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Change in Structural and Thermal Properties of Textile Fabric Packages Containing Basalt Fibres after Fatigue Bending Loading

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Abstract
The aim of this work was to determine the influence of the fatigue bending of textile packages consisting of aluminised basalt woven fabrics, textile inserts and linings on their structural and thermal insulation properties. For the process of bending, an STM 601/12 device of the SATRA company was used. Three kinds of aluminised basalt woven fabrics were examined in our research, differing in the mass per square meter and textile packages. In the paper the bending process of basalt fabrics and their textile packages are described. A proper combination of material components enabled the creation of five variants of textile packages. The next state of our work was the examination of changes in heat transport properties of the textile packages before and after fatigue bending. As a conclusion we state the influence of fatigue bending on heat transport properties.

Key words: *basalt fibres, aluminised basalt woven fabrics, fatigue bending test, thermal properties.*

Introduction

Nowadays there are many available solutions of clothes protecting workers against hot factors, e.g., protecting against thermal radiation, high temperature, air flow, or flames. Some clothes are made on the basis of aluminised fabrics from glass fibres. From the point of view of the kind of aluminised fabrics from glass fibres used it is possible to distinguish two types for general and special applications of the products. Type E glass fibres are intended for general application in final products. They have worse mechanical properties, but a lower price in comparison to the second basic type of glass fibres – type S [1].

The alternative for textile fabrics made from glass fibres are aluminised basalt fabrics, which can be used in the production of protective clothing designed for workers who are in danger caused by hot factors. Basalt fibres belong to the group of thermo-resistant fibres characterised by ultra-high heat resistance, small thermal conductivity, good thermal resistance and low values of elongation at break. Basalt fibres are of natural origin, made from solid rocks. Basalt is a stone, very hard and resistant to the influence of acid and alkaline factors [2 - 7].

A comparative analysis of basalt fibres with traditionally used glass fibres of the E type and carbon fibres showed that basalt fibres are characterised by bigger values of tensile strength, Young modulus and by a bigger range of working temperatures. Recent research showed that they have a good thermal resistance and humid absorption. They are resistant to the influence of high temperature for a short time period up to 750 °C, whereas during longer work the working temperature is in the range from 260 °C to 700 °C. These parameters cause that basalt fibres belong to the group of heat resistant fibres. What is also important, they are not influenced by erosion [7]. Therefore basalt fibres are a perfect alternative for glass fibres presently used. However, they have not been used up to the present by Polish manufacturers. Although information about different aspects of basalt fibre application in world literature is superfluous, there is a need for conducting investigations with basalt fibres from the point of view of different application conditions. The work presented by us is such an example.

Protective clothing during use is affected by fatigue loading, mainly of a bending character. It is already known that such an impact influences the structure of fabrics and, therefore, may cause cracks and other defects. Their influence on the mechanical properties can be assumed without any doubts, and only the range of the property changes can be questioned. But a suspicion may arise that also the thermal properties of the fabrics bent changed after fatigue loading. Therefore the aim of this work was to verify the thesis that the process of the fatigue bending of aluminised basalt fabrics and textile packages containing these fabrics influences not only the structural properties, but also heat transport by changing the structural properties. We decided to apply bending tests and determined the structural and thermal properties before and after the test. For carrying out the research, the De Mattia method was used, which is known to enable the creation of proper conditions of the test

Object of research

Basalt woven fabrics were produced by the Basaltex a.s. Company in the Czech Republic and aluminised by Termoizol, Poland. Aluminum foil was glued to the basalt fabrics with the use of the glue Butacoll A+, which is insoluble in water and made from the ingredients of epoxid resins. The method of binding the foil on both sides does not influence fabric flexibility nor its protective properties and exact sensory comfort. The first step in the process of joining the aluminum foil with the basalt fabrics was degreasing on both surfaces of the materials. Then the exact amount of glue was put on the aluminum foil (foil thickness 12 μm): 0.25 mm for variant T_I and 0.45 mm for variants T_II and T_III. Layer joining was carried out under pressure at a temperature of + 100 °C from the moment of putting the glue. Next two-stage drying of the material followed, first from the foil side and

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then from the fabric side. The speed of movement for fabric T_I was 1.5 m/s and for fabrics T_II and T_III – 1.0 m/s. The fabrics investigated were characterised by a plain weave. Additionally in fabric T_III the weave was reinforced by a steel wire (wire diameter 0.1 mm), which was introduced as each third weft into basalt fabric T_III. The steel wire caused an increase in the fabric tear strength, the resistance to small splashes of molten metal, water vapour permeability, and the resistance to cuts and puncture; however, it probably also changed the thermal properties slightly. The next step in preparing the textile packets was the choice of thermo insulating inserts. The choice of material packages was based on their right destination for clothing protection against thermal radiation.

