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Sensitivity of Temperature Field to Material Parameters within the Clothing Laminate Process

Abstract
Textile laminate is created by introducing a thermoplastic polymer between the inner layer and outer material, which is then softened by heat. The connection is secured by adhesive properties of the polymer and the pressure applied after the heating zone. The state variables are defined as thus: the temperature of the heating zone and the pressure of rollers for the pressure system. The heat problem is described by the heat transport equation as well as the boundary and initial conditions. The distributions of the mean temperature within the polymer layer can be determined by numerical simulation. The sensitivity of the temperature field to the selected material parameters within clothing laminates is determined.

Key words: *sensitivity, temperature field, clothing laminates.*

Nomenclature

A *matrix of heat conduction coefficients, W/(m K),*

c *heat capacity, J/(kg K)*

h *surface film conductance, W/(m² K),*

$\mathbf{q}$ *vector of heat flux density, W/m²,*

$\mathbf{q}^*$ *vector of initial heat flux density, W/m²,*

$q_n = \mathbf{n} \cdot \mathbf{q}$ *heat flux density normal to the surface defined by the unit normal vector $\mathbf{n}$, W/m²*

T *temperature, K/°C,*

T^0 *prescribed value of temperature, K/°C,*

T_∞ *surrounding temperature, K/°C,*

t *real time, s,*

σ *Stefan-Boltzmann constant, W/(m² K⁴),*

ε *emissivity of material producing the radiation (grey body), -.*

Introduction

Inlayers secure the aesthetic qualities and material stiffness against the creasing of clothing laminates [9 - 11, 17, 20]. The practical aspects of the lamination are discussed by different authors. The form durability and some practical aspects are discussed by Pawłowa, and Szafranska [16, 19]. Wiezlak, Elmrych-Bochenska and Zielinski [20] discuss the basic technological parameters of clothing laminate, characteristics of the materials and the polymers applied. The fundamental problem is the choice of technology, particularly the heating system to soften the polymer. Some technological information is given in many sources, for example, cf. [1], Sroka & Koenen [16], and by the manufacturers of fusion presses [2]. A new fusion press - FX Diamond was presented in 2013 and is one of the most advanced fusing devices [3]. The press FX Diamond has low energy consumption that results from: (1) the separate structure of the feeding belt of the nearly constant temperature, (2) encapsulation of the heating elements, (3) separation of the heating zone from other machine parts. The temperature is controlled directly at the belt by means of a specially developed system. The final results are improved due to the precise control of the fusing parameters: temperature and pressure, which is important because modern clothing laminates have a narrow range of temperature determined by the melting point of the polymer. Sources that describe fusing devices [2, 3] do not specify the tolerances of state parameters, i.e. the temperature and pressure. Physically speaking, the temperature tolerance should ensure a correct and stable lamination process and should be not greater than 2%. In addition, a uni-form distribution of the heat flux density on the surface of the heating elements should be provided. The structure and thickness of the material also influence the distribution of heat inside the textile laminate. The aluminium encapsulation of the heating element absorbs only a little part of the heat, and consequently the heat transfer to the fusing material is optimised. The heating system applied is 3/2 bottom/top, which creates the initial warm-up system for outer wear fabrics.

There are two parameters describing the physical state of clothing laminates i.e. the state variables: the temperature of the heating zone and the pressure applied for the roller system after heating. The heating time is closely related to the temperature to ensure adequate softening of the polymer. Some additional parameters can describe the structure and affect the state variables.

Physically speaking, heat transport within the laminate is descibed by the heat transfer equation and the set of boundary and initial conditions, cf [7 - 11]. The differential heat transfer equation can be solved by the numerical integration described, for example, by Kosma [12].

