KAUNAS UNIVERSITY OF TECHNOLOGY

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THE INFLUENCE OF FABRIC STRUCTURE ON THE QUALITY AND FUNCTIONALITY AN EMBROIDERY ELEMENT

Summary of Doctoral Dissertation
Technological Science, Materials Engineering (T 008)

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INTRODUCTION

The development of the textile and garment sector is being restructured and modernized. Strong competition, changing consumer demands, demand for innovative products, short-term agreements with customers and a growing attention to a knowledge-based society encourages manufacturers of embroidery systems to rapidly adopt new technologies, including information and telecommunication ones, along with striving to be the leader in the development of new products. The application and development of electrically conductive embroidery systems is closely associated with the development of smart textile technologies. The latest smart embroidery systems are able to receive cell signals, control health status, warn at risk, measure blood pressure, etc.

The formation of defects in embroidery systems is a problem faced during the technological processes, when textile materials are mechanically exposed to pressing, crushing, stretching, buckling and being pierced many times by the tip of the needle. As a consequence of this, the form, composition, geometric parameters, mechanical and physical properties of the embroidery elements change depending on the parameters of the technological process, nature of loads, stitching method and the properties of the material. Therefore, assessment of the deformation of textile materials is extremely important when examining the factors influencing the quality and functionality of embroidered systems. Recently, scientists have started taking an interest in this problem, however, it is still not widely investigated, and there is a lack of qualitative analysis of the embroidery element itself.

Electrically conductive systems are increasingly used in various technical areas: design of sensors, as conductors and protection against static charges, etc. There are several kinds of conductive textile threads, i.e. with a conductive coating, with a conductive filler, and fully eccentrically conductive threads. Their mechanical behaviour is close to the behaviour of textile threads, but they have some defects: they have a rough surface structure, they are quite expensive, and therefore it is important to acheive a high quality and functional embroidered system. In order to get the precise shape of an embroidery element it is important to evaluate the process technological factors, position of an embroidery element with respect to the direction of fabrics, and the structure and properties of materials used in the embroidered system.

Square shaped embroidery elements with good electrostatic properties are often used in the development of embroidered textile “electronic” systems, and are therefore recommended for the production and application of portable dipole antennas, sensors, etc.

The functionality and features of embroidery conductive systems have been widely discussed in scientific research. However, it should be emphasized that the majority of research involves general peculiarities of the development of embroidery systems without considering the influence of technological factors on geometric parameters, quality and functionality of the embroidery element.

Relevance of the dissertation

Considering the needs of consumers and competitive market conditions, producers of textile materials and compounds must guarantee high quality products throughout the entire service life. Precision, reliability, appearance, wear properties and functionality of embroidered elements have a significant influence on the high qualitative requirements. This doctoral thesis deals with the subject of compliance of geometrical parameters of embroidery elements with the design size, and electrical conductivity of conductive closed-circuit embroidery elements by analyzing the technological parameters of the process, the physical properties of the fabric, and the operating factors. The research provides a quantitative assessment on non-compliance of closed-circuit embroidery elements with the design size and its functionality depending on the structure of the fabric, which may be useful for the rapidly growing development of advanced technologies, identifying causes of various defects and developing new quality requirements and standards for embroidered items.

The aim of the doctoral dissertation

To investigate and assess the influence of fabric structure on the quality and functionality of embroidery elements.

Tasks of the thesis:

1. to assess the impact of fabric structure and technological parameters of the compliance and shape of the embroidered element to match the designed size;
2. to analyze factors that affect geometrical parameters of square shaped closed-circuit embroidery elements and assess the uncertainty of research method;
3. to identify the influence of technological parameters of the embroidery process on geometrical parameters and electrical conductivity of square shaped closed-circuit embroidery elements;
4. to investigate and analyze the influence of operating factors on geometrical parameters and electrical conductivity of conductive square shaped closed-circuit embroidery elements.

Novelty and practical value of the dissertation

In most cases, scientific literature provides a description of embroidered systems only by a visual assessment of an element, and there is a lack of deeper investigations; such as the influence of the textile material properties and technological parameters on geometrical parameters and functionality of embroidery elements. The accuracy of shapes is one of the main qualitative requirements of functional embroidery elements, and therefore it is very important to select both textiles with appropriate properties and appropriate technological parameters. It should be emphasized that defects, such as non-compliance of embroidery elements to the project size, deformation of shapes, slippage of threads, buckling, etc. are the most visible defects, therefore special attention must be paid to the analysis of the factors that have an influence on defects.

The thesis provides research on the accuracy of geometrical parameters of closed-circuit embroidery elements, taking into account the fabric properties and technological parameters of the process. In addition, an assessment of the uncertainty of method of the analysis of geometric parameters of embroidery elements is included. The expanded measurement uncertainty of each embroidery element circuit was measured by using the Monte Carlo Simulation Technique. The thesis also provides research and analysis of the influence of technological parameters of the embroidery process on electrical conductivity of the embroidery element. The influence of speed of the embroidery process on the quality of embroidery elements was also assessed. The study includes research and analysis of the influence of exploitation factors on conductivity and geometrical parameters of the electrically conductive embroidery element. The research gives an assessment of the influence of the width and exploitation of the circuit on conductivity of embroidery elements. Additionally, a quantitative assessment on non-compliance of closed-circuit embroidery elements with the design size and its functionality depending on the fabric structure is assessed, and may be useful for identifying the causes of various defects and developing new quality requirements and standards for embroidered items.

Approval of the research results. The results of the research are presented in 10 scientific publications, 5 of them – in the issues that correspond to the list of Institute of Scientific Information (Web of Science), 2 – in the issue, which corresponds to the list of data base of an Institute of Scientific Information and 3 publications – in the other referred scientific publications in International Database. The results have been presented at 10 international conferences.

Structure of the doctoral dissertation. The doctoral dissertation consists of an introduction, 3 chapters, conclusions, list of references (135 entries) and a list of scientific publications. The material of the doctoral dissertation is presented in 103 pages, including 34 figures and 5 tables, along with 5 annexes (including 12 figures and 1 tables).

CONTENT OF THE DOCTORAL DISSERTATION

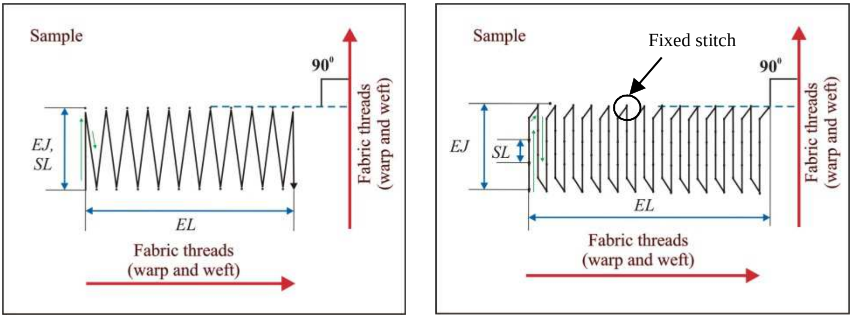
Introduction presents the relevance of the dissertation, states the objective of the thesis, and describes the novelty and practical value.

Chapter I provides a review of scientific literature related to the topic of the dissertation.

Chapter II part one. Presents the basic characteristics of the investigated selected fabrics and embroidery, conductive threads and original research methods.

The characteristics of the tested fabrics were determined in accordance with the following standards: the thread density was determined according to LST EN 1049-2, surface density and linear density were determined in accordance with LST ISO 3801, and the thickness of the material was determined in accordance with LST EN ISO 5084. In addition, performce measurements using the SCHMIDT thickness gauge under load and no-load conditions, pressure 1,0 kPa, measurement error is 0,01 mm are discussed. The filling index of the fabric e_s and the linear filling indexes e_m, e_a were calculated by applying a medium warp and weft density P_m and P_a per unit length (cm^{-1}), and the thread contouring diameter of the fabric (d_{km}, d_{ka}) (when $e_m \geq 1$ or $e_a \geq 1$, e_s=1).

Chapter II part two. The shape of embroidered items is obtained by filling the embroidered area with two different filling types *Z (zigzag) and T (tatami)* (Fig. 1).



a b

Fig. 1. Diagram of assembling of the embroidery element, when: a – filling type *Z*; b – filling type *T*, where *EJ* – embroidery element width, *SL* – stitch length, *EL* – embroidery element length

6 samples of each fabric under investigation have been embroidered during the research.

Technique used for determining the length and width of strip-shaped embroidery elements. The embroidery process of the strip-shaped embroidery element is performed at 4 different speeds V, min^{-1}: 600, 800, 1000 and 1200. The samples are embroidered in the directions of warp and weft threads using filling types Z and T.

The length and width of the embroidery elements were measured using a COREL DRAW 12 software package. Scanned sample images are transferred to a computer media and opened at a scale of 1:1 in the COREL DRAW 12 programme and were measured by increasing the resolution. The measuring diagram of the strip-shaped elements is shown in Fig. 2.

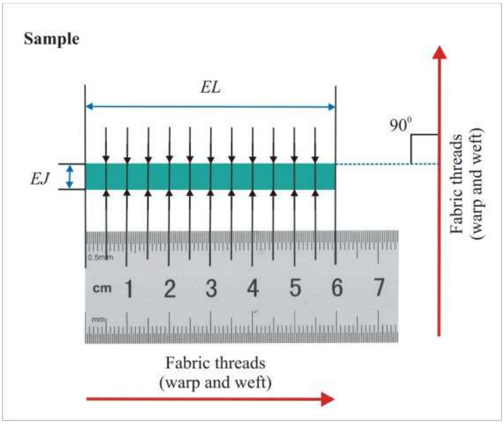


Fig. 2. Strip-shaped embroidery element length and width measurement diagram where: *EJ* – embroidery element width, *EL* – embroidery element length

The research analyzes the average lengths and widths obtained. The coefficient of variation in the length of the element did not exceed 4 %, the coefficient of variation of the width did not exceed 5 %.

Research methodology for the investigation of close-circuit square-shaped embroidery elements. 60 × 60 mm square-shaped close-circuit elements were embroidered using filling type *T*. The selected circuit widths of 6 mm, 10 mm, 14 mm, 18 mm, and 22 mm allowed different shapes of elements to be obtained. Point *A* is the start and end point of the embroidery process (Fig. 3). The embroidered element is obtained by embroidering two segments in the weft direction – segments *AB, CD*, and by embroidering two segments *BC, DA* in the warp direction. The geometric parameters of the elements were measured using the COREL DRAW 12 software package. The results of the investigation were statistically processed and the variability of the results did not exceed 6 %. Measurement tolerances have varied from ± 1% to ± 5%.

<u>Research methodology for the investigation of contour width of square-shaped elements.</u> Measurements of the contour width *EW* are carried out on all sides of the square within the length and height of the element, at the intersection points of the inside circuits, and at quarter and central points of the inside circuits. The measurement diagram is shown in Fig. 3.

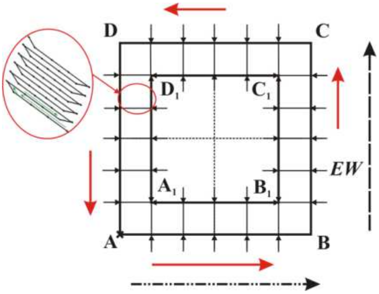


Fig. 3. The embroidery element contour width measurement diagram: where *EW* – the contour width of the embroidered element, A – the start and end points of embroidery, → – embroidery direction, -··-··→ in the direction of weft ---→ – in the direction of warp

The research analyzed the average obtained width of the embroidery element *EW*. The overall relative incorrectness of the results of measurements ranged from 1 % to 5 %. The coefficient of variation did not exceeded 5%.

<u>Research methodology for measuring of uncertainty of contour width of square-shaped embroidery elements.</u> The reliability of analysis method of geometric parameters for the investigated embroidery elements was analyzed taking into account general, group and specific research factors. The uncertainty is analyzed by evaluating the sources of process factors for systematic or random errors. Calculation of uncertainty is based on the available different variables.

The study considers that the components $\Delta l_{ic}, \Delta l_{SP}, \Delta l_{dp}$ are fixed at zero rather than uncertainties thereof, and they are not related. Where: Δl_{SP} – the influence of sample preparation process, Δl_{ic} – the influence of digital image calibration, Δl_{dp} – the influence of data distortion.

When analyzing the metrological parameters of the measurement method, it is intended that the parameters defining the measurement uncertainty value are adequate for the measuring purposes, i.e. the required accuracy. Based on this statement, the study analyzed the uncertainties of the measurement method.

The uncertainty of the result is evaluated according to a Flow Algorithm Scheme provided in Fig. 4.

