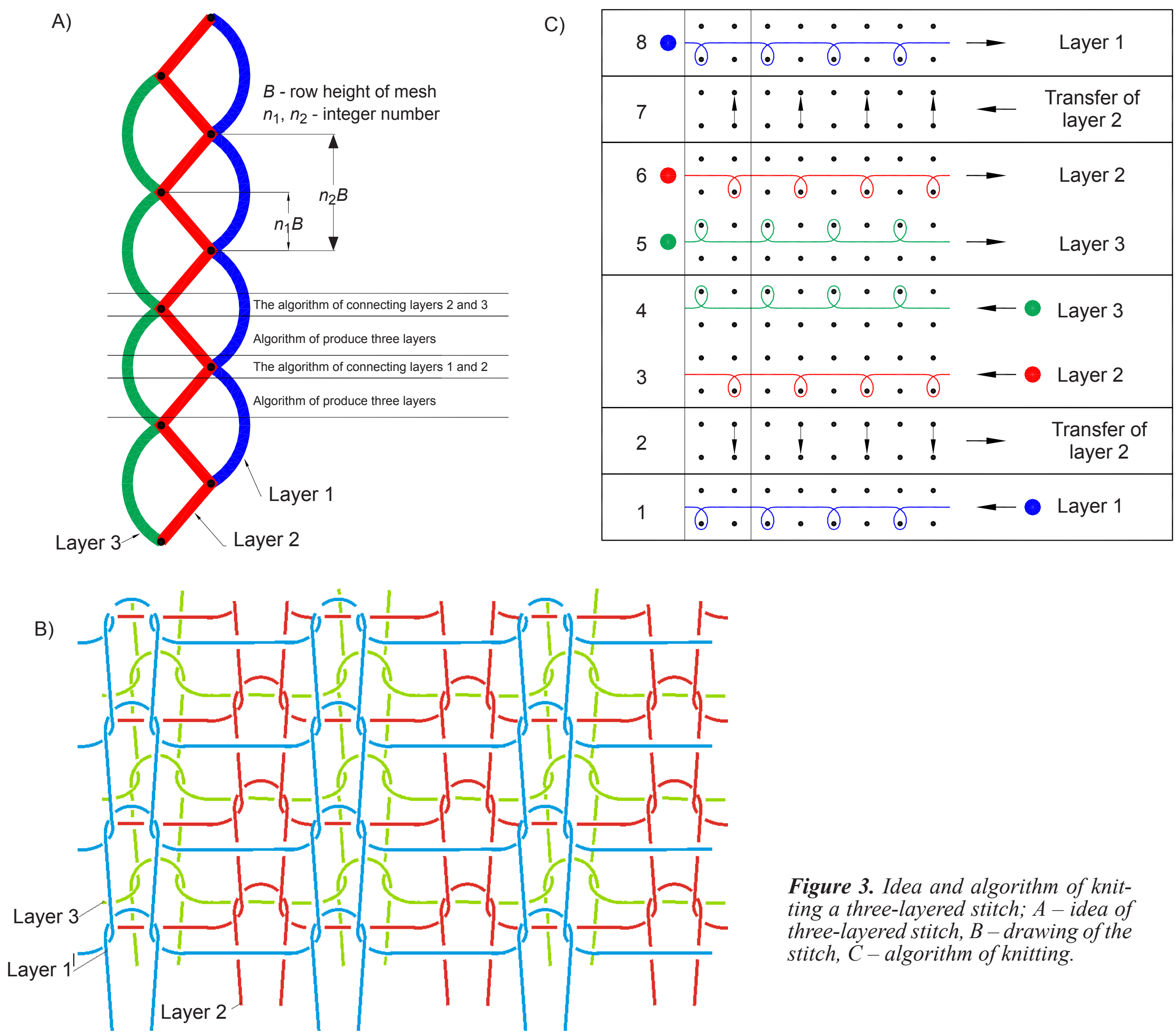

Figure 3. *Idea and algorithm of knitting a three-layered stitch; A – idea of three-layered stitch, B – drawing of the stitch, C – algorithm of knitting.*

aspects of their production and application.

From these brief considerations and analysis of the literature, it results that:

- regulation of the thickness of a distance knitted fabric conducted only by changing the distance between the needle beds is insufficient, as it does not enable to obtain stitches of thickness greater than two needle pitches,
- in the case of flat knitting machines, monofilament threads must be introduced in a way that other threads forming knitted layers hold them in courses, where there are needles working, on which the threads were previously fed.