The main goal of the paper is to determine the sensitivity of the temperature field to material parameters within clothing laminates. The sensitivity can be defined as the impact of material parameters on the state variable defining heat transfer – the mean temperature of the polymer layer. The analysis is based on previous works concerning the 3D space heat transfer within inlayer materials and clothing laminates [8 - 11]. The novelty elements are the application of the sensitivity approach, the point-wise distribu-

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tion of the polymer and the housing secured considerably better by the thermal isolation. Thus the new fusing press FX Diamond is considered, which was presented in 2013. The mean temperature is determined at 27 points for each polymer element, which make the analysis accurate [11]. The orthotropic heat transfer is described within textile structures by means of the matrix of heat conduction coefficients. Characteristics of the state variable (i.e. the mean temperature of the polymer) are defined as time-dependent, instead of the previous function of the temperature for the heating plate. Available literature concerning clothing laminates does not contain a description of the mean temperature distribution as a state variable, nor a numerical simulation of the heat transfer for orthotropic materials, or a sensitivity analysis of the temperature with respect to material parameters.

Basic parameters of adhesive connection within clothing laminates

The correct clothing laminate is connected by means of a polymer adhesive layer softened by the heat transfer. Different aspects of the adhesive connections were discussed in [1, 10, 11, 18]. There are two basic technological parameters of clothing laminates, called state variables. The state variable is the temperature controlled directly at the transport belt on the FX Diamond device [3]. The feeding belt is separate and there is no cooling of the internal transport belt outside the machine. Heating units are encapsulated as well as decoupled from the machine frame to secure extremely low heat loss [3]. The temperature distribution depends on the heat transfer system. The system applied is 3/2 bottom/top of the encapsulations made of aluminium [2, 3]. There is a standard layout for the fabrics and interlinings in the outer wear. The external fabrics are gradually warmed at the first stage by the bottom heater to minimise shrinkage, which is an advantage for heavy fabrics. The higher the temperature the lower the polymer viscosity. In this case, the polymer penetrates the insert and impregnates the external textile material. The temperature most applied is $T = (90 - 120)$ °C [1, 18, 20].

The parameter closely related to the temperature is the heating time. A properly defined time is necessary to transfer heat into both the clothing and inlayer materials as well as to help create a stable laminate. An appropriate exposure time causes that the polymer is softened by the heat. The shorter the time at the same temperature the harder the polymer, and adhesion within the connection is reduced. The longer the time at the same temperature the more fluid the polymer, i.e. better penetration of both the external material and inlayer. The time most applied is $t = (12 - 18)$ s [1, 18, 20].

The state variable affecting the stability of the laminate is the pressure of rollers on the unit surface. The pressure system works separately immediately after leaving the heating zone. The new FX Diamond device can be equipped with two pressure systems: the FX 100/1400 and the Constant Pressure Appliance CO-PRA, both of which have the standard and double pressure performance of the optimal adjustement of soft or medium. Of designated use are pressure sensitive materials (soft system) and outer wear (medium system). Low pressure causes that the connection between the insert and fabric is weak. Increased pressure causes that the polymer penetrates the insert, the adhesive points are flattened, and the touch is hard. The pressure most applied should be in the the range $(3 - 30) \cdot 10^{-4}$ N/m² [1, 18, 20].

There are a few other parameters describing the laminate and affecting the state variables.
- Inlayer structure, defined by material parameters characterising the heat transfer, and for the heating stage - the matrix of heat conduction coefficients.
- Material composition, i.e. the kind of fibres applied.
- Fibre density and finishing procedure to secure a soft textile feel.
- Purpose and place of application, which determine the model description; the point-wise polymer distribution is introduced and the standard description of both the outer wear and inlayer are applied.
- Kind of adhesive; the most popular are powders made of polymers; this material is analysed next.
- Adhesive spread procedure, i.e. the point-wise or continuous method; the point-wise adhesive points are assumed.
- Distance between the polymer points, i.e. regular net or irregular adhesive points; the regular net is determined.

Thermoplastic adhesive is formed as polymer powder by the diversified spread procedure. Some questions regarding the polymer and its spread procedure are explained in [11, 18]. The most popular is hard-melting polyamide characterised by high adhesion to textiles after the finishing procedure of the waterproof surface prepared using siliceous organic compounds. It can be also applied to inlayers made of woven fabrics. Its melting point is 110 – 120 °C and the melt flow index $(15 - 40) \cdot 10^{-3}$ kg/10 min. Low-melting polyamide can be used to connect leathers and furs as well as inlayers made of knitted fabrics. The melting point is 90 – 100 °C, and the melt flow index is comparable.