Table 1. Characteristics of aluminised basalt fabrics.

Symbol of fabric	Mass per square meter, g/m^2	Thickness, mm	Thread count of warp g_o and weft g_w, number of threads/dm
T_I	275	0.28	g_o = 30 g_w = 30
T_II	390	0.48	g_o = 70 g_w = 70
T_III	350	0.47	g_o = 100 g_w = 100

Table 2. Characteristics of thermo isolating insert

Thermo insulating insert	Mass per square meter, g/m^2	Weave	Number of wales and courses, number of threads/dm
Non-flammable knitwear lining CARBO with carbon fibres (RekSwed)	150	interlock	P_k = 130 P_r = 150
Lining type Protex M® frote	200	single jersey	P_k = 111 P_r = 100

Table 3. Composition of textile packages.

Symbol of packages	Aluminised basalt fabric	Thermo insulating insert
W_1	T_II	Non-flammable knitwear lining CARBO (RekSwed)
W_2	T_III	
W_3	T_I	
W_4	T_I	Yellow nonwoven with Kevlar fibres, thick thermo insulating insert (RekSwed) + Non-flammable knitwear lining CARBO (RekSwed)
W_5	T_III	Yellow nonwoven with Kevlar fibres, thick thermo insulating insert (RekSwed) + lining type Protex M® frote (RekSwed)

Methodology

Fatigue bending test

In the first stage the process of bending was carried out on the aluminised basalt fabrics. In the next step the textile packages were tested. The De Mattia method was used, which enabled to show the real conditions of work of the final product. The samples of fabrics of 37.5×125 (±1) mm prepared were folded twice. Slightly stretched samples were placed between two clamps of the device. Before the main test a series of initial measurements were carried out in order to define the number of bending cycles of the main test. The initial research was carried out by switching the device to fully fit 1,000 cycles. If changes in the material were not noticed the device was switched on for another 1,000 cycles. Such a process finally allowed us to set the number of cycles equal to a level of 10,000 cycles. After the test time an organoleptic evaluation of the fabrics tested was carried out.

Organoleptic evaluation of damage

Evaluation of the fatigue banding tests was carried out organoleptically in accordance with Standard PN-EN-ISO 7854:2002.

- Evaluation of the resistance to cracking after bending – cracks occurring on the bent surface. Scale for determining the resistance assessment (allowable for the indirect assessment): 0 – no change; 1 – slight changes; 2 – moderate changes; 3 – significant changes.
- Characterisation of cracks occurring on the sample.
  - Crack depth: 0 – no cracks; A – cracks on the surface or finishing, without exposure of the middle layer (thermo-isolating insert, lining); B – cracks of the middle layer, (thermo-insulating insert, lining); C – cracks up through the aluminised fabric, the insert to the lining or in the case of double layer packages – through the whole package material; D – cracks through the whole package in the case of three - layer packages.
  - Number of cracks.
  - Length of cracks, mm [13].

For research according to point 2, computer analysis of the fabric surfaces picture was done using Matrox software PC-V. The software and Zeiss microscope gave an opportunity to get a digital