Reference [14] presents an algorithm of forming a distance weft-knitted fabric of relatively great thickness in comparison to the needle pitch of the knitting machine on which the fabric was formed. The distance knitted fabrics produced were modified by introducing elastomeric threads into their structure.

As a result, it was found [1] that:

- it is possible to produce a distance weft-knitted fabric of thickness greater than 2 needle pitches of the knitting machine used,
- introduction of elastomeric threads into the structure increases the density and thickness of the knitted fabric up to 4 times in relation to the most basic case of a distance weft-knitted fabric produced without elastomeric threads,
- addition of elastomeric threads increases the surface mass.

The authors pointed out technological limitations [14] which prevent from obtaining a distance weft-knitted fabric of thickness greater than 6 needle pitches of the knitting machine on which it was produced. The limitation results from geometric dependencies between the elements forming the loops of knitted fabrics.

An example of an algorithm for producing a distance weft-knitted fabric developed in [14] is shown in ***Figure 2***.

In the studies [15, 16] algorithms for producing multi-layered weft-knitted fabrics with up to 6 knitted layers are presented. The idea, drawing and exemplary algorithm of such a stitch are presented in ***Figure 3***.

The aim of this study was to overcome the limitations described in [14], that is obtaining distance knitted fabrics of thickness greater than 6 needle pitches. It was achieved by a combination of the technology of distance weft-knitted fabrics, described in [14], and that of multi-layered weft-knitted fabrics, described in [15, 16] as well as by introducing additional elastomeric threads into the knitted layers, next to the core threads.

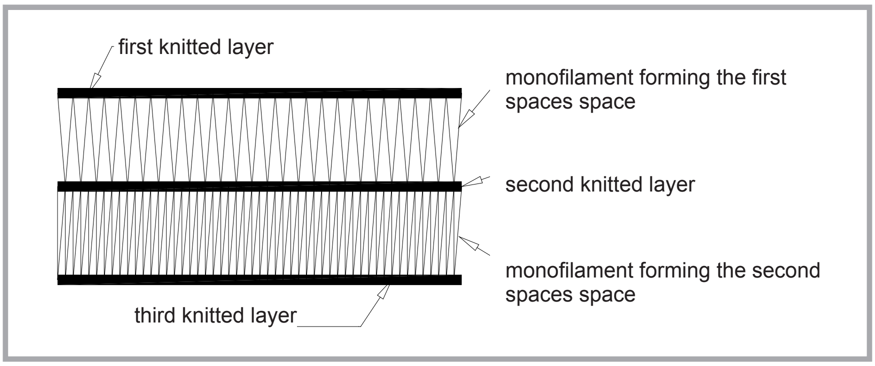

Figure 4. Structure of a multilayered spacer fabric.

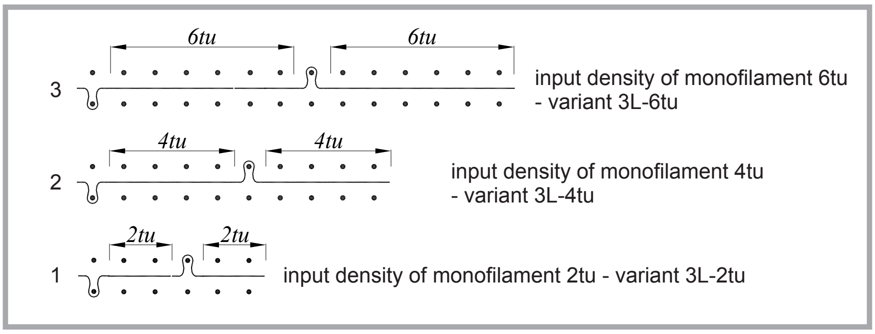

Figure 5. Principle of knitting-in and marking the variants of five-layered spacer fabrics.

The combination of these technologies was made on a flat knitting machine operated numerically by STOLL of the CMS 530HP E5 type, including the use of a dedicated studio of CAD/CAM, M1PLUS, cooperating with this machine.

The advantage of this machine was an optional electronic selection of needles, which enabled a simple realisation of the algorithms developed.

