IMPACT OF MATERIAL PARAMETERS ON TEMPERATURE FIELD WITHIN CLOTHING LAMINATES

Ryszard Korycki[1]; **Halina Szafranska**[2]
[1]Lodz University of Technology, Faculty of Material Technologies and Textile Design,
Department of Technical Mechanics and Computer Science, Lodz, Poland;
[2]University of Technology and Humanities, Faculty of Material Science, Technology and
Design, Department of Shoes and Clothing Technology, Radom, Poland
e-mail: [1]ryszard.korycki@p.lodz.pl

Abstract

Inlayers secure both aesthetic qualities and stiffness against creasing of clothing laminates. Laminate is created by thermoplastic glue between inlayer and clothing material which is softened by heat. State variable is temperature. Temperature distributions within laminate can be determined by numerical simulation for different temperatures of heating plates. Impact of different material parameters on temperature distribution is analysed.

Introduction

Inlayers secure aesthetic qualities and material stiffness against creasing of clothing laminates [1, 2, 3, 4]. Some paremters of inlayers are discussed by different authors [3, 4]. The substantial problem is a choice of technology, i.e. heating system applied to soften the polymer during lamination cf. Sroka, Koenen [5]. There are some important technological parameters of clothing laminates: temperature, heating time, pressure applied after heating, external material characteristics, kind of polymer glue, characteristics of a heater system.

Let us first determine the physical model. State variable is the temperature within laminate structure which consists of inlayer, external material and polymer glue points. It should effectively describe the technological process. The structural shape is defined by vector of crucial point coordinates. The most important information is the temperature distribution within laminate during the heating phase. The only heat source are heaters in a heating device. Heat is transported through inlayer, polymer glue layer and textile material. There are different heat loss mechanisms by radiation, convection and conduction on appropriate material surfaces.

The next step is to describe the mathematical model. Heat transfer is described by heat transport equation and set of boundary and initial conditions, cf. Li [6]; Dems, Korycki [7]. Heat transfer equation is the second-order differential correlation with respect to vector of coordinates. The problem can be solved by using different methods. The most popular is the numerical integration within structure [8, 9]. The other method is to introduce first variational form and find its solution.

The main goal is to analyze the sensitivity of temperature field of polymer glue layer with respect to different material and technological parameters. Various descriptions of polymer glue distribution can be introduced. It can be modeled as a separate layer or by means of regular or irregular distributed points. Additionally, different heat-insulating protections can be introduced to improve heat transfer, cf. side housings. Generally speaking, the analyzed problem has a 3D space character. To simplify the solution, some cases can be reduced to an optional cross-section of structure. Therefore, space 3D problem can be reduced to its plane 2D cross-section. The important factor describing the structure can be the mean temperature in the glue layer which is assumed as a comparative element to estimate the sensitivity.

1 Description of heat transport

Clothing materials and inlayer made of textiles have periodically repeteable structure which should be first homogenized. There are a few effective homogenization methods [7, 10]. The most applied is the *rule of mixture* defined in the following form.

$$\lambda_z = \lambda_m \xi_m + \lambda_f \xi_f ; \quad \xi_m = \frac{V_m}{V_m + V_f} ; \xi_f = \frac{V_f}{V_m + V_f} . \tag{1}$$

where V_m is volume of fibres in m^3, V_f is volume of interfiber spaces filled by air or the glue in m^3, λ_m; λ_f describe heat conductivity coefficients of material (m) and filling (f) in $W/(m\ K)$, ξ_m; ξ_f are volume coefficients of fibres of volume V_m and the interfiber spaces of volume V_f.

Heat is transported through polymer points as well as air between the glue. Both polymer glue and air are homogeneous. The polymer glue layer should secure the correct connection between the inlayer and textile material. The most effective method is to apply the point-wise spread procedure of polymer. We obtain regular and irregular polymer point distribution for different scales described as “mesh” parameter or “computer point” parameter. Consequently, the most simple and effective method is to define polymer glue as the continuous layer.