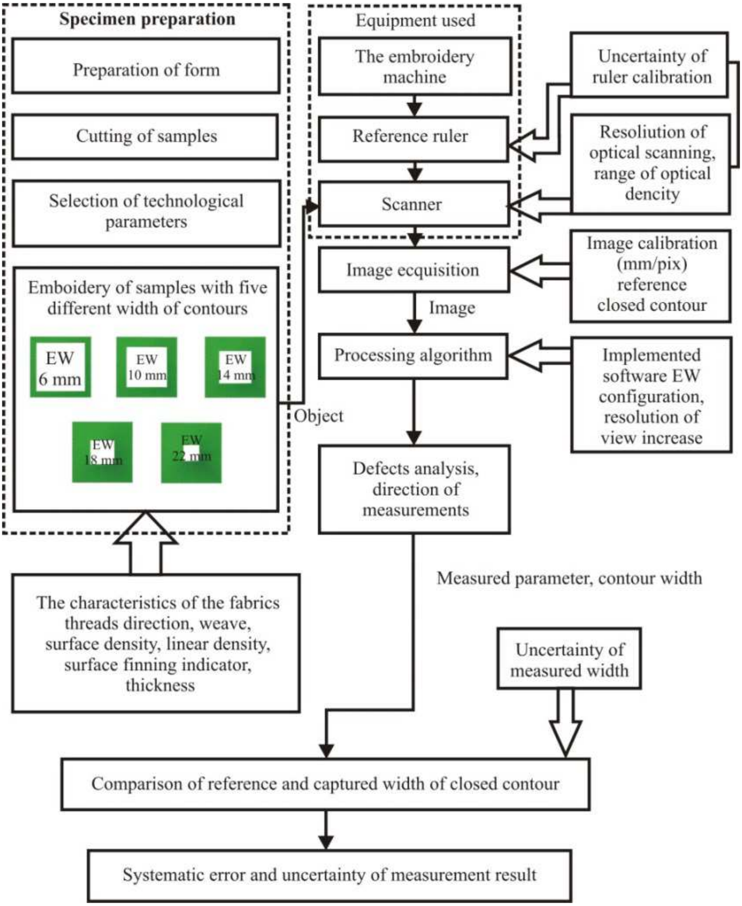


Fig. 4. Flow chart of geometrical parameters (width) measurement and sources of uncertainty

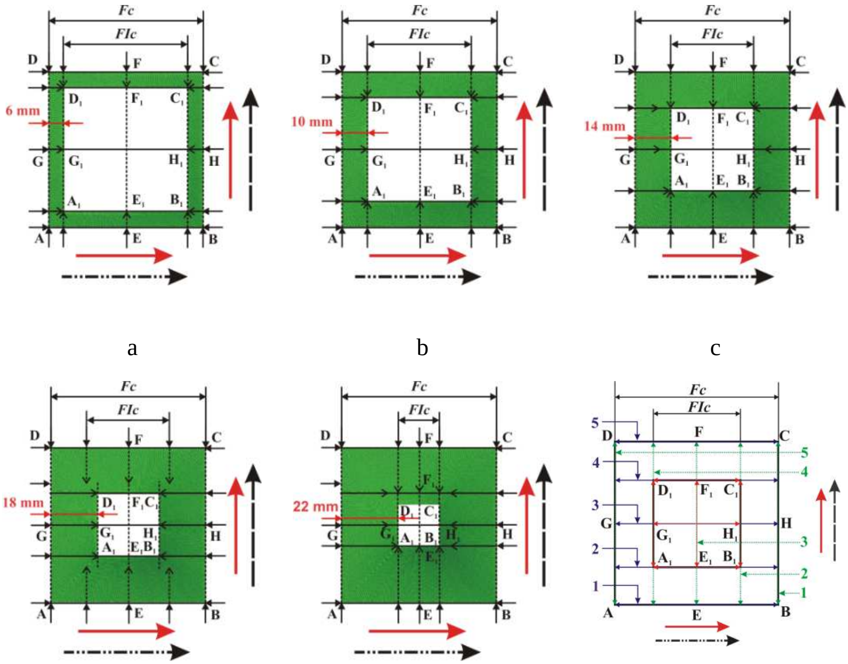
The extended uncertainty of five different circuit widths was evaluated by using the Monte Carlo simulation technique. The algorithm for the Monte Carlo technique analyzes total uncertainty components:

- standard deviation of the obtained average results for warp direction contour width measurement;
- standard deviation of the obtained average results for the weft direction contour width measurement;
- reference ruler calibration uncertainty;
- digital image calibration;
- data processing;

- preparation of element.

The linear displacement detected during the investigation is related to the displacement measurements and digital image analysis. The expanded measurement uncertainty is calculated using a coverage factor of k = 2, with normal distribution and coverage probability P = 0.95. The thesis calculates the maximum deviation from the average error of circuit width, i.e. standard uncertainty is 0.07 mm, related to a contour width of 18 mm.

<u>Research methodology for the investigation of inside and outside widths of square-shaped elements.</u> Due to the peculiarities of the closed circuit and square shape, the investigation analyzes the outside element width *Fc* and inside element width *FIc* (Fig. 5).



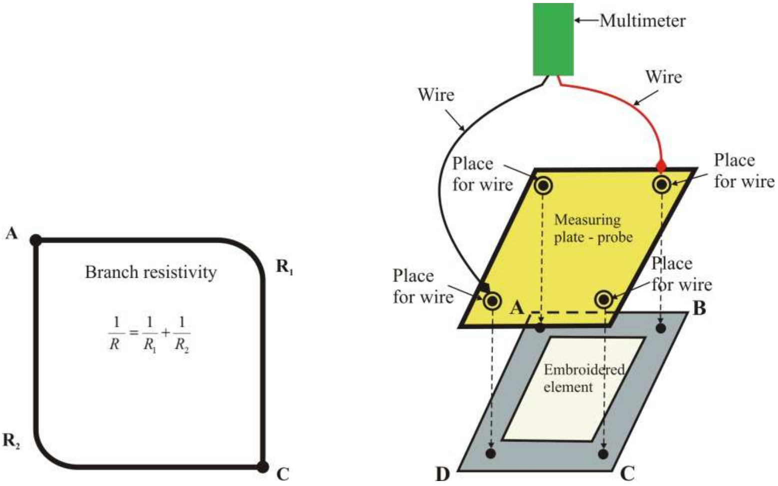
a b c

d e f

Fig. 5. Square-shaped embroidery element outside width *Fc* and inside width *FIc* measurement diagram: where a – contour width 6 mm, b – contour width10 mm, c – contour width14 mm, d – contour width 18 mm, e – contour width 22 mm, f – outside width *Fc* measured sections diagram, → – embroidery direction, -··-··→ – in the direction of weft, – – → – in the direction of warp

The outside element width *Fc* measurement was carried out within the length of the sides, at the intersection points of the inside circuits, and at the central points of the circuits (Fig. 5., f). Measuring points of the outer width *Fc* of the square-shaped embroidered elements in the direction of axis x of the diagrams are marked with numbers *1, 2, 3, 4, 5*. The inside element width *FIc* was carried out within the length and the center of the sides (Fig. 5). The experiment examines the outside *Fc* and inside *FIc* widths of the embroidered elements. The arithmetic average of 6 samples is considered as the final width values. The measurement tolerance has varied from ± 1% to ± 2%. The coefficient of variation did not exceeded 5 %.

Research methodology for square-shaped electrically conductive embroidery elements. 60 × 60 mm and 6 mm and 14 mm wide closed circuit square-shaped embroidery elements have been used for the research in order to evaluate the influence of technological parameters on the electrical conductivity of the embroidery elements. The embroidered closed-circuit elements of widths 6 mm and 14 mm were made using type *T* filling with two stitch densities: 3 stitches/mm and 4.5 stitches/mm (Fig. 3). Measurements of resistance of the investigated closed circuit to the electrical conductivity (electrical resistivity) *R* (Ω) were carried out within the range of the square-shaped circuit (Fig. 6, a). In the study, the measuring wires are firmly connected to the measured circuit by attaching them to a special frame (Fig. 6., b).



a b

Fig. 6. The analyzed diagrams of the electrically conductive embroidery element: a – electrical resistivity diagram, where *R* (Ω) – electrical resistivity; b – electrical resistivity measurement scheme

The measurements of the electrical resistivity of the embroidered square-shaped contour embroidery elements were performed using a multimeter BRYMEN BM811S.

The obtained averages of electrical resistivity R of the embroidered closed-circuit element were analyzed. Statistical processing determined the value of the variation coefficient to be up to 6 %, and the relative error of the measurements was from ±1 % to ± 7%.

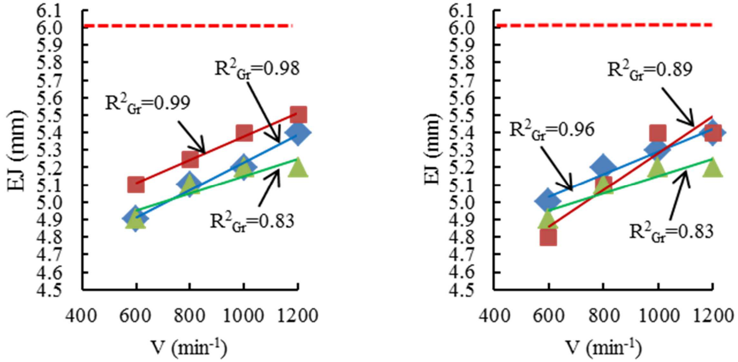
Evaluation of changes of geometric parameters of the electrically conductive embroidery element after a washing cycle. After the process of embroidery with conductive thread, in order to estimate the influence of operating factors on the element's contour width CS_K the objects tested in accordance with LST EN ISO 6330:2012 have been treated with seven wash cycles and dried by hanging up in the extended position. The width of the embroidery element contour CS was measured before each wash cycle, and the width CS_K –after the first, third, fifth and seventh wash cycle. The widths of the electrically conductive embroidery elements CS and CS_K were measured according to the above methodology. The contour width measurement diagram is shown in Fig. 7.

Research measurement results were obtained from the arithmetic average of five samples. Disseminating research results of contour width of all investigated sample elements is low, the coefficient of variation did not exceeded 6 %, and the relative error of measurements did not exceeded 7 %.

Chapter III part one.

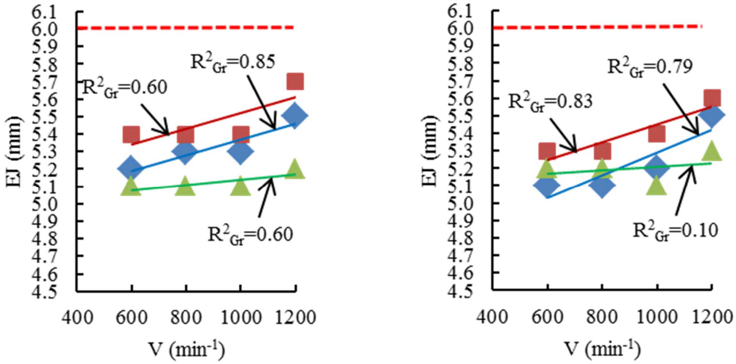
The influence of technological factors and material properties on geometrical parameters of a strip-shaped embroidery element. The investigation of lenghts of embroidery elements EL formed with filling type *Z* and different speed levels, and when comparing them with the design size has shown that the length of the embroidery element closest to the designed one was obtained when the the embroidery element was performed on the fabric A2 in the weft direction with the speed of the embroidery process $V = 1000$ min^{-1}. When the embroidery element is formed with filling type *Z*, in all cases the length of the element is less than the length of the designed element. The results of the investigation of width of the embroidery element *EJ* showed that using different embroidery speed results in an uneven width of the embroidery element. In most cases, there is a strong linear dependence between the width of the embroidery element *EJ* and embroidery speed *V*, min^{-1}(Fig. 7).