Technological assumptions for the algorithms of knitting developed

Yarn Kevlar 49 from filament fibres of 158 tex linear density was used in the knitting tests. A polyamide monofilament with a diameter of 0.25 mm was used as a thread connecting the knitted layers, keeping the distance between them, and shaping the thickness of the knitted fabric. The number of monofilament threads in one course of stitch in all the variants was the same. ULTRASONIC elastomeric threads with a linear density of 152 tex were introduced into the external layers of the knitted fabric. Elastomeric thread was fed together with Kevlar yarn, with 100% draft. All variants of the knitted fabrics were formed with the same setting parameters of the knitting machine.

According to the initial assumptions, the task of elastomeric thread was to increase the thickness of the knitted fabric by reducing the distance between the loops. As results from the experiment, the introduction of an elastomeric yarn into the knitted layers increases the thickness of distance knitted fabric by bringing together the wales and, consequently, a perpendicular arrangement of monofilament threads in relation to the knitted layers. A distance knitted fabric with elastomeric thread added to its structure is more resistant to compressive forces acting perpendicularly to the surface of the stitch, which is consistent with theoretical considerations carried out by the authors of [3 - 5].

A basic assumption for the development of knitting algorithms for distance knitted fabrics with three knitted layers was a diversification of the knitting-in of monofilament threads, which keep the distance in a course of the knitted fabric. It should be noted that the algorithm described and principles for its development are of a general character, as they focus on the process of knitting with the use of flat and cylindrical knitting machines. The idea of the structure of a distance knitted stitch with three knitted layers is shown in ***Figure 4***.

The basis for the realisation of the idea presented in ***Figure 4*** was a knitting algorithm for a three-layered stitch shown in ***Figure 3***. Innovation of the algorithm, given in ***Figure 3***, was in the tasks introducing monofilament threads into the structure, combining individual knitted layers. Modern technology of knitting realised on knitting machines with an electronic selection of needles and transfer enables to produce distance knitted fabrics as a base using multi-layered knitted fabrics. Three variants of this stitch were made, varying in thickness, regulated by the compactness of the connection of the knitted layers. The variants were marked as follows: 3L-2tu, 3L-4tu and 3L-6tu, where tu – is the needle pitch, and the number stands for the amount of needle pairs omitted between successive needle pairs knitting-in the monofilament.

In the case of distance knitted fabrics with three knitted layers, possibilities of shaping the thickness of the stitch are limited compared to distance knitted fabrics with two knitted layers. This is caused by the knitting technique every second needle. The monofilament was knitted-in at an interlock gating of needles.

The principle of knitting-in a monofilament and marking the variants of knitted fabrics is illustrated in ***Figure 5.***

The report of introducing a monofilament included the cooperation of four systems, repeated systematically three times. This gave 12 threads of monofilament in each course, which means that in a hook of one needle knitting-in the monofilament, beside the core thread, there are 6 threads of monofilament located at the end of the report. Variants 3L-2tu, 3L-4tu and 3L-6tu were characterised by a similar arrangement of monofilament threads with and without elastomeric threads, which is illustrated as exemplary variant 3tu with a schematic course of threads on the needles (***Figure 6***).

Knitted fabric made without elastomer has a very loose structure of low filling, which makes it unsuitable for practical use.

Note: all of the variants of knitted fabrics are made with the same parameters of the knitting process i.e. initial tension, sinking depth and take-down force. The stretch of elastomeric thread in each case was 100%. All variants were made on a flat knitting machine - Stoll CMS 530 HP; E5, from filament Kevlar yarn of 158 tex, 152 tex elastomer and polyamide monofilament of a diameter of the cross-section equal to 0.25 mm.