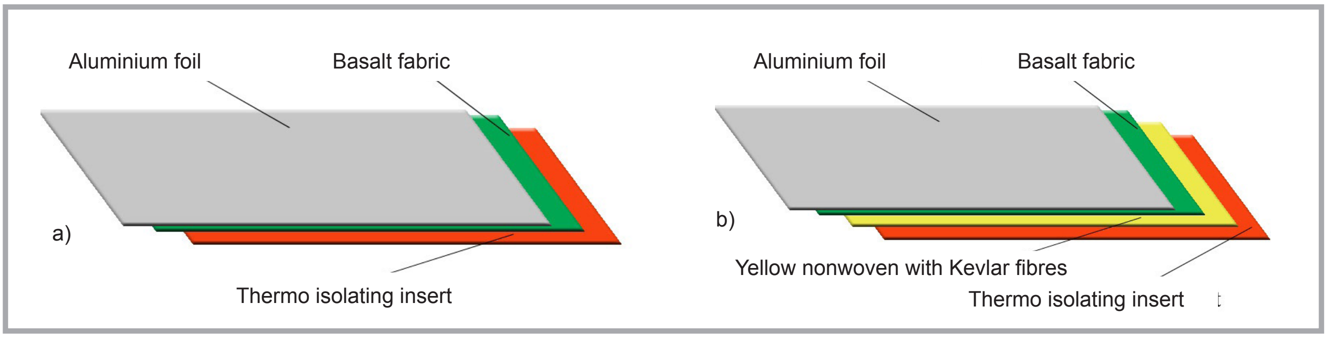

Figure 1. Schematic diagram of layers of textile packages examined; a) scheme of packages examined: W_1, W_2, W_3, b) scheme of packages examined: W_4, W_5

Table 4. *Analysis of structural damage to textile packages: W1* - W5* - samples W1 - W5 after bending process.*

Object of testing		Degree of resistance to cracking	Depth of cracks	Number of cracks	Average length of cracks, mm
W_1*	Warp direction	3.0	C	13	3.2
	Weft direction			11	4.6
W_2*	Warp direction	2.5		9	5.3
	Weft direction			9	5.2
W_3*	Warp direction	3.0		8	3.8
	Weft direction	2.5		4	4.0
W_4*	Warp direction	2.0		6	4.9
	Weft direction	2.5		8	5.0
W_5*	Warp direction	2.5		12	5.9
	Weft direction	2.0		7	8.7

picture and its memory was additionally used. A stereoscopic microscope Stemi 2000-C equipped with a scaled ruler was also used, which helped to check cracks of 1 mm length. The magnification of the microscope measuring the depth of cracks enables observation of which layer of the package has been cracked and allows to count the number of cracks. Changes in the structure of the textiles took place in the working area of the samples. The sample working area was the area of the fabric between the clamps of the working device.

Heat transport properties

Comparison of the values of thermal properties of the basalt fabrics and packages before and after the fatigue bending test was performed with the use of an Alambeta device. In the first stage tests were carried out before the cyclic process. The thermal conductivity, thermal diffusion, heat resistance and thickness of the sample were measured. Then the samples prepared for testing were placed in the bending device and the process of bending was done. After the bending test, the same parameters of the samples were measured again on the Alambeta device**.** The measurement was based on the conditions, i.e determination of the heat flux produced by the upper plate, which penetrates the textile material perpendicular to the cold lower plate. Research was carried out in repeatable conditions. The package tests during the measurement were always positioned in the same way - with the aluminium foil directed towards the upper plate of the Alembeta device. The substitute values of thermal conductivity of the packages are comparable as the configuration of layers was always the same.

Results

Structural changes in textile packages after the bending process

The structure resistance of the textile packages with the use of aluminised basalt fabrics was influenced by the process of their bending.

A description of changes in the structure of the aluminised basalt fabrics and textile packages with an aluminised basalt fabric content is presented in ***Table 3***.

The damage after the fatigue bending process contained all the damages which appeared on the surface of the samples examined. For textile package W_1 the cracks took up the whole sample working area, with concentration on the bending line of all layers. An analogous situation took place for textile package W_2, with the biggest amount of cracks appearing on the bending line of all layers. For textile package W_3 cracks were noticed along the warp and weft directions, also their concentration on the bending line. For textile package W_4 there were similar cracks as for textiles W_1 and W_2. But in textile package W_5. after the fatigue banding process, the cracks were the biggest and some holes had appeared. Therefore it is possible to conclude that the basalt fabrics and, especially, the textile packages underwent significant damage as a result of 10,000 cyclic bending.