Polyester is characterised similarly to polyamide. Polyester is highly adhesive to artificial silk and used in ready-made clothes for ladies. Laminates are wash-resistant to 40 °C.

Polyetylene is usually applied to the inlayers of dress shirts; laminates are wash-resistant to 90 °C. The melting point is 120 °C and the melt flow index $15 \cdot 10^{-3}$ kg/10 min. The disadvantage is that high values of pressure should be applied during the lamination.

The textile inlayers can be made of different fabrics, which depends on the intended use. An outer wear of significant surface mass (mantles, uniforms) is typically laminated with inlayers of woven fabrics. Products of medium surface mass (jackets, mantles) and lightweight clothing (lady's jackets) have inlayers made of knitted fabrics. Thin textiles (ready-made clothes for ladies, the collars and cuffs of shirts, the front of jackets) are laminated with inlayers made of nonwovens of $30 \cdot 10^{-2}$ kg/m² surface mass.

■ Description of heat transfer

The space textile structure can be described by means of a set of geometrical parameters **x**. Let us determine the point-wise polymer adhesive layer as separate points and the air between the materials. Each component is now homogeneous (the air/the polymer). The external thermal isolation are the side housings, which significantly reduce heat transfer through convection and radiation from the inlayer to the surrounding. It can be assumed that the heat transfer conditions are the same in any cross-section, i.e.
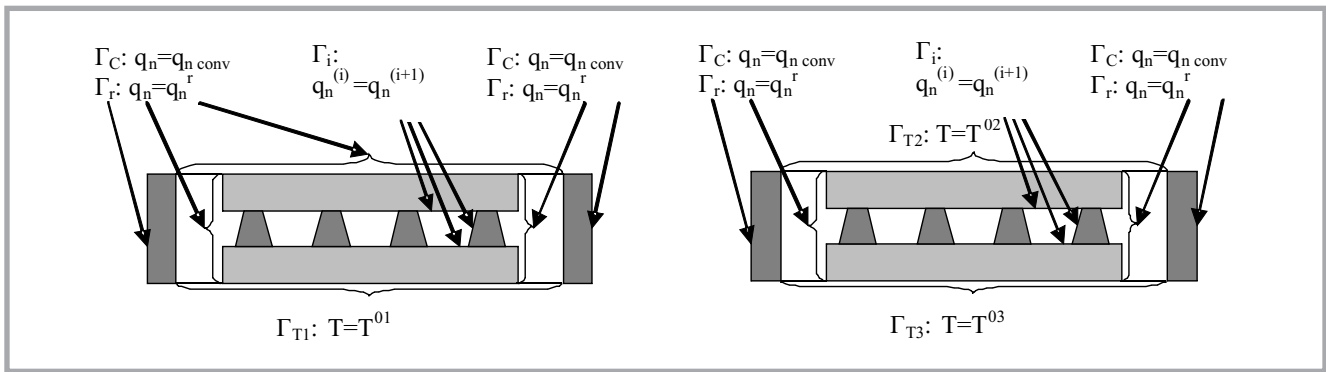
Figure 1. *Boundary conditions of complex inlayer structure; a) first zone (bottom heating), b) second zone (top heating)*

the 3D space problem is reduced to a 2D plane description.

Physically speaking, heat transfer is defined by a second-order differential equation with respect to the temperature and a first-order with respect to time. Boundary conditions depend on the structure of the heating zone. Let us introduce the heating zone 3/2 bottom/top [3]. The first part (*Figure 1.a*) is subjected at the bottom to a temperature of prescribed value T^{01}. This portion Γ_T is characterised by the first-kind boundary condition. The side and top structural boundaries are subjected to convectional and radiational heat loss. It follows that these boundaries Γ_C Γ_r are subjected to the third-kind as well as radiation conditions. The radiation can be described [7, 8, 10, 11] as the fourth power of the temperature. The fourth-kind conditions introduce the same heat flux densities on the internal boundaries Γ_i. The initial condition describes the temperature distribution within the strucutre at the process's beginning. The second zone (*Figure 1.b*) has a top heater of a prescribed temperature T^{02} instead of convection and radiation. The first-kind condition is defined for the part Γ_T. All other boundaries have the same descriptions. The set of conditions has the general form for the (*i*)-th structural layer (see *Equation 1*).