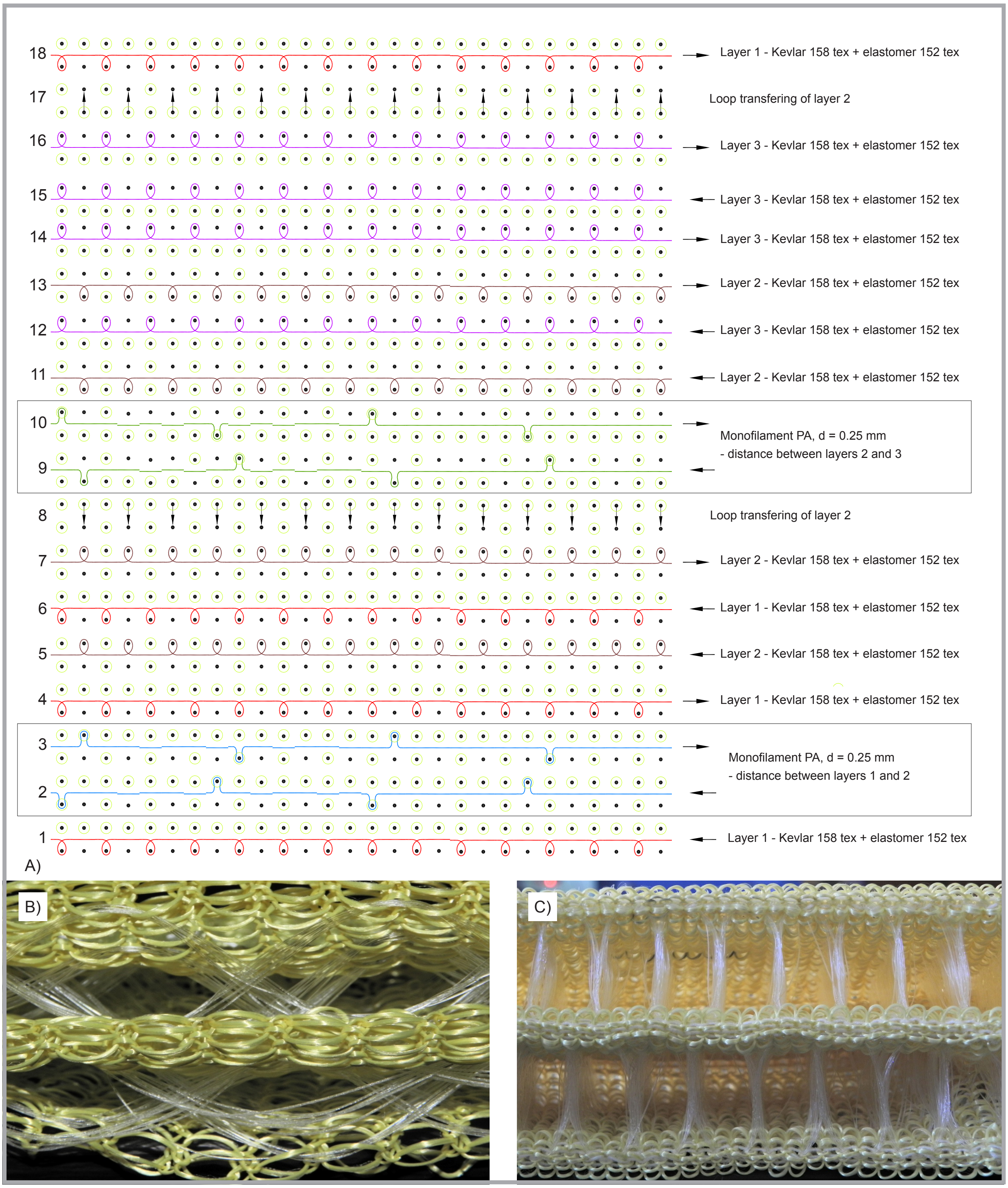

Figure 6. *Variant 3L-6tu of a multilayered spacer fabric with a thickness of 12tu, with five layers. A – algorithm of knitting (green circle on a needle means that in its hook there is a loop), B – photograph of a cross-section of a knitted fabric made without elastomer thread, C – photograph of a cross-section of a knitted fabric made with elastomer thread.*

Analysis of structural parameters of distance knitted fabrics

Density of three-layered distance knitted fabric

The density of spacer fabrics with three knitted layers does not depend on their thickness.

The addition of elastomeric thread into the structure of a knitted fabric makes it compact, that is, increases the density of wales and courses.

Distance knitted fabrics of three knitted layers and two connecting monofilament layers made without elastomer have a very low filling of the core threads, caused by the necessity of using a knitting technique on every other needle, which allows for a parallel formation of three knitted fabrics, but at the expense of their filling.

Table 1. Parameters of test stitches made with and without elastomeric thread.

Parameter	Variant 3L-2tu,		Variant 3L-4tu,		Variant 3L-6tu,	
	without elastomer	with elastomer	without elastomer	with elastomer	without elastomer	with elastomer
% of Kevlar 158 tex	71.4	52.5	71.8	53.4	72.9	53.7
% of elastomer 152 tex	------	27.3	------	27.9	------	27.8
% of monofilament	28.6	20.2	28.2	18.7	27.1	18.5
Density of wales P_k, wales/100 mm	12	24	12	27	12.5	25
Density of courses P_r, courses/100 mm	50	80	50	80	50	80
Length of thread in a loop for a basic stitch l, mm	19.2					
Thickness, mm	20.1	28.7	25.0	45.2	40.0	62.0
Surface mass M, g/m^2	1536	4333	2512	4040	1071	4270