The results of the research have shown that the length and width of the embroidery element formed with another filling type *T*, also do not match the design size and depends on the speed of the embroidery process (Fig 8).



a b

Fig. 7. Dependance of width *EJ* (mm) of the embroidery element formed with filling type Z on the embroidery speed *V*, min^{-1}, when the fabric embroidery direction: a – in the direction of warp, b – in the direction of weft, width of the designed element; ◆ – fabric A1; ■ – fabric A2; ▲ – fabric A3



a b

Fig 8. Dependence of width *EJ* (mm) of the embroidery element formed with filling type *T* on the embroidery speed *V*, min^{-1}, when the fabric embroidery direction: a – in the direction of warp, b – in the direction of weft, when - - - – width of the designed element; ◆ – fabric A1; ■ – fabric A2; ▲ – fabric A3

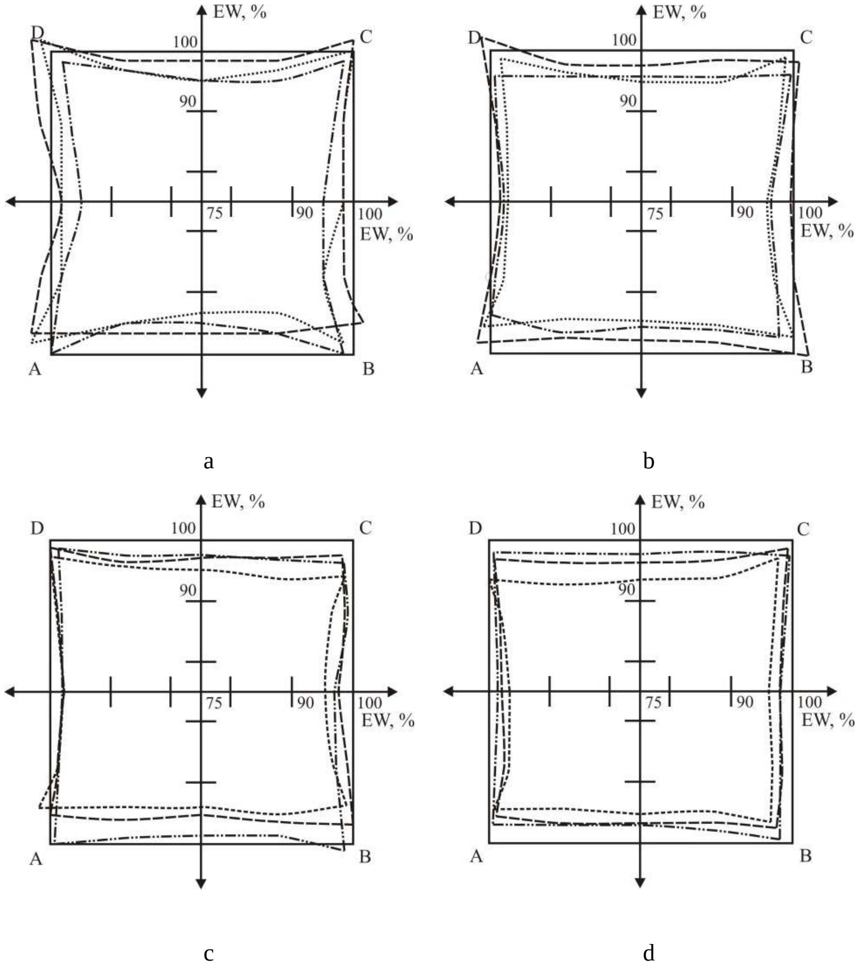
The analysis of investigation results of embroidered elements formed with filling type *T* and warp and weft directions showed that the *EJ* width of the embroidery element is closest to the designed width at the maximum speed of V=1200 min^{-1}. On both fabric directions there is a strong linear correlation dependance of width of the embroidery element on the embroidery speed (R^2_{Gr} to 0.85) (Fig. 8).

When comparing different filling types *Z* and *T*, it was found that the length of the embroidery element *EL* embroidered with filling type *Z* is less than the length of the designed element, whereas the length of the embroidery element embroidered with filling type *T* is close or higher.

The research determined that the width of the embroidery element *EJ* increases along with the increasing embroidery speed *V*. When forming embroidery elements with filling types *Z* and *T*, at the process speeds of 600, 800 and 1000 min^{-1}, width of the element *EJ* from ~ 10 % to ~ 18.3 %, and at the process speed of V = 1200 min^{-1} from ~ 5 % to ~ 11.7 % obtained less than the designed value.

Analysis of compliance of different contour widths of square-shaped embroidery elements to the designed elements. Analysis of contour width of the embroidery element *EW* and its comparison with geometrical parameters of the designed element showed that contour width *EW* in warp and weft directions does not meet the designed value (Fig. 9).

The most accurate contour width of the embroidery element fabric A1 (~ 2.1 % less than the designed width) was obtained by embroidering at a minimum width of 6 mm (Fig. 9., a). Comparison of all A2 fabric closed circuit square-shaped embroidery element contour widths *EW* with the designed one and internal comparison shows that the most accurate contour width of the embroidery element *EW* meeting the designed width was obtained in the warp direction sections of 6 mm and 10 mm sample contour widths (Fig. 9).

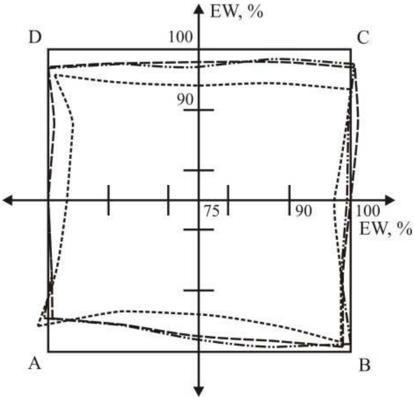


a

b

c

d



e

Fig. 9. Contour width of the embroidery element *EW* (%) when contour width of the designed element: a – 6 mm, b –10 mm, c – 14 mm, d – 18 mm, e – 22 mm, where — – contour width of the designed element *EW*(%), contour width of the embroidery element *EW* (%)accomplished on: ┄┄ –fabric A1, – – – – fabric A2, –··– – fabric A3

The research showed the slippage of fabric threads with respect to the other contacting system in the elements with at maximum contour width of 22 mm. The investigation showed the formation of a fabric buckle at the corners of the embroidery elements, which is not covered with embroidery threads. Buckling of textile fabrics can be observed under crushing and low longitudinal forces. During buckling, due to transverse compression forces, they lose flatness , form a round wave that changes in shape with increasing compression deformation. This defect-buckling and lack of stitches at the corners of the embroidery element can be described as the effect of the buckling phenomenon that is strongly affected by tensile stress concentrations formed near the defect.

The obtained width of the smallest contour of embroidered elements *EW* of fabric A3 in the warp direction section *BC* is ~ 3.3 % less than the designed width, the width in the other section of the same direction *DA* is ~ 1.7 % less (Fig. 9., a). The investigation of widths of embroidered elements of fabric A3 in the warp direction showed that the average value of width *EW* is up to ~ 1.7 % less than the designed width.

The comparison of the investigated embroidery elements contour widths *EW* of all fabrics in the warp and weft direction with the designed one shows that in most cases the embroidery elements of twill weave fabric A2 are closest to the designed value (the obtained width *EW* is from ~ 0.1 % to ~ 3.4 % less than the designed one) (Fig. 9).

The investigation of changes in the width of the closed-circuit square-shaped embroidery elements showed a linear reverse dependence between fabric filling indexes and changes in *EW* contour width Δ*P* (%), which means that the fabric thread filling indexes affect the geometrical parameters of the close-circuit embroidered element. The investigation showed an average and high inverse dependence (Fig. 10).

It can be stated that in most cases the contour width *EW* of the closed-circuit square-shaped embroidery element is closer to the designed width in the warp direction. In the investigated case, the linear filling indicators e_1 in the warp direction is from ~ 33 % to ~ 45 % higher than the linear filling indicators e_2 in the weft direction. The determined A2 fabric filling indicator e_s is from ~ 1.4 % to ~ 6.9 % higher than those of other investigated fabrics. Thus, taking into account the characteristics of the investigated fabrics and after an evaluation of the results, it can be stated that the filling indicators have a significant influence on the contour width of the embroidery element.

The information obtained during the investigation shows that five *EW* widths of the investigated fabrics embroidery elements are not equivalent to the designed width and also depend on technological peculiarities of the filling type, composition of fabric and direction of stitches of the embroidery element in respect of the fabric. The obtained results show that the elements are closer to the designed size at a higher filling index of the fabric.

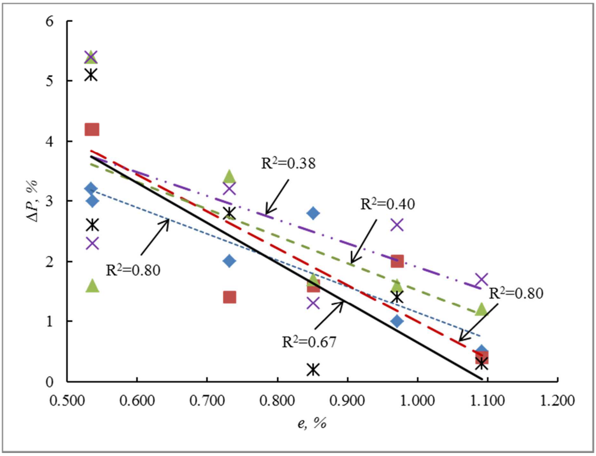


Fig. 10. The dependency of contour width changes of the embroidery element Δ*P* (%) on the indexes of fabric filling e (%), when the contour width of the embroidery element *EW*: ◆ – 6 mm; ■ – 10 mm; kai ▲ – 14 mm; kai × – 18 mm; kai ✳ – 22 mm

Uncertainty assessment of an investigation technique for contour width of square-shaped embroidery elements. According to the developed investigation technique the analysis used the Monte Carlo Simulation Method, in which uncertainties of individual components affect total uncertainty. It can be assumed that the uncertainties of individual components have an influence on the total uncertainty, and their components $\Delta l_{ic}, \Delta l_{SP}, \Delta l_{dp}$, despite their uncertainties, are not related to each other. It is believed that the measurements used are considered to be independent of the sample position and the standard width in the area.

The total deviation of the test sample width from the designed sample is as follows:

$$\Delta l = ((\bar{l}_{w1} + \bar{l}_{w2})/2) - l_s + \Delta l_{ic} + \Delta l_{dp} + \Delta l_{SP}; \tag{1}$$

The information obtained during the investigation shows that the average dissipation of the measured values of different woven samples and contour width is equal to 3.5 %, and the absolute value varies from 0.2 mm to 0.8 mm depending on the width of the contour (6 mm – 22 mm).

The contour width of the element in both directions of warp and weft are highly correlated with each other. Therefore, the standard uncertainty of measurement of the nominal contour width of the individual samples consists of three components, one of which is the correlation component of the estimation of the contour width in different directions. Covariation of estimates l_{w1} and l_{w2} gives an additional contribution to the uncertainty of measurement of the width. Multiple measurements of samples of the same width allowed the calculation of average standard deviations in both directions of warp and weft, as well as an evaluation of the correlation coefficient. Therefore, the following formula is used for the calculation of a total uncertainty in the estimation of the sample width:

$$u(l_m)_i = \sqrt{\sigma^2(\bar{l}_{w1})_i + \sigma^2(\bar{l}_{w2}) + 2\sigma(\bar{l}_{w1})_i \cdot (\bar{l}_{w2})_i r(\bar{l}_{w1_i}\bar{l}_{w2_i})} \tag{6}$$

It was revealed that in most cases the sample is dominated by the component of the sample preparation (which represents on average around 40 % of the total standard uncertainty). The components of uncertainty of measurement of contour width in both directions of warp and weft represent on average around 25 % of the total standard uncertainty and decreases with increasing contour width (Fig. 11).

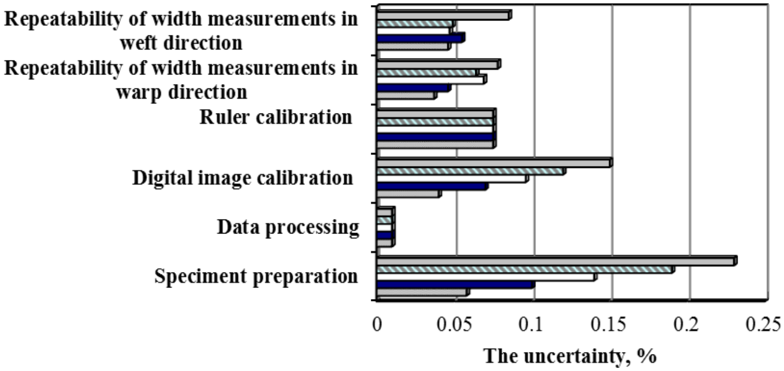
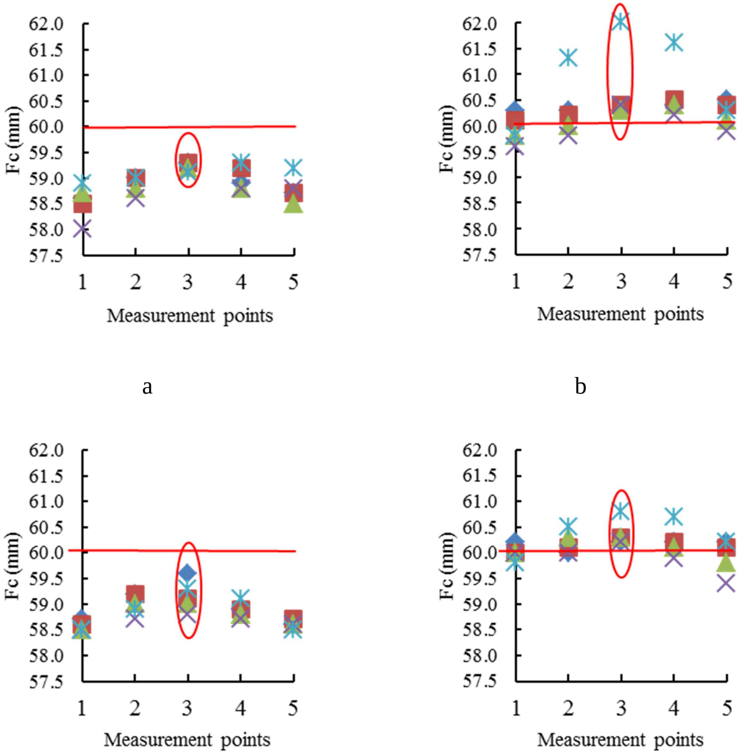


Fig. 11. The influence the uncertainty components % on the total uncertainty, when the contour width of the embroidery element: ▩ – 6 mm, ■ – 10 mm, □ – 14 mm, ▨ – 18 mm, ▒ – 22 mm

The investigation showed that in the case of defined material characteristics, this method has a negative error of ~ 2.4 %, with an expanded uncertainty of ~ 3.3% for measuring the width of the embroidered contour between 6 and 22 mm. The obtained tolerance is not high and the results are reliable. On the other hand, this shows that particular attention should be paid to the preparation of the sample and on the measurement of width of the closed-circuit embroidery element in relation to the direction of fabric threads.