The heat transport equation should be solved for consecutive heating times and different forms of the adhesive aggregation. Heat transported from the heating elements to the textile laminate causes a phase change in the adhesive. The temperature does not rise until all of the polymer has melted. Physically speaking, the entire system can be characterised by thermal equilibrium during this process. Thus the melting point is determined by the temperature at which the solid polymer changes to semifluid aggregation.

The amount of heat which changes a unit mass of the solid into the same mass of not-solid aggregation is defined as the latent heat of fusion. The melting point as well as the heat of fusion are known for each type of polymer, which simplifies the theoretical analysis. The phase change can be described practically by the prescribed value of the heat conduction coefficients for the polymer applied. These values can be determined experimentally and formulated as a database.

To obtain a solution, the equation can be integrated within the inlayer and in time by any analytical method, for example the Gauss procedure.

Determination of textile porosity

Textile porosity is determined by means of different air fractions inside the textile product. The "external" porosity can be described by the fibre fraction and free spaces within the textile on a macroscale. The „internal" porosity is defined as the air contribution inside the fibres, which results from the process of their formation and is, in fact, the "internal" non-homogeneity of fibres. Two-stage homogenisation is necessary to generally define the textile structure by the effective porosity as well as the elementary homogenisation of fibres. According to the method used, heat transfer is de-

termined in a homogeneous structure. The effective material porosity ε describes its inhomogeneity. We can apply different homogenization methods, the most efficient being the "rule of mixture".

Theoretical analysis of textile porosity is difficult because the geometrical description of textiles is too complicated. The available literature does not contain an explicit assessment of theoretical methods of measurement nor apparatus used to determine these values. According to [5], the mass fraction of textile fibres can be determined for complex multilayer knitted fabrics but not within a specific layer. The fibre fraction within textile products is described by means of the linear, surface or volume cover factor. Technologically speaking, the most important is the surface volume factor [14, 15]. Another indirect method can determine the air permeability [15], but it is not always effective enough.

Thus the most efficient and practical is computer image analysis. The fibre fraction of a textile is described by digital analysis of a binary image in the plane system and is a function of the greyscale transfromed to a current bitmap. The main difficulty is to clearly determine the boundaries between the object measured and the background on the image analysed. Thus different image segmentation techniques can be applied [2, 3].

$$\begin{cases} \operatorname{div}\mathbf{q}^{(i)} = c^{(i)}\dfrac{\partial T^{(i)}}{\partial t} \\ \mathbf{q}^{(i)} = \mathbf{A}^{(i)} \cdot \nabla T^{(i)} + \mathbf{q}^{*(i)} \end{cases} \mathbf{x} \in \Omega; \quad \mathbf{x} = \begin{Bmatrix} x \\ y \end{Bmatrix}$$