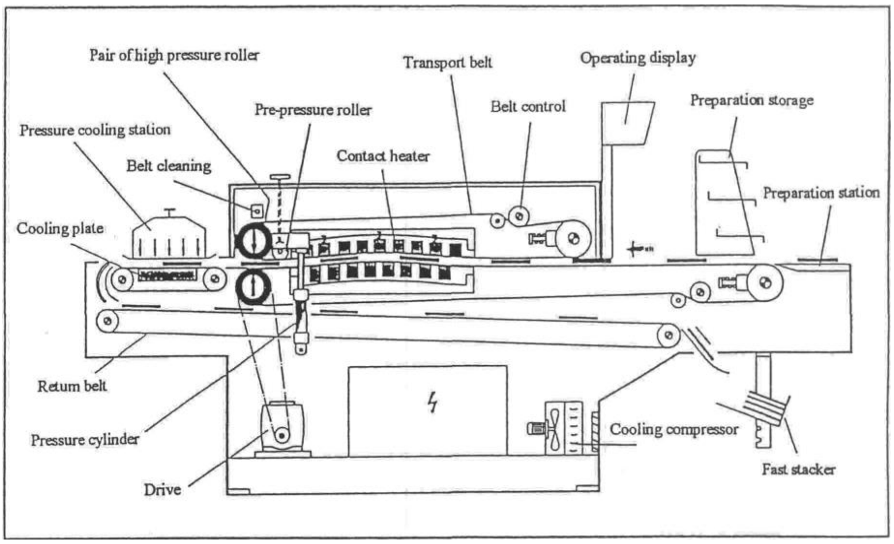

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Fig. 1: *Scheme of the continuous automatic fusion press KFH 600 for shirt – and blouse fusion with pressure cooling station at the output*

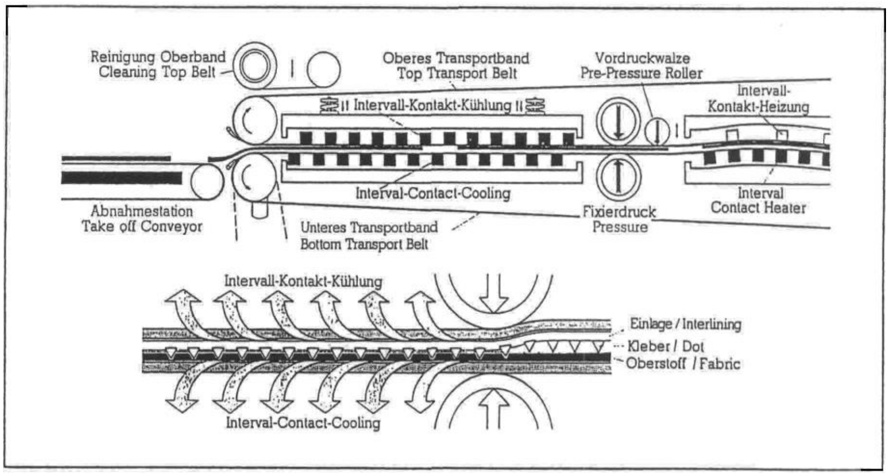

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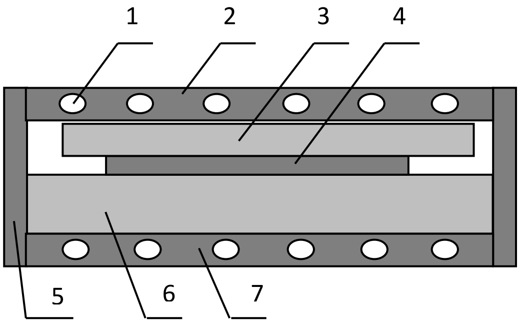
Fig. 2: *Scheme of the Interval Contact Cooling with the CoolVac System*

The desription of heat transport depends on technology and heating press applied. There are different solutions of various heating systems. Let us assume the continuous automatic fusion press KFH 600 for shirt – and blouse fusion with pressure cooling station at the output, cf. Sroka and Koenen [5], Figure 1, Figure 2. Press device has the additional contact cooling to secure the regular heat transport and equalized temperature within glue layer. Let us assume the steady heat transport described by time-independent heat flux density of heating devices. Neither inlayer nor textile structures contain heat sources. The only heat source are always heaters within heating press. It means that heat can be only lost during heating process by laminate. Heat can be accumulated by textile fibers and transported to surroundings through external structural boundary. Introducing now heat balance which is the sum of heat losses, we formulate the heat transport equation. It is the second-order differential equation with respect to vector of coordinates. To solve the above equation, it is necessary to determine the set of boundary conditions. It depends on the particular solution of heating press, cf. Figure 3.