***Investigation of accuracy of the width of the outer and inner squares of the square-shaped embroidered elements*.** The results show that the average outer width Fc of the element made on fabric A1 does not meet the fabric in the direction of warp. The comparison of the outer width Fc of the entire embroidery element of fabric A1 at different meassuring points with the designed width, leads to the conclusion that the outer width *Fc* at the measured angular positions and at the center is determined to be uneven (Fig. 12., a, b).

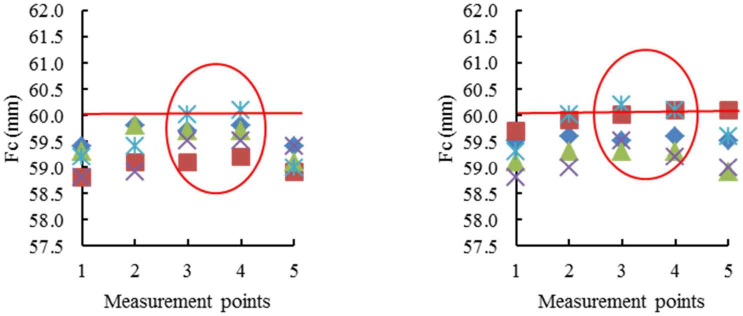


a

b

c

d



e f

Fig. 12. Outer width *Fc* of the embroidery elements, when the contour width of the designed element is ◆ – 6 mm, ■ – 10 mm, ▲ – 14 mm, × – 18 mm, ✳ – 22 mm: a – accomplished on fabric A1 in the direction of warp, b – accomplished on fabric A1 in the direction of weft, c – accomplished on fabric A2 in the direction of warp, d – accomplished on fabric A2 in the direction of weft, e – accomplished on fabric A3 in the direction of warp, f – accomplished on fabric A3 in the direction of weft

The investigation found that in the direction of the warp of fabric A1, at the marginal measured points, the change in the outer width of the entire element is that Fc is ~ 3.3 % greater than at the centre, where the change in the outer width of Fc is ~ 1.2 %. Meanwhile, the obtained outer width Fc in the direction of weft at the marginal measured points of the section AB (Fig. 12., b, measured points 1, 2) is closer to the designed value than at the section *CD* (Fig.12., b, measured points 4, 5). It should be emphasized that the determined outer width *Fc* of the element at the central measured points is from ~ 0,5 % to ~ 3,4 % greater than the designed one (Fig.12., a, b, measured points 3).

The analysis of shape of the inner square showed that in many cases the inner shape of the embroidery element does not match the designed shape. The results showed that the inner width of the square *FIc* of fabric A1 in comparison with the designed width in the direction of the warp has changed more at the corners than at the center. Taking into account the average value, the obtained inner width *FIc* of the closed-circuit square-shaped elements of width of 6 mm, 10 mm and 18 mm accomplished on fabric A1 in the direction of the warp is ~ 0,6 % to ~ 1,3 % less than the designed value. The change in the inner width *FIc* of the inner square embroidery elements of 14 mm contour width in comparison with the designed value in the direction of the warp at the measured points B_1C_1, E_1F_1 have met the designed value. In general, it was found that the obtained width *FIc* in the direction of the weft is closer to the designed value.

The investigation found that the direction of the embroidery, fabric properties and the contour width of the embroidery element has a significant influence on the quality of the embroidery element. In this case, in all the investigated fabric, the obtained elements of fabric A2 were closer to the designed value.

The investigation of widths of the embroidery elements accomplished on fabric A2 showed that the width of the entire element Fc mostly differs at the ends of the measurable sections, and in most cases the outer width Fc is less than the designed width. (Fig. 12., c, d). The obtained width Fc of the embroidery elements of width of 6 mm, 10 mm and 14 mm in the direction of the warp is ~ 1.3 % to ~ 2.5 % less than the designed value (Fig. 12., c). However, the obtained width Fc of the embroidery elements in the direction of weft is close to the designed width (Fig. 12., d).

The entire outer width Fc of fabric A2 in the direction of weft, with the contour width of 6 mm, 10 mm, 14 mm, is determined as close to the designed value. (Fig. 12., d). Investigation of elements with contour width of 18 mm accomplished on fabric A2 showed that the entire width Fc in the direction of warp in all measured points varied from 58.5 mm to 58.8 mm, i.e. the obtained outer width Fc is from ~ 2 % to ~ 2.5 % less than the designed one. Whereas the obtained entire width Fc at some points of elements of the mentioned contour width in the direction of weft is close to the designed value. Investigation of the shape of the elements with the highest contour width of 22 mm and its comparison with the designed one showed that the obtained entire width Fc of fabric A2 in the direction of warp is from ~ 1.2 % to ~ 2.5 % less than the designed width, whereas the width of the element in the direction of weft in most cases is larger by approximately ~ 0.7 % than the designed one (Fig. 12).

The analysis of inner width FIc of the inner square of embroidery elements accomplished on fabric A2 showed that in most cases the average width FIc in the direction of warp is less than the designed one. It is established that the difference is ~ 1.3 % when the width contour is 6 mm and 10 mm. In results of elements of a larger contour width of 14 mm and 18 mm, their width differs by ~ 0.9 %. Whereas the investigation of the elements with the largest contour width of 22 mm showed that the obtained average width Flc of the element in the direction of warp is ~ 3.1 % larger than the designed width.

The obtained average square width Flc of fabric A2 in the direction of weft in the case of larger contour widths of 14 mm, 18 mm and 22 mm is ~ 0.6 %, ~ 1.7 %, ~ 4.4 % larger than the designed width. Fabric weave, structure, direction and physical characteritics have a significant influence on deformations. The investigated woven fabrics differ by the type of weaving and level of yarn crimp – these factors are important when applying embroidery threads into the structure. The comparison of results of inner contour widths FIc of all the investigated group of samples showed that in general, the inner contour width *FIc* of elements accomplished on fabric A2 is closest to the designed width. During stretching, the tensile strength of the fabric yarns, along with increasing friction between yarns and depending on the type of the woven fabric and characteristics – affects the occurrence of higher tensile strength. Therefore, it can be said that during the formation of stitches, the yarn systems are unevenly compressed and this affects the obtained results related to the inner width *FIc* of embroidery elements.

The investigation of embroidery elements accomplished on fabric A3, showed that the outer width *Fc* of the embroidery element in both directions of fabric yarns is similar (Fig. 12., e, f). In most cases, the entire square width *Fc* of the elements embroidered in warp and weft directions is up to ~ 1 % less than the designed one. The analysis of elements with contour widths of 6 mm, 14 mm and 22 mm accomplished on fabric A3 in the direction of warp shows that the entire outer width *Fc* differs from the designed width by approximately ~ 0.8 %. When the contour width is 10 mm, then the entire width obtained is ~ 1.7 % less than the designed one. When the width is 14 mm, then the entire width *Fc* obtained is ~ 1.3 % less than the designed one (Fig. 7., e). Investigation of the shape of the elements with the smallest contour width of 6 mm showed that the determined width of the entire square *Fc* in this direction is ~ 0.8 % less than the designed width. The closest entire width *Fc* of fabric A3 in the direction of weft is obtained with a contour width of 10 mm.

For samples with contour widths of 14 mm and 18 mm, the entire outer width *Fc* obtained is ~ 1.5 % less than the designed width. In the case of the maximum width, the *Fc* width differs from the designed one by ~ 0.3 % (Fig. 12., f). The outcome of the investigation showed that in all cases the shape of elements embroidered on fabric A3 in both directions is narrower at the edges than that in the center (Fig. 12., e, f). In both directions, the obtained outer width *Fc* does not meet the designed value by up to ~ 1.7 %. In the case under investigation, the linear filling indexes of fabric A3 in different directions are closer than those of other investigated fabrics.

The investigation showed that regardless of the contour width, the outer width *Fc* of the embroidery element in all cases is narrower at the edges than that in the center. This applies to both directions of fabric yarns (Fig. 12.). In most cases, the investigated embroidered elements were of smaller size (Fig. 12.). Diameter, density, length of threads, fabric weave, how tight the fibres are placed, interconnected with each other and fiber cohesiveness are the most important factors that influence the geometrical parameters of the fabric. Since the surface density of fabric A2, yarn density and linear density is the highest of all the investigated fabrics, then the obtained elements accomplished on fabric A2, taking into account their average values, are closer to the designed value than those of other fabrics (Fig. 12).

Based on the results obtained, it can be stated that the determined changes in geometrical parameters of embroidery elements have an influence on the stability and accuracy of the embroidery element. Direction of the process, with respect to the fabric structure and technical characteristics of used filling type, are very important for the accuracy of embroidery elements (Jucienė, etc., 2016). In this case, filling type T, with the wider closed square-shaped contour, longer lines of stitches are formed in the embroidery elements compared to those in the investigated narrower contours. Considering the filling type *T* of the embroidery, stitch overlap is on the reverse side of the embroidery system, therefore, the yarn tensile loads are not uniformly distributed. When joining longer lines of stitches of filling type *T*, the upper sewing thread passes more times through the needle hole than in shorter stitch lines, therefore the embroidery elements of wider closed contour undergo higher mechanical stress.

The analysis of shapes of elements revealed one common defect of the shape – curved sides at the center of the square (Fig. 13).

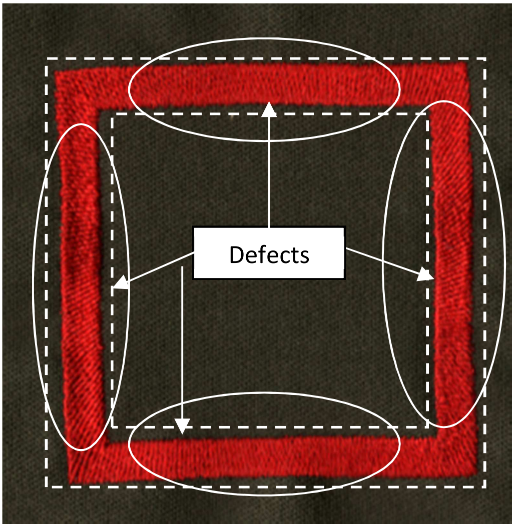
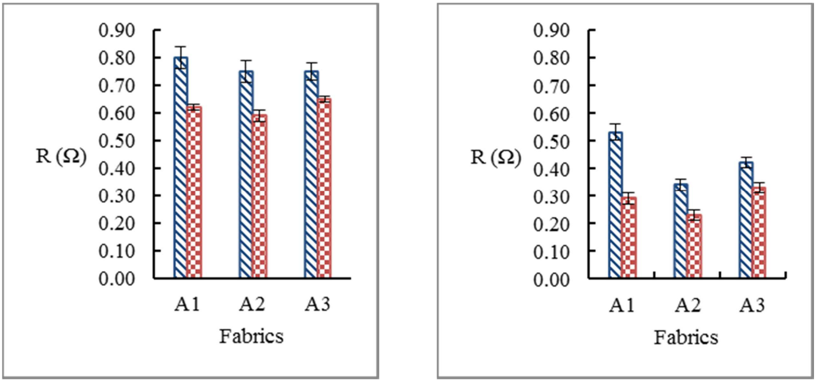


Fig. 13. Defects of sides of square-shaped embroidery elements accomplished on fabric A3 elementų

The analysis showed that the conformance of geometrical parameters of the embroidery elements to the designed value is closely related to the shape stability. It was determined that the investigated geometrical parameters of closed-circuit square-shaped elements, i.e. outer width *Fc* and inner width *Flc*, is different in relation to the fabric yarn system.