$$
\begin{aligned}
&T^{(i)}(\mathbf{x},t) = T^{0k}(\mathbf{x},t) \ \ \mathbf{x} \in \Gamma_{kT}; \ \ k = 1,2,3 \\
&q_{nC}^{(i)}(\mathbf{x},t) = h\big[T(\mathbf{x},t) - T_{\infty}(\mathbf{x},t)\big] \ \ \mathbf{x} \in \Gamma_C; \\
&q_n^{r(i)}(\mathbf{x},t) = \sigma\varepsilon\big[T(\mathbf{x},t)\big]^4 \ \ \mathbf{x} \in \Gamma_r; \qquad (1) \\
&q_n^{(i)}(\mathbf{x},t) = q_n^{(i+1)}(\mathbf{x},t) \ \ \mathbf{x} \in \Gamma_i; \\
&T^{(i)}(\mathbf{x},0) = T_0^{(i)} \ \ \mathbf{x} \in (\Omega \cup \Gamma).
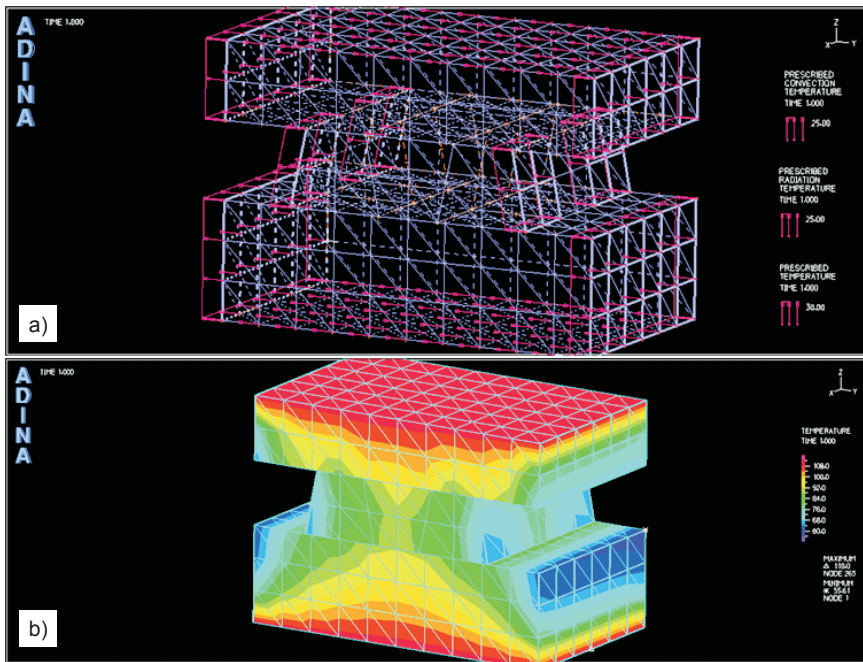\end{aligned}
$$

Equation 1.

Figure 2. *Finite Element Net and example of temperature map; a) Finite Element Net for separate polymer points within glue layer, b) temperature of upper and lower surfaces T = 110 °C; temperature in housing T_∞ = 25 °C.*

Table 1. *Heat transfer coefficients for fibre densities of textile materials; 1 – wool: 175 kg/m³; cotton: 150 kg/m³; 2 – wool: 180 kg/m³; cotton – 155 kg/m³; 3 – wool: 185 kg/m³; cotton: 160 kg/m³.*

Fiber density	λ_{11}, W/(mK)		λ_{22}, W/(mK)		$\lambda_{12} = \lambda_{21}$, W/(mK)
	wool	cotton	wool	cotton	
1	0.048	0.036	0.045	0.034	0
2	0.052	0.040	0.049	0.038	0
3	0.056	0.044	0.053	0.042	0

Table 2. *Heat transfer coefficients for different inlayer materials.*

Fibre	λ_{11}, W/(mK)	λ_{22}, W/(mK)	$\lambda_{12} = \lambda_{21}$, W/(mK)
Lycra	0.025	0.023	0
Cotton	0.040	0.038	0
Viscose	0.063	0.055	0
PE / PA	0.100	0.090	0

A measurement algorithm for computer image analysis can be found in [6, 14, 15]. Measurement methods based on digital technology and data acquisition of image analysis are non-destructive and allow to obtain objective and unambiguous results. Consequently the relationships between structure and process parameters can be specified.

■ Numerical solution of problem

Let us assume the woven fabric and cotton inlayer of the orthotropic heat transfer properties. Both textiles should be homogenised by means of any method, e.g. *rule of mixture* [13]. The material parameters are defined according to [4, 13].