1 – heating elements, 2, 7 – heating devices, 3 – inlayer, 4 – homogenized polymer layer, 5 – side thermal housing, 6 – outer textile material

Source: Own

Fig. 3: *Scheme of material layers in heating device*

The upper part of inlayer and the lower part of textile material are exposed to constant temperature $T = T^0$. This boundary portion Γ_T is subjected to the first-kind condition. The side parts of heated elements as well as external housing are subjected to convective and radiative heat transport. There are boundary parts Γ_C and Γ_r loaded by convectional and radiational heat flux densities i.e. the third-kind and radiation conditions. We assume on internal boundaries Γ_i the same heat flux densities, i.e. the fourth-kind conditions. Heat transport equation for *(i)*-th layer supplemented by set of conditions is shown in Figure 4 and described by Eq. (2).

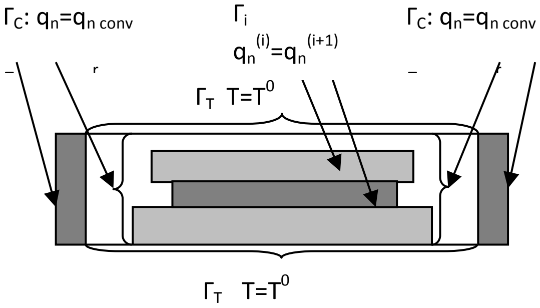


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Fig. 4: *Boundary conditions of system inlayer – polymer glue – textile material*

$$\begin{cases} \mathrm{div}\mathbf{q}^{(i)} = 0 \\ \mathbf{q}^{(i)} = \mathbf{A}^{(i)} \cdot \nabla T^{(i)} + \mathbf{q}^{*(i)} \end{cases} \quad \mathbf{x} \in \Omega; \quad \mathbf{x} = \begin{Bmatrix} x \\ y \end{Bmatrix}; \quad \begin{array}{l} T^{(i)}(\mathbf{x}) = T^0(\mathbf{x}) \quad \mathbf{x} \in \Gamma_T; \\ q_{nC}{}^{(i)}(\mathbf{x}) = h[T(\mathbf{x}) - T_\infty(\mathbf{x})] \quad \mathbf{x} \in \Gamma_C; \\ q_n{}^{r(i)}(\mathbf{x}) = \sigma[T(\mathbf{x})]^4 \quad \mathbf{x} \in \Gamma_r; \\ q_n{}^{(i)}(\mathbf{x}) = q_n{}^{(i+1)}(\mathbf{x}) \quad \mathbf{x} \in \Gamma_i. \end{array} \tag{2}$$

where **q** is vector of heat flux density, $\mathbf{q}^*$ is vector of initial heat flux density, $q_n=\mathbf{n}\cdot\mathbf{q}$ denotes vector of heat flux density normal to surface defined by unit vector **n**, **A** is matrix of heat conduction coefficients, T is temperature, t is real time, T^0 denotes prescribed temperature, h is surface film conductance, T_∞ is surrounding temperature, σ is Stefan-Boltzmann constant.

2 Impact of material parameters on temperature field

There are some basic parameters which can influence the clothing laminate. The most important are the following:

- Type of laminate. Inlayer can be made of different textiles: fabrics, knitted fabrics and non-wovens which depends on predicted applications. Thus, surface mass and internal porosity are also important and limited for the specific laminate.
- Type of fibers within inlayer; the most popular are: polyester, polyamide, cotton, viscose, Lycra-fibers and bamboo fibers.
- Place and area of application which determines stiff or the more flexible connection.
- Finishing procedure which secures stability and aesthetic qualities of textile laminate.
- Lamination technology defined by heat source parameters, location of heating devices, time of heating and time of pressure, force within the pressure roller etc.

Let us analyze the sensitivity i.e. the impact of the above mentioned parameters on temperature distribution within polymer glue layer. To determine temperature fields in textile laminate, it is convenient to assume the same heat flux density of the heater. The homogenized polymer layer has the same geometry and heat transport conditions within the heating device. The heat description is consequently simplified to the 2D plane problem.