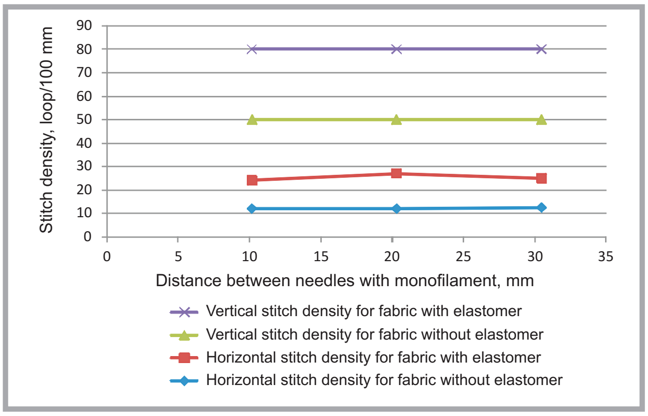

***Figure 7.** Change in density of spacer fabrics with five layers made of 158 tex Kevlar after modification with elastomer thread.*

Surface mass

As expected, the introduction of elastomeric threads into the structure of spacer fabrics causes an increase in the surface mass (***Figure 8***). The average value of the surface mass of knitted fabrics with elastomeric threads is 2.5 times higher than the value of surface mass without such threads, which is explained by the mass fraction of elastomeric threads in the structure of the knitted fabric and by the increase in the compactness of the surface. It should be noted that distance knitted fabrics without the elastomer are less geometrically stable.

Five-layered distance knitted fabrics – thickness

The thickness of spacer fabrics with five layers increases with an increase in the distance between the successive needles knitting-in the monofilament thread.

The addition of a highly elastic thread to the structure of the stitch increases its thickness compared to such a stitch made without elastomeric thread.

Spacer fabrics with five layers have a higher value of thickness than those with two knitted layers [14, 15]. The graph in ***Figure 9*** shows the influence of the report of knitting-in monofilament threads, expressed by the distance between the needles knitting-in the monofilament, on the value of the thickness of knitted fabrics. The horizontal axis presents the distance, in millimeters, between the subsequent needles knitting-in the monofilament in the knitted fabric. The largest distance used was 30 mm, i.e. six needle pitches. As can be seen, the maximum thickness of the knitted fabrics was 40 mm, that is 8 needle pitches for the knitted fabric without elastomer thread and 62 mm, that is about 12 needle pitches, for the knitted fabric with elastomer thread. The introduction of elastomer thread into the structure of distance knitted fabric with five knitted layers increases the thickness by 50% as compared to knitted fabrics without elastomer thread. The graph in ***Figure 10*** (see page 73) enables to predict the thickness of a knitted fabric, regardless of the needle pitch of the knitting machine used, as the value of the thickness of knitted fabrics is presented by the multiplicity of the needle pitch.

The interlock method of introducing monofilament used causes the grouping of successive threads introduced in the same locations within the stitch.

Summing up the variants of distance knitted fabrics formed, they differed in the density of knitting-in the monofilament linking the external layers of the stitch, giving different values of thickness of the knitted fabric and affecting their mechanical properties.

As expected, the introduction of elastomeric threads into the layers of a distance knitted fabric with five layers increases its density.