The matrix of heat transfer coefficients for fabrics is described as follows:

$$\mathbf{A}^{(i)} = \begin{vmatrix} \lambda_{11}^{(i)} & \lambda_{12}^{(i)} \\ \lambda_{21}^{(i)} & \lambda_{22}^{(i)} \end{vmatrix} \; ; i = 1, 3.$$

Wool has constant heat transfer coefficients
$\lambda_{11}^{(1)} = 0.052$ W/(mK),
$\lambda_{22}^{(1)} = 0.049$ W/(mK) &
$\lambda_{12}^{(1)} = \lambda_{21}^{(1)} = 0$
whereas cotton has
$\lambda_{11}^{(3)} = 0.040$ W/(mK) &
$\lambda_{22}^{(3)} = 0.038$ W/(mK);
$\lambda_{12}^{(3)} = \lambda_{21}^{(3)} = 0.$

The adhesive is defined by the isotropic heat transport $A^{(2)} = |\lambda^{(2)}| = \lambda$ of the temperature-dependent heat transfer coefficient

$\lambda = 0.08$ W/(mK) for $T < 115$ °C,
$\lambda = 0.10$ W/(mK) for 116 °C $< T < 125$ °C,
$\lambda = 0.11$ W/(mK) for 126 °C $< T < 135$ °C
and
$\lambda = 0.12$ W/(mK) for 136 °C $< T < 145$ °C.

The heat transfer capacity of wool is equal to $c = 1350$ J/(kgK), cotton $c = 1300$ J/(kgK) and polymer $c = 1200$ J/(kgK).

The porosities of both textiles are assumed as constant $\varepsilon = 0.350$. The free spaces between polymer points are filled by air of constant heat transfer coefficient $\lambda = 0.028$ W/(mK) and constant heat transfer capacity $c = 1005$ J/(kgK). The surrounding temperature within the housing is assumed equal to $T_\infty = 25$ °C. The surface film conductance has the same constant value $h = 0.075$ W/(m²K) with respect to the increased thermal isolation of the fusing machine.

Structural shapes are approximated by a space Finite Element Net of 4-nodal elements, shown in ***Figure 2***. The problem should be solved using a 3D description because convection and radiation are defined by the ADINA-program as a spatial function. The heat transfer equation can be integrated numerically using the Gauss procedure [12]. Temperature maps help to create the mean temperature within the adhesive layer, an example of which is in ***Figure 2***, determined by means of 27 points located symmetrically in each 3D polymer element [11].

Let us next describe the sensitivity of the temperature field with respect to basic material parameters. The first three basic prameters described in Subclause 2 can be included; others are already specified in the model defined. First we consider the impact of material porosity on the mean temperature within the adhesive layer. The heating units are completely encapsulated and both of the bottom/top heating housings are made of aluminium. The temperature maps are symmetrical relative to the vertical plane. Thus the temperature of heating elements rises to the maximum value of 130 °C in less than 1 s. We obtain a non-linear dependence between the temperatures within the polymer layer in time, see ***Figure 3***, which the result of a change in heating system from the bottom to the top of the heating element. The difference between the mean temperatures for different material porosities changes from 9.2% for minimal to 4.1% for maximal values of

temperature. We conclude that the temperature is sensitive to change in material porosity within both textile materials.

Next the impact of fibre densities on the mean temperature within the adhesive layer will be analysed. Change in the mass determines the various heat transfer coefficients. Calculations are determined similarly to the previous case, and the porosity of both textile materials is $\varepsilon = 0.350$. The heat transfer coefficient after homogenisation vs. fibre density is defined in **Table 1**. The temperature maps are similar to those previously obtained, cf. **Figure 4**. Differences in the mean temperatures are not greater than 2%, and consequently it is not sensitive to changes in the fibre density within the inlayer.