The assessment of functionality of electrically conductive embroidery elements**.** The electrical conductivity of the circuit is analyzed by evaluating the electrical resistivity R of the embroidered closed-circuit. The higher the resistance in electrical circuits, the lower the conductivity, and vice versa – the lower the resistance, the higher the conductivity. The analysis of electrical conductivity of the embroidered closed-circuit element showed that the difference in the electrical resistivity *R* depends on the technological parameters. When the elements were filled with a higher stitch density (4.5 stitches/mm) and the contour was 6 mm and 14 mm wide, in all cases the obtained electrical conductivity was higher than those elements filled with a density of 3 stitches/mm. The obtained results showed that conductivity of closed-circuit embroidery elements of 14 mm contour width was ~ 34 % to ~ 61 % greater than that of 6 mm wide. In this case, the determined electrical resistivity R (Ω) is from 0.59 Ω to 0.80 Ω (Fig. 14).

This comparison of electrical resistivity *R* of all the investigated fabrics of 6 mm contour width filled with a density of 3 stitches/mm and 4,5 stitches/mm, shows that conductivity of elements filled with density 4,5 stitches/mm is higher by ~ 19 % to ~ 21 % (Fig. 14., b). Among all test samples under investigation, the greatest conductivity was achieved when the elements were accomplished on fabric A2. In this case, the electrical resistivity *R* of fabric A2 elements was 0.59 Ω and 0.75 Ω, which is from ~ 6 % to ~ 9 % lower than the resistance *R* of the other test samples (Fig. 14., a).



a b

Fig. 14. Resistance of the embroidery closed-circuit element to the electrical conductivity *R*, when the designed contour width of the element is: a – 6 mm; b –14 mm, in case of stitch densities ▨ – 3 stitches/mm, ▦ – 4,5 stitches/mm

Experimenting on the elements of a wider 14 mm contour width filled with stitches of different density showed that the conductivity was by ~45 % to ~61 % higher when the stitch density was 4.5 stitches/mm. In this case, the electrical resistivity R of the embroidered elements accomplished on fabric A2 was also the lowest and their electrical conductivity in comparison to the elements accomplished on the other fabrics was by ~ 32 % to ~ 38 % higher (Fig. 14., b).

Analysis of factors that have an influence on functionality of electrically conductive embroidery elements showed the linear dependence between fabric filling indexes and electrical resistivity, where the reverse correlation coefficient R_K between the index of the fabric filling and electrical resistivity R (Ω) in cases where the stitch density of the contour was 4.5 stitches/mm was from 0.9 to 0.95.

The results of the analysis showed that in general cases the stitch density used in the process has the greatest influence on conductivity of the embroidery elements. The highest electrical conductivity was determined when the contour width was larger, which in the case under investigation was 14 mm, and the stitch density was 4.5 stitches/mm. In general, the highest electrical conductivity was obtained when the embroidery elements were produced on fabric A2 (Fig. 14).

The performed analysis showed that in most cases a higher electrical conductivity is obtained in closed-circuit square-shaped 14 mm width contour fabrics of different weave than in 6 mm contour width elements (Fig. 14).

The investigation showed that the electrical conductivity of closed-circuit square-shaped 14 mm width contour elements is ~ 34 % to ~ 61 % higher than the conductivity of 6 mm width contour elements, the electrical resistivity R (Ω) obtained 0.59 Ω to 0.80 Ω. The research found that the contour width and stitch density has a great influence on the electrical conductivity of closed-circuit embroidery element depending on characteristics of the fabric. The highest electrical conductivity was reached on the elements of a wider, 14 mm contour width and stitch density 4.5 stitches/mm.

Analysis of the investigation results revealed that the difference between the electrically conductive element contour width *CS* in the direction of warp and weft ΔE (%) varies compared with the designed one (Fig. 15 – 16).

When comparing the results of contour widths *CS* of all electrically conductive embroidery elements fabric samples within and between the designed values, it was found that contour width *CS* is closest to the designed one when the samples contour width is 14 mm and the applied density of 4.5 stitches/mm. In general, the average contour width *CS* closest to the designed one was obtained in samples accomplished on fabric A2, only ~ 1.8 % greater than the designed one. The greatest non-compliance of contour width *CS* with the designed size (on average, up to ~ 3.5%) was obtained mostly in samples accomplished on fabric A3 (Fig. 15 – 16).

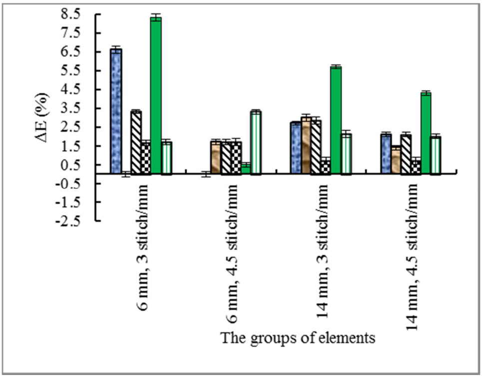


Fig. 15. Difference ΔE (%) of the contour width CS of electrically conductive embroidery elements with the designed size in the direction of warp, when the contour width of the designed element is x axis: 🟦 – fabric A1 contour side *BC*; 🟫 – fabric A1 contour side *AD*; ▧ – fabric A2 contour side *BC*; ▦ – fabric A2 contour side *AD;* 🟩 – fabric A3 contour side *BC*; ▥ – fabric A3 contour side *AD*

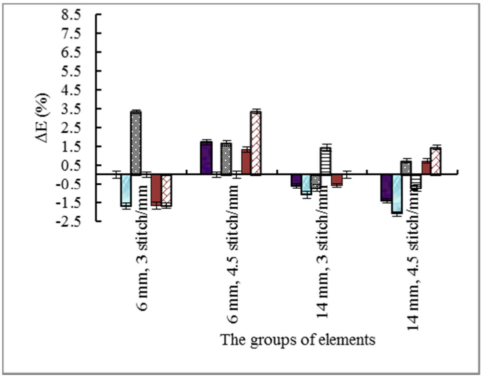


Fig. 16. Difference ΔE (%) of the contour width CS of electrically conductive embroidery elements with the designed size in the direction of weft, when the contour width of the designed element is x axis: 🟪 – fabric A1 contour side *BC*; 🟦 – fabric A1 contour side *AD*; ▩ – fabric A2 contour side *BC*; ▤ – fabric A2 contour side *AD;* 🟥 – fabric A3 contour side *BC*; ▨ – fabric A3 contour side *AD*

The performed analysis showed that in general the lowest obtained electric resistance R=0.23 (Ω) and the highest conductivity was reached on elements accomplished on fabric A2 with a contour width of 14 mm and stitch density 4.5 stitches/mm. It was determined that contour width CS of elements accomplished on fabric A2 with filling index e_s was from ~ 1.4 % to ~ 6.9 % greater than other tested fabrics and is closer to the designed value, i.e. by ~ 1.8 % greater. It was determined that filling indexes have an influence on conductivity of embroidery elements. The obtained linear dependence (R^2_K to 0.95) between the fabric filling index and electrical resistivity R (Ω) with a density of 4.5 stitches/mm showed the influence of fabric characteristics on the functionality of an embroidery element. By linking the functionality of elements with geometrical parameters, it can be seen that the lowest resistance to the electrical conductivity R=0.23 (Ω) and the contour width closest to the designed one (greater by ~ 1.8 %) was obtained with a contour width of 14 mm and stitch density 4.5 stitches/mm. This demonstrates that the same factors have an influence on the functionality and geometrical parameters of the elements.

Influence of exploitation factors on the functionality and geometrical parameters of the embroidery element. The investigation results of electrical resistivity after the exploitation processes showed that wash cycles have significantly changed the electrical resistivity R_E (Ω) of closed-circuit embroidery elements (Fig. 17). It was determined that the electrical conductivity of the tested samples of embroidery elements with a contour width of 6 mm and stitch density 3 stitches/mm changed after the first wash cycle and the electrical resistivity R_E (Ω) reduced: elements accomplished on fabric A1 ~ 2.5 %, elements accomplished on fabric A2~ 14.7 %, elements accomplished on fabric A3 ~ 10.7 %. After three wash cycles, the electrical resistivity R_E (Ω) increased respectively: elements accomplished on fabric A1 ~ 23.8 %, elements accomplished on fabric A2 ~ 9,3 %, elements accomplished on fabric A3 ~ 17.3 %. Upon measuring the electrical resistivity after five wash cycles, it was identified that the electrical resistivity of fabric A1 increased by up to ~ 40 %, elements accomplished on fabric A2 ~ 30.7 %, elements accomplished on fabric A3 ~ 33.3 %. The largest difference ΔER in electrical resistivity R_E (Ω) was obtained after a maximum seven wash cycles: for samples of fabric A1 it increased by up to ~ 51.3 %, for samples of fabric A2 – by up to ~ 50.8 %, for samples of fabric A3 – by up to ~ 40 % (Fig. 17).

The obtained results show that the electrical conductivity has increased after the first cycle. The investigation revealed that the resistance of the elements to the electrical current is higher after 3.5 and 7 wash cycles. When evaluating the average of electrical resistivity difference ΔER with non-washed samples, it was found that exploitation processes have the greatest influence on conductivity on the group of samples of elements accomplished on fabric A1 with contour width 6 mm and stitch density 3 stitches/mm (~ 28.1 %), and the lowest influence (~ 15.3 %) on elements accomplished on fabric A2. The average electrical conductivity difference Δ*ER* of fabric A3 was up to ~ 18.7 %. A strong linear correlation was determined between electrical resistivity and wash cycles (R^2_{KS} to 0.96) (Fig 17).

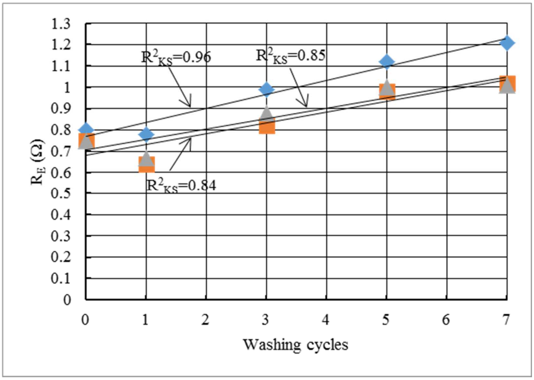


Fig. 17. Electrically conductive 6 mm contour width elements filled with 3 stitches / mm stitch densities closed circuit electrical resistance RE (Ω) after exploitation, where: ◆ – fabric A1 elements; ■ – fabric A2 elements; ▲ – fabric A3 elements

The investigation of the group of samples of embroidered elements with a contour width 6 mm and stitch density 4,5 stitches/mm showed that the electric resistance after the first wash cycle of fabric A1 reduced by ~ 16.1 %, fabric A2 ~ 22 %, fabric A3 ~ 15.4 %. (Fig. 18).

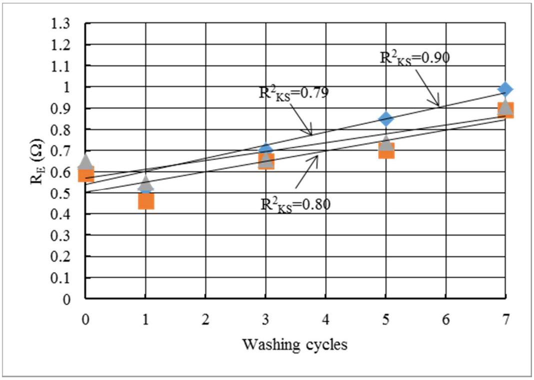


Fig. 18. Electrically conductive 6 mm contour width elements filled with 4.5 stitches / mm stitch densities closed circuit electrical resistance RE (Ω) after exploitation, where: ◆ – elements of fabric A1 ; ■ – elements of fabric A2; ▲ – elements of fabric A3

It was determined that after three wash cycles the resistance to the flow of an electric current of all tested fabrics increased from ~ 1.5 % to ~ 12.9 %. The analysis of conductivity of samples of the mentioned elements after five wash cycles showed that the resistance increased: fabric A1 ~ 37.1 %, fabric A2 – ~ 18.6 %, fabric A3 ~ 13.8 % (Fig. 18).

The analysis of influence of wash cycles on electrical conductivity of embroidery elements with a contour width 14 mm and stitch density 3 stitches/mm showed that the electric resistance of the tested fabric samples decreased from 8.8 % to ~ 24.5 % after the first wash cycle. In this case, a strong linear correlation between electric resistance and wash cycles has been determined (R^2_{KS} to 0.89) (Fig. 19).