Most often cracks in the textile package appeared on the surface layers. For aluminium foil together with basalt fabric cracks usually occurred on the sample bending line. The highest number of cracks was observed in packages W_1 and W_5, causing significant diminishing of the thermal resistance of these packages.

Heat transport through textile packages before and after the bending process

To determine the effect of fatigue bending on the textile packages, heat transport tests were carried out before and after the cycling bending process. Analysis of the impact of the cycle bending on the textile packages with basalt fabrics was conducted taking into account the criterion of the best thermal insulation. The graphs presenting the thermal insulation properties of the textile packages in ***Figure 3*** are marked by the following symbols W_1, W_1*, W_2, W_2*, W_3, W_3*, W_4, W_4*, W_5,W_5*, i.e., before and after the bending process; where * indicates the samples after the bending process. For each sample 60 measurements were made on the Alambeta device.

Analysing the results presented in ***Figure 3.a***, we see that the value of the heat conductivity coefficient for each package increased after the cycling bending process. The surprising result of the increased conductivity of the damaged package structures can be only explained by heat transfer through convection and radiation taking part in the total heat transfer across the packages (and not only by conduction). It should be considered that after the test, the material is characterised by cracks fully filled by air, positioned vertically and not horizontally to the package layers. For horizontal cracks the effect would probably be opposite. For the Alambeta results, statistical analysis by means of a t-Student test was done. The analysis showed that for some variants the differences between the parameters measured are insignificant. Nevertheless the trend in all parameters is visible.

The increase in the thermal conductivity coefficient after the fatigue bending test leads to easier heat transmission through the textile package and, in consequence, may cause damage to the skin, which should be protected by clothing made of the textile packages proposed.

Analysing the thermal diffusion in presented ***Figure 3.b***, it can be concluded that due to the appearance of cracks, the value of thermal diffusion increased (***Figure 3.b***). As a result of the cycle bending heat transfer occurs more easily. It should be mentioned that the great-