The sensitivity of the mean temperature can be also analysed with respect to the type of fibres in the inlayer. The fibres most applied are polyester, polyamide, cotton, viscose, bamboo etc. Thus man-made polyurethane fibre can be also applied (the trade name is Lycra), which is always blended with other materials to secure particular stretch and recovery properties. In fact the choice of fibres determines the heat transfer coefficient. The heat transfer coefficient of fibres before homogenisation is defined in **Table 2**. The porosity of the inlayer material is equal to $\varepsilon = 0.35$ and all other parameters are defined above. The temperature distribution has the same nonlinear character as previously. Distributions of the mean temperatures vs time is nonlinear, cf. **Figure 5**. The higher the heat transfer coefficient of the inlayer material, the better the heat transport through the textile inlayer. The mean temperature within the polymer layer is higher than that for more insulating textiles defined by lower heat transfer coefficients. According to the results of numerical simulations, the distribution of the mean temperature is sensitive to the type of fibre within the inlayer material. The difference between the mean temperatures for different materials changes from 26.1% for minimal to 4.9% for maximal values of the temperature.

The mean temperatures within the polymer layer at the end of the heating stage are always significantly higher than the minimal temperature of the melting point for low-melting polyamide 90 – 100 °C as well as hard-melting polyamide
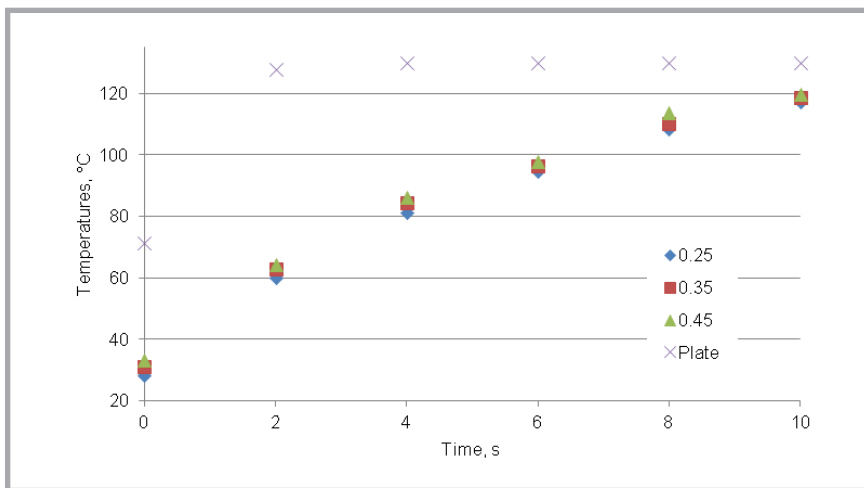

Figure 3. *Mean temperature of polymer layer for different material porosities; t < 6 s bottom heating; t > 6 s top heating.*
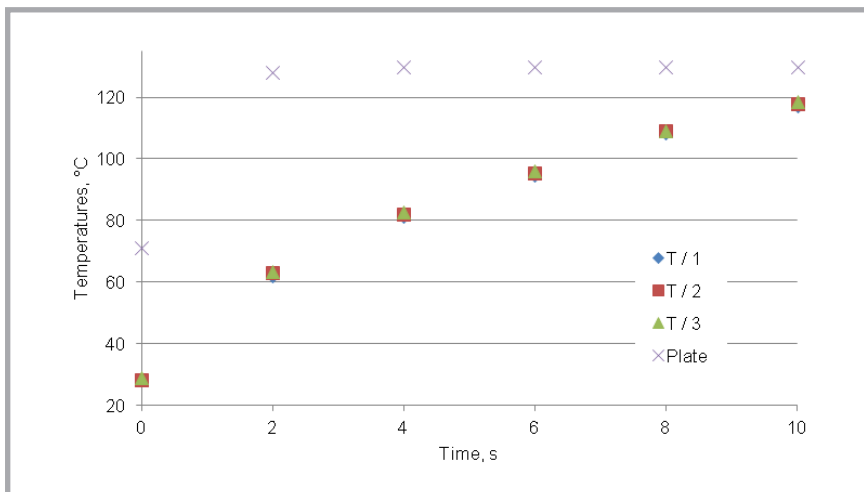