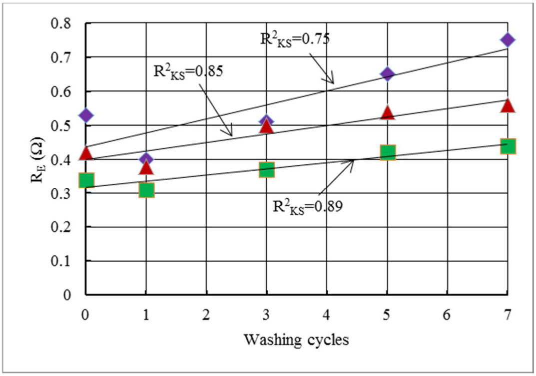


Fig. 19. Electrically conductive 14 mm contour width elements filled with 3 stitches / mm stitch densities closed circuit electrical resistance RE (Ω) after exploitation, where: ◆ – elements of fabric A1; 🟩 – elements of fabric A2; ▲ – elements of fabric A3

The obtained results showed that after seven wash cycles, the electric resistance of the tested samples has increased from ~ 40 % to ~ 59.7 % (Fig. 18). Exploitation processes had the greatest influence on the embroidered elements of fabric A1. The determined strong linear correlation dependence (R^2_{KS} to 0,90) (Fig. 18) of electric resistance of elements with contour width 6 mm and stitch density 4.5 stitches/mm on the number of exploitation processes shows that the electric conductivity reduces with increasing exploitation. The investigation showed that the electric resistance of the tested samples with contour width 14 mm and stitch density 4.5 stitches/mm reduced against that of previously investigated groups of samples. It was determined that exploitation processes mainly influenced the electrical resistivity after the seventh wash process. In all cases, a strong linear correlation was obtained (Fig. 20).

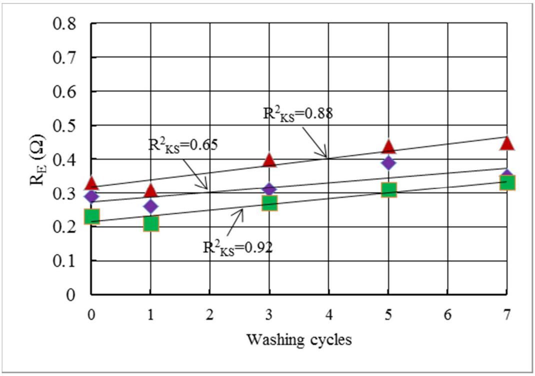


Fig. 20. Electrically conductive 14 mm contour width elements filled with 4.5 stitches / mm stitch densities closed circuit electrical resistance RE (Ω) after exploitation, where: ◆ – elements of fabric A1; 🟩 – elements of fabric A2; ▲ – elements of fabric A3

In general, in the cases the electrical conductivity of fabric A1 embroidery elements with a contour width of 6 mm, the resistance has increased on average ~ 28.1 % (Fig. 17). The exploitation processes had the least impact on fabric A2 samples – in this case the electrical resistivity has only increased on average by ~ 14 %. The obtained results of the electrical resistivity showed the variability of electrical conductivity of the investigated samples depending on technical parameters and quantity of exploitation processes. This is because the investigated samples were embroidered with different contour widths of 6 mm and 14 mm using different stitch densities of 3 and 4.5 stitches/mm. In addition, the samples were mechanically exposed to different cycles and a number of wash processes, during which they were soaked in washing detergents, compressed, rolled, yarn fibers were exposed to friction forces and are therefore more deformed. This aspect affects the faster wear of the product.

The obtained results showed that the electrical conductivity of none exploited elements was higher than those after the 3, 5 and 7 wash cycles (Fig. 17 – 20). The number of wash cycles influences the level of exploitation and moisture of the element. The more often the embroidery element is washed and exposed to moisture and mechanical effects, the more the surface of the element is mechanically exposed and, as a result, the conductivity for absorption increases, resulting in the fabric shrinking and a decrease of electrical conductivity.

The investigation showed that the electrical conductivity of the investigated fabrics varies depending on the characteristics of the fabric, technological parameters and quantity of exploitation processes. It was determined that the exploitation processes mainly affected the electrical resistivity after the seventh wash cycle. In all cases, a strong linear dependence between electrical resistivity and exploitation cycles (R^2_{KS} to 0.96) was obtained.

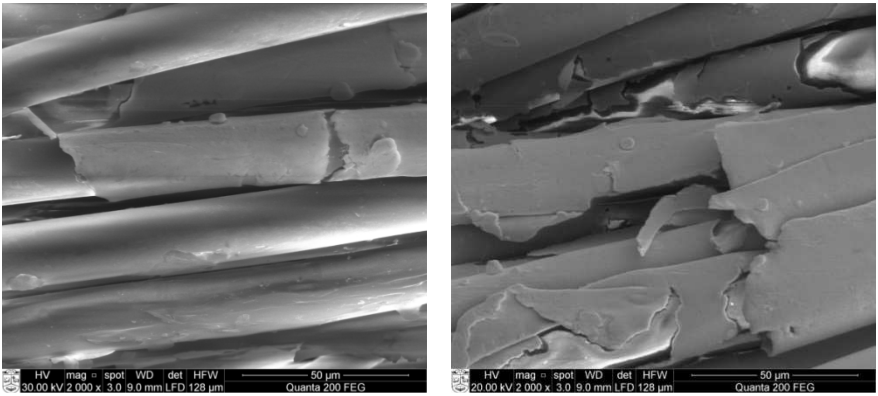
The investigation found that the minimum resistance to electrical conductivity R_E =0.33 (Ω) was determined for samples accomplished on fabric A2, with a contour width of 14 mm and stitch density 4.5 stitches/mm. It was found that the least influence on the electrical conductivity for all groups of investigated embroidery elements was after the first wash cycle, as the electrical conductivity in all tested cases improved after that.

The obtained results showed that after the wash cycles, the contour width of the element CS_K in warp and weft directions was different. It is important that the width CS_K both for embroidered samples CS and washed samples is different between the sides of the same direction.

Comparing the results of all four investigated groups of washed embroidery elements, it was found that in most cases the contour width CS_K in the direction of warp was greater than the embroidered size, but was the closest to it. It was determined that after processes of exploitation, the least difference in width CS_K was found in a group of samples with the element width 6 mm and density 3 stitches/mm. In most cases it was found that the contour width value CS_K moved away from the width of the embroidered contour *CS* after 5 and 7 wash cycles.

Washing is a very common and important process used in cleaning and decoration of various textile products. Due to moisture absorption during washing, the fibers swell and change structure, along with physical and mechanical characteristics of the fabric. Fiber moisture absorption, evaporation phenomena and structural changes are closely interrelated. With the larger number of wash cycles, the diameter of fibers increases; resulting in structure swelling and expansion (Fig. 21).

The comparison of pictures with images of the surfaces of embroidered electrically conductive elements before (Fig, 21., a) and after washing (Fig, 21., b) revealed differences: the fibers were swollen after washing and became thicker, with visible fiber lesions, broken ends and a distorted shape. Therefore, it can be argued that the influence of exploitation on the changes in characteristics of embroidery elements is significant. In the investigated case after 7 wash cycles, the average width of the contour CS_K of the tested fabrics increased from ~ 2.2 % to ~ 4.1 %.



a b

Fig. 21. SEM photos of A2 elements for conductive fabric: a – sample before washing; b – sample after 7 wash cycles

The analysis showed that the width of the embroidery element CS_K was mostly influenced by the higher number of wash cycles and application of higher stitch density. When the embroidery element is made using higher density stitches, 4.5 stitches/mm, in most cases the contour width CS_K in the diderction of warp after the exploitation processes was greater than the designed value, and varied in the direction of weft. It was found that in general, the contour width CS_K , which is closest to the embroidered contour width CS, was obtained in the elements accomplished on fabric A2 in the direction of warp after 1 and 3 wash cycles. During exploitation cycles, the embroidered systems are affected by various mechanical forces in different directions of the fabric, they swell - resulting in irreversible changes in their surface, shape and properties.

The investigation showed that after exploitation, the electrical conductivity and contour width of electrically conductive embroidery elements appeared to have differences in different exploitation conditions and changed depending on the parameters of technological mode, selection of element size and fabric direction. The linear dependence between electrical resistivity and exploitation cycles with correlation coefficient up to $R^2_{KS} = 0.96$, which was revealed in the investigation, shows that the exploitation processes have a great influence on the electrical conductivity of the elements. The performed analysis showed that the higher the electrical conductivity of the elements and the size of the element contour width CS_K closest to the designed one, was identified on elements accomplished on fabric A2, where filling indexes are higher by up to ~ 28 % in the direction of warp, up to ~ 37 % in the directioon of weft, and the general e_s is from ~ 1.4 % to ~ 6.9 % higher than those of other investigated fabrics. As a result, the elements made on this fabric showed the best indicators of functionality and geometrical parameters after the exploitation process.

CONCLUSIONS

1. The analysis of the results showed the differences of length and width of the embroidery elements under the same conditions depending on the type of filling and the direction of the embroidery element in relation to the fabric. In the case of the embroidery element with filling type *Z*, the obtained length in all cases is less than the designed length (to ~ 1.7 %), and in the case of filling type *T*, the obtained embroidery element length is greater than the designed one (to~ 1.5 %).
2. The investigation found that the width of the element embroidered with filling types *Z* and *T*, compared with the designed element width, differs and may vary from ~ 5 % to ~ 20 %. In all the investigated cases, the obtained width of embroidery elements is less than the designed width of the element. In most cases, the width of the element embroidered with filling type *T* is closer to the designed one than that of the embroidered element with filling type *Z*.
3. The investigation showed the strong linear dependence (R^2_{Gr} iki ~ 0,99) between the width of the embroidery element and the embroidery speed. In general, the obtained length and width of samples of the embroidery elements accomplished on the denser fabric A2 with a larger surface density are closer to the designed one than those of elements accomplished on other fabrics.
4. A strong correlation between fabric filling indexes and changes in contour width of the embroidery element has been determined. The obtained linear inverse dependence (R^2 iki ~ 0,80) showed that the technological parameters and properties of fabric structure determine the reaction of systems of embroidered elements to external influences and precision. The contour width of the embroidered element closest to the designed size was obtained on fabric A2 at an embroidery speed of 1200 min^{-1} using filling type *T* in the direction of warp.
5. It was determined that the investigated geometrical parameters, the outer and inner widths are different for the fabric yarn system. The investigation found that irrespective of the width of the contour in both directions of the fabric yarn, the outer width of the element in all cases was narrower at the corners than at the center of the sides and does not meet the designed size by up ~ 6.5 %
6. The reliability of the investigated measurement technique for closed-circuit square-shaped embroidery elements applied for analysis of geometrical parameters is directly related to the measurement uncertainty, which objectively reflects the spread of component values. It was found that, in the

case of material characteristics defined using this method and intended for measuring of contour width of embroidered element from 6 mm to 22 mm, the typical negative error is ~ 2.4% with an expanded uncertainty of ~ 3.3%.

7. The analysis of the effect of the combined standard uncertainty components on the measurement result has shown that particular attention should be paid to the preparation of the sample and the measurement of the width of the embroidered closed contour element, depending on the direction fabric yarns. The components of this uncertainty makes approximately ~ 65% of the total standard uncertainty.
8. The investigation found that after the first wash cycle the electrical resistivity of embroidery elements reduced from 2.5 % to ~ 24.5 % compared to the non-washed samples, and after the third, fifth and seventh wash cycle the electrical resistivity increased by up to ~ 28.1 %. In all cases, the obtained strong linear dependence (R^2_{KS} iki ~ 0,96) between the electrical resistivity and exploitation cycles shows a reduction of electrical conductivity with the higher number of wash cycles.
9. After analyzing the functionality of the elements and the accuracy of their geometrical parameters, it was found that the minimum electrical resistivity 0.23 (Ω), and the contour width closest to the designed one (~ 1.8% higher) were obtained when the contour width of the elements was 14 mm and the density was 4.5 stitches/mm. The investigation showed that the functionality and geometrical parameters of the elements are affected by the same factors of technological process, i.e. contour width and stitch density.
10. During the investigation the highest electrical conductivity was determined when the contour width is larger (14 mm), and the stitch density is 4.5 stitches/mm. Strong linear dependence (R^2_K iki ~ 0,81) between fabric filling indexes and electrical resistivity shows that fabric characteristics have a significant influence on the functionality of the elements.
11. The performed analysis showed that after exploitation the strongest electrical conductivity of the elements and the contour with closest to the designed one was obtained in the elements accomplished on fabric A2, with filling indexes in the direction of warp by up to ~ 28 % and in the direction of weft ~ 37 %, with the total filling indicator from ~ 1.4 % to ~ 6.9 % higher than those of other investigated fabrics, and for this reason; features of functionality and geometrical parameters of the elements accomplished on this fabric were the best after the exploitation process.
12. The research showed that in order to obtain precise electrically conductive embroidery systems it is recommended to use a filling type with denser stitches. When the embroidery elements are filled with higher density stitches of 4.5 stitches/mm and contour widths are 6 mm or 14 mm, in all cases the electrical conductivity is higher than the elements with a filling density of 3 stitches/mm. The obtained results showed that the conductivity

of 14 mm contour width embroidery elements was from ~ 34 % to ~ 61 % higher that those of 6 mm contour width. In this case, the detected electrical resistivity was from 0.59 Ω to 0.80 Ω.

13. Taking into account the results of the research, the accomplishment of embroidery elements requiring high precision on dense fabrics with higher filling characteristics (recommended close to 0.9 – 1 filling index) is recommended. The higher filling rates in denser fabrics prevent fabric compression between introductions of a needle with embroidery threads in the confined space and the twisting of the fabric yarns in relation to each other, thus ensuring a decrease in the contour width of the embroidery element compared with the designed width.