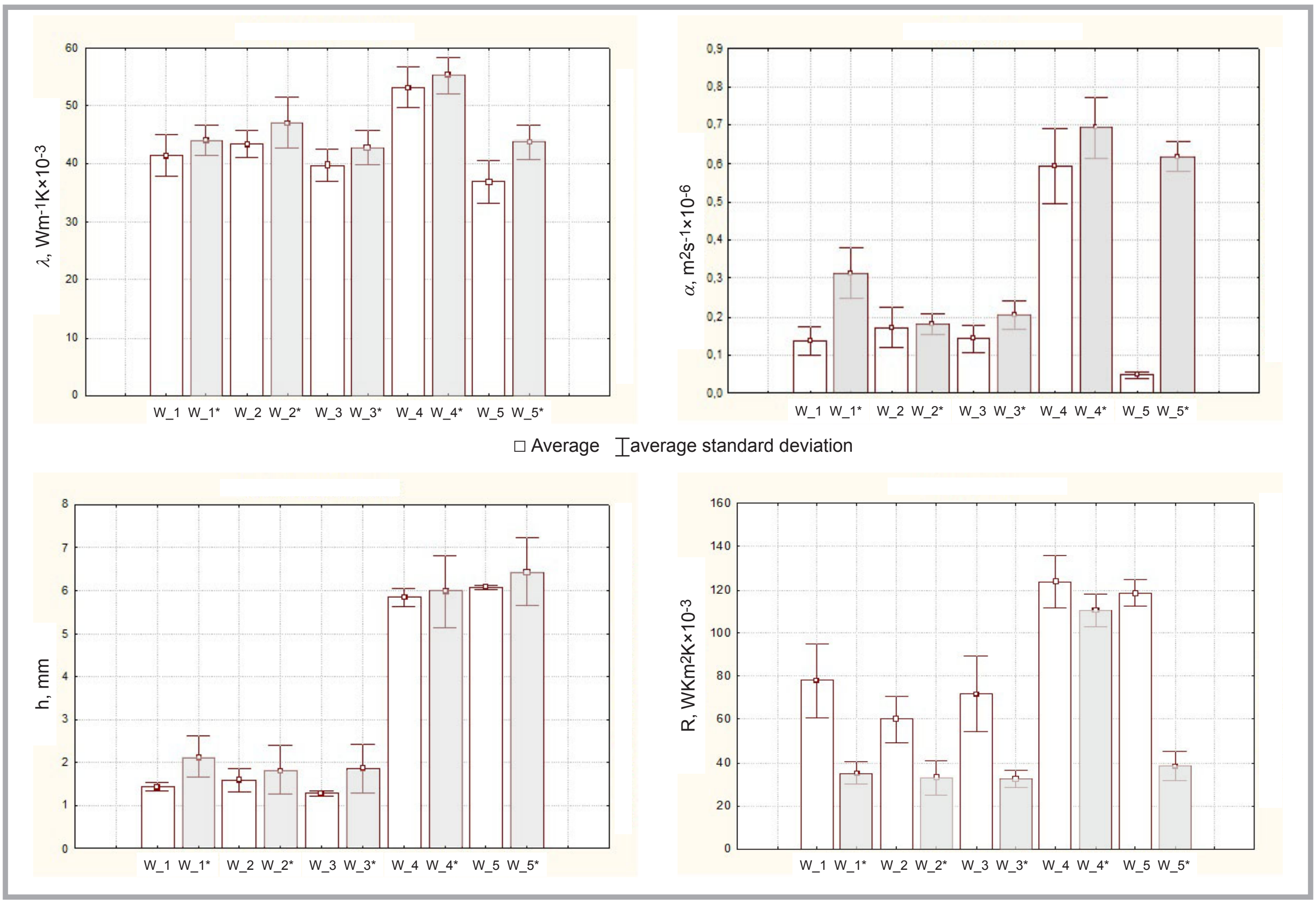

Figure 3. *Values of: a) the heat conductivity coefficient, b) thermal diffusion, c) thickness of the sample and d) heat resistance with standard deviation before □ and after □ the bending process for samples W_1, W_1*, W_2, W_2*, W_3, W_3*, W_4, W_4*, W_5, W_5*.*

est difference occurred for sample W_5 (compare ***Figure 3.a*** and ***3.c***). Even the standard deviation cannot weaken the difference.

The thickness values of the textile packages presented in ***Figure 3.c*** increase insignificantly, but are characterised by great standard deviation. This is due to irregular damage to the package structure.

Heat resistance is a parameter affecting the thermal performance of the product. The resistance largely depends not only on the conductivity but also on the package thickness. Providing greater insulation is achieved using insert layers, which often are made from carefully selected materials. ***Figure 3.d*** shows the values of heat resistance of the textile packages with aluminised basalt fabrics before and after the cycling bending process. After the fatigue bending test the thermal resistance of the packages decreased.It should also be stated that the thickness increased for all packages as well.

As can be seen, the bending process affected the thermal insulating properties of all samples tested, which reduces the thermal resistance and increases the heat transfer.

Based on the analysis of results of the thermal conductivity coefficient, the thermal diffusion, the thickness and thermal resistance of the textile packages, we can find a significant negative influence of fatigue bending on the thermal insulation, which means that setting a package of top quality insulation in protecting clothing must be thoroughly analysed taking into account the character of its application. Moreover we can state that of the packages tested the best insulating properties are shown by three-layer packages W_5 and W_4, containing Kevlar fibres and insulating insert.

Conclusions

Analysis of results showed that the cycling bending process of the textile packages created longer cracks than in the case of bending only aluminised basalt fabrics without the contribution of an insulating insert. The paper presents the results of heat transfer through textile packages before and after fatigue bending. The research carried out on textile packages containing aluminised basalt fabrics showed the negative influence of cyclic bending on the thermo-insulation properties. Aluminised basalt fabrics are characterised by high resistance to radiation. Nevertheless the outer layer of the textile packages is subjected to damages. During the cycling bending process the layer of aluminium foil on the basalt fabric broke, which is dangerous because during work the protective clothing is always bent many times, causing a decrease in thermal insulation after 10, 000 bending cycles. The higher thermal conductivity coefficient is caused by the material cracking.

Tests performed within the framework of the project EUREKA E! 4505/13/NCBiR/10 confirmed the thesis that fatigue bending influences heat transmission through textile packages. Therefore thermal comfort while wearing protective clothing cannot be assured during long time periods and the degree of clothing damage should be observed to avoid unpleasant work accidents.

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