Figure 4. *Mean temperature of polymer layer for different fibre densities; T/1 wool: 175 kg/m³; cotton: 150 kg/m³; T/2 wool: 180 kg/m³; cotton – 155 kg/m³; T/3 wool: 185kg/m³; cotton: 160 kg/m³; t < 6 s bottom heating; t > 6 s top heating*
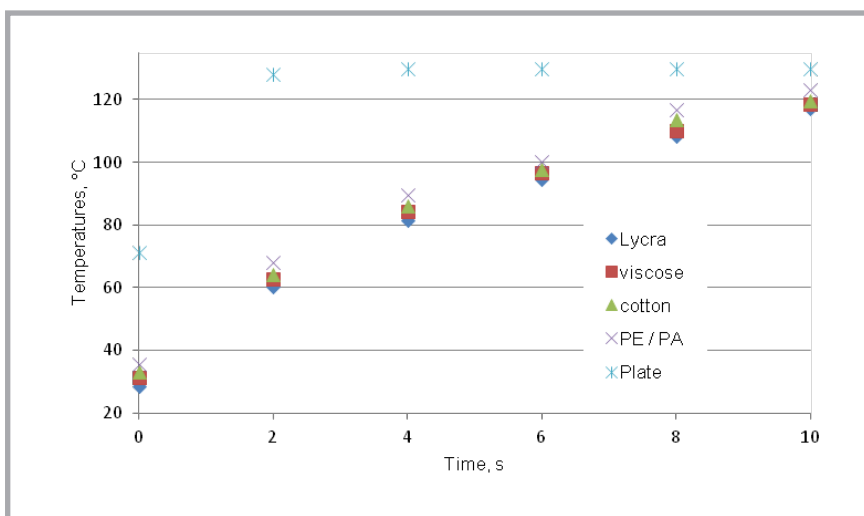

Figure 5. *Mean temperature of polymer layer for different inlayer materials;t < 6 s bottom heating; t > 6 s top heating.*

110 – 120 °C. It means we can create a durable textile laminate for disadvanta-

geous boundary conditions, i.e. unsatisfactory temperature within the housing.

The new FX Diamond fusing press has improved heat insulation protecting against excessive heat loss. The existing structures of fusing machines are describe in [2], as well as Sroka, Koenen [18], Pawłowa, Szafrańska [14]. The heating units of the previous fusing machines are characterised by not targeted heat transfer without loss of energy. Both the thermal insulation of a heating unit made of aluminium and the geometry of the heating zone are now optimised [3]. Thus the surface film conductance is considerably lower than for traditional devices. Therefore the heating time according to numerical simulations is much shorter (about 2 s) than before.

◼ Conclusions

The technology of clothing lamination is complex and consists of two independent processes: the heating of all components and pressure to create an adhesive connection. First temperature maps should be determined to calculate the state parameter i.e. the mean temperature within the polymer layer. The temperature maps give additional information about the minimal and maximal temperatures within the polymer layer. The minimal values are always greater than the melting point for both high- and low-melting polyamide. It follows that a correct and stable clohing laminate can be created because the polymer adhesive reaches the melting point for unfavourable conditions. This conclusion is technologically important. The state parameter (the mean temperature) is determined within 27 points for each adhesive element, which helps to create the correct results. Thus the heat transfer modelling presented seems to be an effective tool to determine the mean temperature within the polymer layer during the heating phase of the lamination process.

Next we can describe the sensitivity of the mean temperature to material parameters, i.e. some parameters which influence the state variable. The mean temperature is sensitive to changes in the material porosity within textiles as well as the type of fibre within the inlayer material, but it is not sensitive to changes in the fibres density within the inlayer. Other parameters (place and area of application, finishing procedure, lamination technology etc.) can be analysed by an adequate description of the physical and mathematical model and its boundary conditions.

A sensitivity analysis can be applied to optimise the shape of the inlayer material to secure optimal conditions for a clothing laminate. We define a space 3D optimal connection with respect to the different lamination parameters. There is the typical numerical problem of one- and multicriterial optimisation, which can be solved using common optimisation techniques.

The results obtained can be verified by means of temperature measurements at specified points of textile laminates. The problem is beyond the scope of the theoretical paper presented and will be discussed in the next article. The subsequent work will be devoted to the modelling and analysis of the pressure zone, pressure rollers and their optimization, as well as giving a comprehensive description of the laminate creation.

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