A LIST OF REFERENCES

1. ANGELOVA, R. A., SOFRANOVA, D., and NIKOLOVA, V. A Case Study on the Defects in Industrial Manufacturing of Embroidered. Textiles. Journal of Multidisciplinary Engineering Science and Technology. (JMEST). 2016, 3(12) 6373-6376. ISSN: 2458-9403.
2. BRIEDIS, U., VALIŠEVSKIS, A., and GRECKA, M. Development of a Smart Garment Prototype with Enuresis Alarm Using an Embroidery-Machine-Based Technique for the Integration of Electronic Components. Procedia Computer Science. 2017, 104, 369-374.
3. CHAURAYA, A., SEAGER, R., WHITTOW, W., ZHANG, S., and VARDAXOGLOU, Y. Embroidered Frequency Selective Surfaces on Textiles for Wearable Applications. Loughborough Antennas & Propagation Conference. 11-12 November 2013, Loughborough, UK. 2013, 388-391.
4. CHERNENKO, D. A. Systematization of Design Parameters for Automated Embroidery and Modeling of Deformation System of "Fabric-Embroidery” Ph. D. Thesis Orel, Russia, 2006, p. 132.
5. KUO, C. F. J., and JUANG, Y. A study on the recognition and classification of embroidered textile defects in manufacturing. Textile Research Journal. 2016, 86(4) 393-408

A LIST OF PUBLICATIONS, PARTICIPATION AT CONFERENCES

1.1. Publications referred in the Journals from the main list of Clarivate Analytics Web of Science

1. Juchnevičienė, Žaneta; Meškuotienė, Asta ; Jucienė, Milda ; Dobilaitė, Vaida ; Sacevičienė, Virginija. The evaluation of the uncertainty of the research method

on the geometrical parameters of the embroidery elements. The Journal of The Textile Institute 0 (2017), ©2018. The Textile Institute ISSN: 0040-5000 (Print) 1754-2340 (Online) Journal homepage: http://www.tandfonline.com/loi/tjti20.

2. Juchnevičienė, Žaneta; Briedis, Ugis; Vališevskis, Aleksandrs; Jucienė, Milda; Dobilaitė, Vaida; Sacevičienė, Virginija. Electrical conductivity of a closed-circuit embroidery element // Proceedings of the Estonian Academy of Sciences. Tallinn : Estonian Academy Publishers. ISSN 1736-6046. eISSN 1736-7530. 2018, vol. 67, iss. 2, p. 158-164. DOI: 10.3176/proc.2018.2.07. [DB: Conference Proceedings Citation Index - Science (Web of Science); Science Citation Index Expanded (Web of Science); Scopus] [M.kr.: 08T]

3. Juchnevičienė, Žaneta; Jucienė, Milda; Dobilaitė, Vaida; Sacevičienė, Virginija; Gulbinienė, Ada. The research on the accuracy of the geometrical parameters of the closed-circuit embroidery element // Materials science = Medžiagotyra. Kaunas : KTU. ISSN 1392-1320. eISSN 2029-7289. 2018, vol. 24, iss. 4, p. 453-459. DOI: 10.5755/j01.ms.24.4.18843.

4. Juchnevičienė, Žaneta; Jucienė, Milda; Dobilaitė, Vaida; Sacevičienė, Virginija; Radavičienė, Svetlana. Analysis on the conformity between the closed-circuit embroidery elements of different widths and the digitally designed elements // Autex research journal. Warsaw : De Gruyter. ISSN 1470-9589. eISSN 2300-0929. 2018, vol. 00, p. 1-7. DOI: 10.1515/aut-2018-0047.

5. Juchnevičienė, Žaneta; Jucienė, Milda; Radavičienė, Svetlana. The research on the width of the closed-circuit square-shaped embroidery element // Materials science = Medžiagotyra. Kaunas : KTU. ISSN 1392-1320. eISSN 2029-7289. 2017, Vol. 23, iss. 2, p. 186-190. DOI: 10.5755/j01.ms.23.2.16095.

1.4. Publications in other Scientific Literature

1.4.2. Conference materials

1. Juchnevičienė, Žaneta; Briedis, Ugis; Vališeviskis, Aleksandras; Jucienė, Milda; Dobilaitė, Vaida; Sacevičienė, Virginija. Influence of technological factors on geometrical parameters of electrical conductive embroidered element // Mechanika 2018: proceedings of the 23rd international scientific conference, 18 May 2018, Kaunas University of Technology, Lithuania / Kaunas University of Technology, Lithuanian Academy of Science, IFTOMM National Committee of Lithuania, Baltic Association of Mechanical Engineering. Kaunas : Kaunas University of Technology. ISSN 1822-2951. 2018, p. 62-67. [M.kr.: 02T]

2. Juchnevičienė, Žaneta; Jucienė, Milda; Dobilaitė, Vaida; Sacevičienė, Virginija; Radavičienė, Svetlana. The research and the assessment of the speed of the embroidery process on the quality of the embroidery element // Mechanika 2017 : proceedings of the 22nd international scientific conference, 19 May 2017, Kaunas University of Technology, Lithuania / Kaunas University of Technology,

Lithuanian Academy of Science, IFTOMM National Committee of Lithuania, Baltic Association of Mechanical Engineering. Kaunas : Kaunas University of Technology. ISSN 1822-2951. 2017, p. 159-165. [M.kr.: 08T]

3. Juchnevičienė, Žaneta; Jucienė, Milda; Radavičienė, Svetlana. Investigation of the influence of embroidery process speed on the embroidered element width // Magic world of textiles [elektroninis išteklius]: 8th international textile clothing & design conference, October 2-5, 2016, Dubrovnik, Croatia : book of proceedings / University of Zagreb. Faculty of Textile technology. Zagreb : University of Zagreb. ISSN 1847-7275. 2016, p. 297-302. Prieiga per internetą: <http://itcdc.ttf.unizg.hr/> [žiūrėta 2016-10-10]. [M.kr.: 08T]

4. Juchnevičienė, Žaneta; Jucienė, Milda; Radavičienė, Svetlana. The influence of technological factors on embroidered elements length // AUTEX 2016 [elektroninis išteklius] : proceedings of the 16th world textile conference, 8-10 June 2016, Ljubljana, Slovenia / University of Ljubljana. Faculty of Natural Sciences and Engineering. Ljubljana : University of Ljubljana, 2016. ISBN 9789616900171. p. 1-7. [M.kr.: 08T]

Participation at conferences

1. ,,Advanced materials and technologies: 20th international conference-school“ 27-31 August 2018, Palanga, Lithuania. Juchnevičienė, Žaneta; Jucienė. The Analysis of the Peculiarities of the Functionality and Applicability of the Electrically Conductive Embroidery Systems.

2. ,,Advanced materials and technologies : 20th international conference-school“ 27-31 August 2018, Palanga, Lithuania. Žaneta Juchnevičienė1, Asta Meškuotienė2, Milda Jucienė, Vaida Dobilaitė, Virginija Sacevičienė. The Evaluation of the Uncertainty of the Research Method on the Geometrical Parameters of the Embroidery Elements.

3. ,,Mechanika-2018” 23th International Conference on May 18, 2018, Druskininkai, Lithuania. Conference Proceedings. Žaneta Juchnevičienė, Ugis Briedis, Aleksandrs. Vališevskis, Milda Jucienė, Vaida Dobilaitė, Virginija Sacevičienė. Influence of Technological Factors on Geometrical Parameters of Electrical Conductive Embroidered Element.

4. ,,Baltic polymer symposium 2017“, Tallinn, Estonia, 20-22 September. Juchnevičienė, Žaneta; Briedis, U.; Vasilevskis, A.; Jucienė, Milda; Dobilaitė, Vaida; Sacevičienė, Virginija. Investigation of electrical conductivity of closed-loop embroidered element // Baltic polymer symposium 2017 [elektroninis išteklius] : Tallinn, Estonia, 20-22 September, 2017 / Co-organized by Tallinn University of Technology and COST action CA15107. Tallinn : TTU. 2017, p. 62.

5. ,,Advanced materials and technologies :19th international conference-school“ 27-31 August 2017, Palanga, Lithuania. Juchnevičienė, Žaneta; Jucienė, Milda; Dobilaitė, Vaida; Sacevičienė, Virginija. Analysis and evaluation of closed-loop-shaped embroidered element.

6. **„**Mechanika-2017" 22th International Conference May 19, 2017, Birštonas, Lithuanica. Žaneta JUCHNEVIČIENĖ, Milda JUCIENĖ, Vaida DOBILAITĖ, Virginija SACEVIČIENĖ, Svetlana RADAVIČIENĖ. The Research and the Assessment of the Speed of the Embroidery Process on the Quality of the Embroidery Element” Conference Proceedings.

7. ,,Magic world of textiles [elektroninis išteklius]: 8th international textile clothing & design conference, October 2-5, 2016, Dubrovnik, Croatia Juchnevičienė, Žaneta; Jucienė, Milda; Radavičienė, Svetlana. Investigation of the influence of embroidery process speed on the embroidered element width.

8. ,,Advanced materials and technologies: 18th international conference-school, 27-31 August 2016, Palanga, Juchnevičienė, Žaneta; Jucienė, Milda; Radavičienė, Svetlana. The research on the compliance of the closed circuit embroidery element with the digitally designed one.

9. ,,AUTEX 2016“:16th world textile conference, 8-10 June 2016, Ljubljana, Slovenia. Juchnevičienė, Žaneta; Jucienė, Milda; Radavičienė, Svetlana. The influence of technological factors on embroidered elements length.

10. ,,Advanced materials and technologies:17th international conference-school“ 27-31 August 2015 Palanga, Lithuania. Juchnevičienė, Žaneta; Jucienė, Milda. The Research of Evaluation of Embroidery Electro – Active Textile Materials.

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REZIUMĖ

Tekstilės bei aprangos sektoriaus ir siuvinėjimo sistemų gamybos plėtra yra restruktūrizuojama ir modernizuojama. Stipri konkurencija, kintantys vartotojų poreikiai, inovatyvių produktų paklausa, trumpalaikiai susitarimai su klientais, didėjantis dėmesys žiniomis paremtai visuomenei, skatina siuvinėtų sistemų gamintojus greitai įsisavinti naujas technologijas, įskaitant informacines, bei siekti būti pirmaujančiais kuriant naujus gaminius. Elektrai laidžių siuvinėtų sistemų pritaikomumas ir plėtra yra neasiejamas nuo išmaniųjų tekstilės technologijų kūrimo. Naujausios išmaniosios siuvinėtos sistemos geba priimti mobiliuosius signalus, kontroliuoti sveikatos būvį, perspėti esant pavojui, matuoti kraujospūdį ir kt.

Siuvinėtų sistemų defektų susidarymas yra problema, su kuria susiduriama technologiniuose procesuose paveikus tekstilės medžiagą mechaniškai, kai ji būna spaudžiama, gniuždoma, tempiama, lenkiama ir daugybę kartų perduriama adatos smaigalio. Priklausomai nuo technologinio proceso parametrų, apkrovų pobūdžio, dygsnių atlikimo technologijos ir medžiagų savybių, siuvinėtų elementų forma, sandara, geometriniai parametrai, mechaninės ir fizikinės savybės pakinta. Dėl to, tiriant siuvinėtų sistemų kokybę ir funkcionalumą lemiančius veiksnius, tekstilės medžiagų deformacijų vertinimas turi itin svarbią reikšmę. Pastaruoju metu mokslininkai pradėjo domėtis šia problema, tačiau, ji vis dar nėra taip plačiai tiriama, o išsamių paties siuvinėto elemento ir jo kokybės analizių pasigendama.

Techninėse srityse vis plačiau naudojamos elektrai laidžios sistemos: jutikliai, priimantys, fiksuojantys ir perduodantys aplinkos signalus, laidininkai skirti elektroninėms grandinėms kaip apsauga nuo susidarančio statinio krūvio ir kt. Elektrai laidūs siūlai tekstilėje gali būti kelių rūšių: su laidžia danga, su laidžiu užpildu ir visiškai elektrai laidūs siūlai. Jų mechaninė elgsena artima tekstilinių siūlų elgsenai, bet jie turi trūkumų: jų paviršiaus struktūra šiurkšti, todėl yra pakankamai šiurkštūs. Norint, kad būtų iš karto gauta kokybiška ir funkcionali siuvinėta sistema, t. y. gauti siuvinėto elemento tikslią formą, svarbu įvertinti technologinio proceso veiksnius, siuvinėto elemento padėtį audinio krypties atžvilgiu, siuvinėtos sistemos medžiagų struktūrą ir savybes.