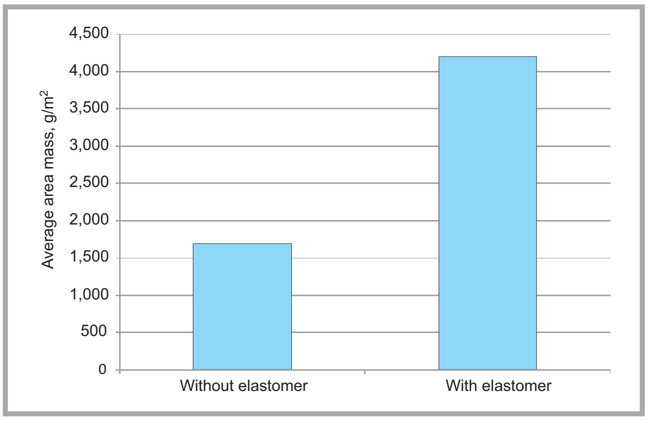

***Figure 8.** Average value of surface mass of spacer fabric with five layers with and without elastomeric threads.*

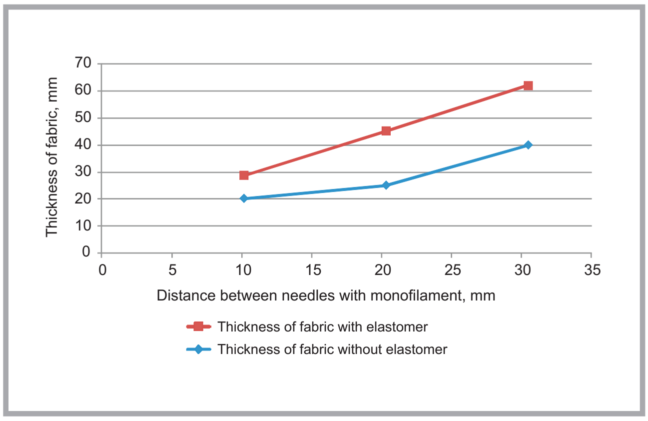

***Figure 9.** Thickness of five-layered spacer fabrics.*

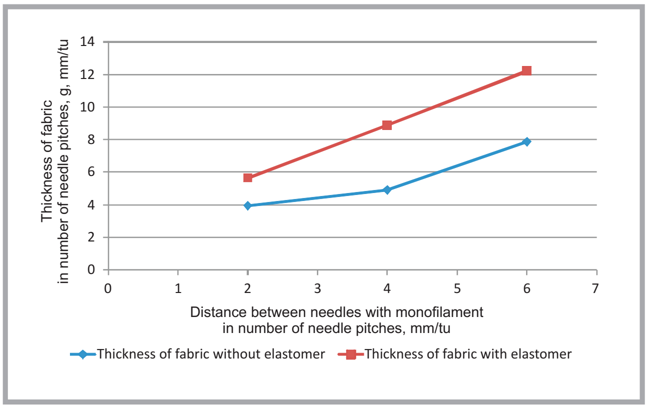

Figure 10. Thickness of five-layered spacer fabrics expressed by the number of needle pitches of the knitting machine on which they were produced.

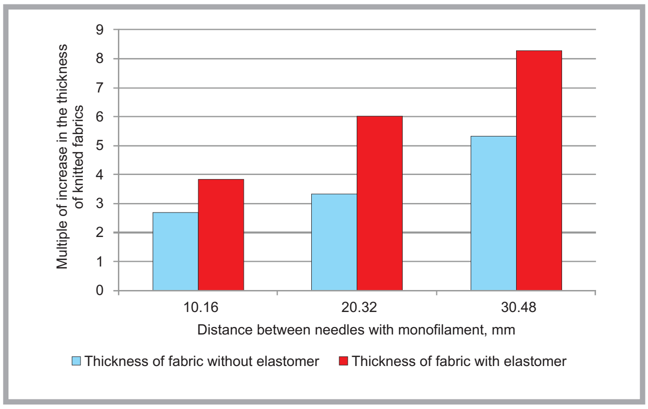

Figure 11. *Multiplicity of the increase in the thickness of five-layered distance knitted fabrics with regard to basic distance knitted fabric presented in* ***Figure 1***.

The multiplicity of increasing the thickness with regard to the most basic variant of distance knitted fabric (***Figure 1***) is shown on the graph in ***Figure 11***.

Conclusions

Modern technology of knitting realised on knitting machines with an electronic selection of needles and two-way transfer of loops enables to produce distance knitted fabrics using multi-layered knitted fabrics as a base.

The thickness of spacer fabric with five layers can be shaped by changing the distance between the successive needles knitting-in a monofilament thread. With an increase in the distance between these needles, the thickness of the knitted fabric increases. It should be noted, however, that the possibility of shaping the thickness of such knitted fabrics is limited due to the geometry of the knitting zone of the knitting machine and the technology of knitting multilayered stitches (knitting on every other needle).

The introduction of elastomeric thread into the structure of component knitted fabrics of the stitch causes the following in regard to knitted fabrics without elastomer threads:

- increase in the density of the knitted fabric within the range of 60 - 100%
- increase in the thickness of the knitted fabric by up to 8 times, compared to a basic variant, in which the monofilament was fed to each pair of needles, made without an elastomer.
- increase in the surface mass, on average 2.5 times.

The algorithms of knitting developed are feasible only when using knitting machines controlled numerically, with an arbitrary electronic selection of needles and possibility of an automatic, two-directional transfer of loops from one bed to another.

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