Kuriant išsiuvinėtas tekstilines ,,elektronines“ sistemas dažnai naudojami kvadrato formos siuvinėti elementai, kuriems būdingos geros elektrostatinės savybės. Dėl paminėtų savybių rekomenduojama, kad šie elementai būtų taikyti gaminant nešiojamų dipolių antenas ir jutiklius. Siuvinėtų elektrai laidžių sistemų funkcionalumas ir jo ypatumai yra itin plačiai nagrinėjami mokslininkų darbuose. Tačiau akcentuotina tai, kad daugiausia šie tyrimai apima siuvinėtų sistemų atlikimo ypatumus, o technologinių veiksnių įtaka siuvinėto elemento geometriniams parametrams, kokybei ir funkcionalumui nėra tirta. Tai rodo, kad siuvinėtų sistemų atlikimas ir jų kokybė, funkcionalumas yra aktuali, reikalaujanti išsamių, sistemos komponentų ir jų charakteristikų įtakos kokybei, analizių. Įvertinus esamą situaciją galima teigti, kad yra būtina atlikti siuvinėtų sistemų kokybei įvertinti naujus tyrimus, kurie leistų kompleksiškai įvertinti siuvinėtų sistemų funkcionalumą.

Temos aktualumas

Siuvinėtų sistemų gamintojai, atsižvelgdami į vartotojų poreikius ir konkurencingas rinkos sąlygas, turi garantuoti aukštą gaminamos produkcijos kokybę per visą dėvėjimo laikotarpį. Siuvinėtų elementų tikslumas, patikimumas, išvaizda, dėvimosios savybės ir funkcionalumas turi didelę įtaką siekiant aukštos gaminio kokybės. Disertaciniame darbe nagrinėjamas siuvinėtų elementų geometrinių parametrų atitikimas projektuotam dydžiui ir elektrai laidžių uždarojo kontūro siuvinėtų elementų laidumas analizuojant proceso technologinius parametrus, audinio fizikines savybes ir eksploataciją. Atliktas tyrimas leidžia, priklausomai nuo audinio sandaros charakteristikų, kiekybiškai įvertinti uždaro kontūro siuvinėtų elementų neatitikimą suprojektuotam dydžiui ir jo funkcionalumą. Šis tyrimas naudingas siekiant sukurti ir tobulinti pažangius technologinius procesus, prieš tai nustatant įvairių defektų priežastis bei tobulinant esamus ar sudarant naujus, siuvinėtų gaminių kokybės reikalavimus ir standartus.

Darbo tikslas

Ištirti ir nustatyti audinių sandaros įtaką siuvinėtų elementų kokybei bei funkcionalumui.

Darbo uždaviniai:

1. įvertinti audinių sandaros ir siuvinėjimo proceso technologinių parametrų įtaką siuvinėto elemento formos atitikimui suprojektuotam dydžiui;
2. išanalizuoti kvadrato formos uždaro kontūro siuvinėtų elementų geometrinius parametrus lemiančius veiksnius ir įvertinti tyrimo metodo neapibrėžtį;

3. nustatyti siuvinėjimo proceso technologinių parametrų įtaką kvadrato formos uždaro kontūro siuvinėto elemento geometriniams parametrams ir elektriniam laidumui;
4. išanalizuoti eksploatacijos veiksnių įtaką elektrai laidaus siuvinėto elemento geometriniams parametrams ir laidumui.

Darbo naujumas

Mokslinės literatūros šaltiniuose, siuvinėtų sistemų kokybė dažniausiai aprašoma tik vizualiai įvertinus elementą, o išsamesnių tyrimų, tokių kaip tekstilės medžiagų savybių ir technologinių parametrų tyrimų siuvinėtų elementų geometriniams parametrams ir funkcionalumui, pasigendama. Funkcionalių siuvinėtų elementų kokybės reikalavimuose formų tikslumas yra vienas iš svarbiausių reikalavimų. Tam labai svarbu parinkti tiek reikiamų savybių tekstilės medžiagas, tiek tinkamus technologinius parametrus. Akcentuotina tai, kad siuvinėtų ir elektrai laidžių siuvinėtų elementų neatitikimas projektuotam dydžiui, formų deformacija, siūlų slydimas, santrauka ir kiti defektai išryškėja dažniausiai, todėl ypatingas dėmesys turi būti skirtas defektus lemiantiems veiksniams analizuoti.

Darbe, įvertinus audinių savybes ir proceso technologinius parametrus, atlikti siuvinėtų uždaro kontūro elementų geometrinių parametrų tikslumo tyrimai, taip pat atliktas siuvinėtų elementų geometrinių parametrų tyrimo metodo neapibrėžties vertinimas. Kiekvieno siuvinėto elemento kontūro išplėstinė neapibrėžtis taip pat apskaičiuota naudojant *Monte Carlo* metodą. Darbe ištirta ir išanalizuota siuvinėjimo proceso technologinių parametrų įtaka siuvinėto elemento elektriniam laidumui. Taip pat įvertinta siuvinėjimo proceso greičio įtaka siuvinėtų elementų geometrinių parametrų charakteristikoms. Disertaciniame darbe ištirta ir išanalizuota eksploatacijos veiksnių įtaka elektrai laidaus siuvinėto elemento laidumui ir geometriniams parametrams. Tyrimų metu įvertinama kontūro pločio ir eksploatacijos įtaka siuvinėtų elementų laidumui.

Darbe atlikti tyrimai leidžia, priklausomai nuo audinio sandaros charakteristikų ir eksploatacijos, įvertinti uždaro kontūro siuvinėtų elementų geometrinius parametrus ir funkcionalumą bei gali būti naudingi nustatant įvairių defektų priežastis ir sudarant naujus siuvinėtų gaminių reikalavimus ir standartus.

IŠVADOS

1. Atlikta rezultatų analizė parodė, kad siuvinėtų elementų ilgis ir plotis esant vienodoms sąlygoms skiriasi priklausomai nuo užpildymo tipo ir siuvinėto elemento krypties audinio atžvilgiu. Kai siuvinėtas elementas yra atliktas užpildymo tipu *Z*, visais atvejais ilgis gautas mažesnis nei suprojektuoto elemento ilgis (iki ~ 1,7 %), o siuvinėjant užpildymo tipu *T*, siuvinėto elemento ilgis gaunamas didesnis nei suprojektuotas (iki ~ 1,5 %).
2. Nustatyta, kad išsiuvinėto *Z* ir *T* užpildymo tipais elemento plotis, lyginant su projektuoto elemento pločiu, nėra vienodas ir gali skirtis nuo ~ 5 % iki ~ 20 %. Visais tirtaisiais atvejais siuvinėtų elementų plotis gautas mažesnis nei suprojektuotas elemento plotis. Daugeliu atvejų siuvinėjant užpildymo tipu *T*, siuvinėto elemento plotis gaunamas artimesnis projektuotam nei siuvinėjant užpildymu tipu *Z*.
3. Tyrime gauta stipri tiesinė priklausomybė (R^2_{Gr} iki ~ 0,99) tarp siuvinėto elemento pločio ir siuvinėjimo greičio. Apibendrinant gauta, kad ant tankesnio, didesnio paviršinio tankio audinio A2 atliktų bandinių, siuvinėtų elementų ilgis ir plotis gauti artimesni projektuotam dydžiui nei elementų, atliktų ant kitų audinių.
4. Nustatyta, kad yra stiprus ryšys tarp audinio užpildymo rodiklių ir siuvinėto elemento kontūro pločio pokyčio. Gauta tiesinė atvirkštinė priklausomybė (R^2 iki ~ 0,80) parodė, kad technologiniai parametrai ir audinių struktūros savybės sąlygoja siuvinėtų elementų sistemų reakciją į išorinį poveikį ir tikslumą. Artimiausias suprojektuotam dydžiui siuvinėto elemento kontūro plotis gautas audinio A2, esant siuvinėjimo greičiui 1200 aps/min ir siuvinėjant užpildymo tipu *T* metmenų kryptimi.
5. Nustatyta, kad uždaro kontūro kvadrato formos tirti geometriniai parametrai: išorinis ir vidinis pločiai, audinio siūlų sistemos atžvilgiu yra skirtingi. Tyrimu nustatyta, kad nepriklausomai nuo kontūro pločio, abiejomis audinio siūlų kryptimis siuvinėto elemento išorinis plotis visais atvejais ties kraštinių kampais siauresnis nei ties kraštinių viduriu ir neatitinka projektuoto dydžio iki ~ 6,5 %.
6. Išanalizuoto siuvinėtų uždaro kontūro elementų matavimo metodo, taikomo geometrinių parametrų tyrimui patikimumas tiesiogiai siejamas su matavimo neapibrėžtimi, kuri objektyviai atspindi dedamųjų verčių sklaidą. Nustatyta, kad esant apibrėžtoms medžiagų charakteristikoms šiuo metodu, skirtu išsiuvinėto kontūro pločiui matuoti nuo 6 iki 22 mm, būdinga neigiama paklaida ~ 2,4 % su išplėstine neapibrėžtimi ~ 3,3 %.
7. Kombinuotų, standartinių neapibrėžties komponentų poveikio matavimo rezultatui analizė parodė, kad ypatingas dėmesys turi būti skiriamas bandinio paruošimui ir siuvinėto uždaro kontūro elemento pločio matavimui, priklausomai nuo medžiagos siūlų orientacijos krypties. Šios neapibrėžties

dedamosios vidutiniškai sudaro apie ~ 65 % bendro standartinio neapibrėžtumo.

8. Nustatyta, kad po pirmojo skalbimo siuvinėtų elementų elektrinė varža, lyginant su neskalbtais bandiniais, sumažėjo nuo ~ 2,5 % iki ~ 24,5 %, o po trijų, penkių ir septynių skalbimų elementų elektrinė varža padidėjo iki ~ 28,1 %. Visais atvejais gauta stipri tiesinė priklausomybė (R^2_{KS} iki ~ 0,96) tarp elektrinės varžos ir eksploatacijos ciklų parodo, kad, esant didesniam skalbimo ciklų skaičiui, elektrinis laidumas sumažėja.
9. Išanalizavus elementų funkcionalumą ir jų geometrinių parametrų tikslumą nustatyta, kad mažiausia elektrinė varža 0,23 (Ω) ir artimiausias kontūro plotis projektuotam dydžiui (~ 1,8 % didesnis) gauti, kai elementų kontūro plotis 14 mm ir tankumas 4,5 dygs/mm. Tyrimas parodė, kad siuvinėtų elementų funkcionalumui ir geometriniams parametrams daro įtaką tie patys technologinio proceso veiksniai, šiuo atveju kontūro plotis ir dygsnio tankumas.
10. Tyrime didžiausias elektrinis pralaidumas nustatytas, kai kontūro plotis yra didesnis (14 mm) ir dygsnių tankumas 4,5 dygs/mm. Stipri tiesinė priklausomybė (R^2_K iki ~ 0,81) tarp audinio užpildymo rodiklių ir elektrinės varžos rodo, kad elementų funkcionalumui audinių charakteristikos turi didelę reikšmę.
11. Atlikta analizė parodė, kad po eksploatacijos stipriausias elementų elektrinis laidumas ir artimiausias kontūro pločio dydis projektuotam gautas elementų, atliktų ant audinio A2, kurio užpildymo rodikliai metmenų kryptimi iki ~ 28 %, ataudų kryptimi iki ~ 37 %, bendras užpildymo rodiklis nuo ~ 1,4 % iki ~ 6,9 % didesni nei kitų tirtųjų audinių ir dėl to šio audinio elementų funkcionalumo ir geometrinių parametrų po eksploatacijos proceso rodikliai geriausi.
12. Tyrimas parodė, kad tikslioms, elektrai laidžioms siuvinėtoms sistemoms gauti, rekomenduotina daugiau naudoti tankesnių dygsnių užpildymo tipą. Kai siuvinėtų elementų plotas užpildytas didesnio tankumo 4,5 dygs/mm dygsniu ir kontūro pločiai 6 mm, 14 mm – visais atvejais elektrinis laidumas didesnis nei elementų, užpildytų 3 dygs/mm tankumu. Gauti rezultatai parodė, kad siuvinėtų 14 mm kontūro pločio elementų uždaros siuvinėtos grandinės laidumas gautas nuo ~ 34 % iki ~ 61 % didesnis kaip 6 mm kontūro pločio elementų laidumas. Šiuo atveju elektrinė varža nustatyta nuo 0,59 Ω iki 0,80 Ω.
13. Atsižvelgiant į tyrimų rezultatus rekomenduojama siuvinėtus elementus, kuriems reikalingas didelis tikslumas, atlikti ant tankių audinių, turinčių didesnius užpildymo rodiklius (rekomenduojama artimus 0,9–1 užpildymo rodikliui). Tankesniuose audiniuose, turinčiuose didesnius užpildymo rodiklius, išvengiama audinio gniuždymo tarp adatos dūrių siuvinėjimo siūlais apribotoje erdvėje ir audinio siūlų persislinkimo vienas kito atžvilgiu,

todėl užtikrinamas siuvinėto elemento kontūro pločio sumažėjimas lyginant su suprojektuotu.

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