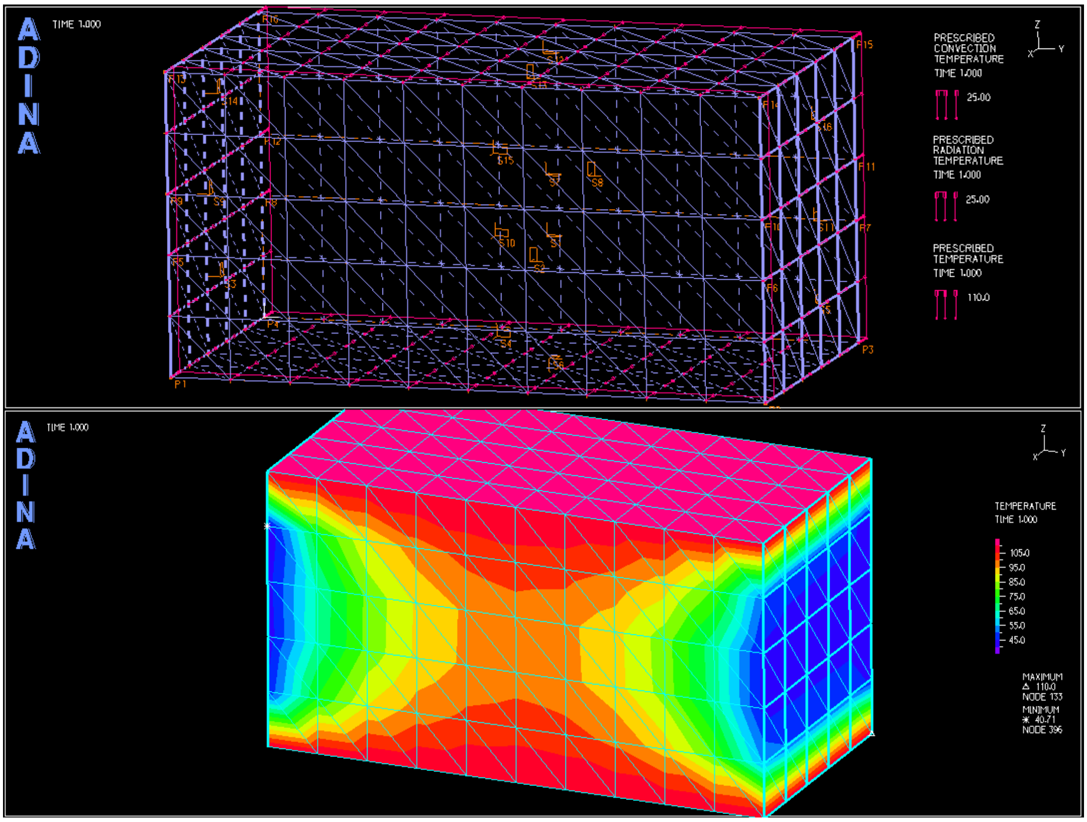
2.1 Impact of material porosity on temperature field

We assume the outer textile made of woven fabric and the cotton inlayer, both of isotropic heat transfer properties. Material parameters can be defined according to [6,11,12]. Isotropic material has the single-component matrix of heat transfer coefficients defined for *i-th* layer $\mathbf{A}^{(i)} = |\lambda^{(i)}| = \lambda$; i=1,2,3; (for inlayer, polymer layer, outer textile material). Heat transfer coefficient of cotton fibre before homogenization is constant $\lambda=0{,}072W/(mK)$ whereas of polymer glue temperature-dependent: $\lambda=0{,}08W/(mK)$ for $T<115°C$, $\lambda=0{,}10W/(mK)$ for $116°C<T<125°C$; $\lambda=0{,}11W/(mK)$ for $126°C<T<135°C$; $\lambda=0{,}12W/(mK)$ for $136°C<T<145°C$. The heat transfer capacity of cotton is $c=1320J/(kgK)$; polymer $c=1200J/(kgK)$. The porosity of cotton fabric is assumed as constant $\varepsilon=0{,}350$. The air content within the layer of polymer is also defined as constant $\varepsilon=0{,}450$. Free spaces are filled by air of the constant heat transfer coefficient $\lambda=0{,}028W/(mK)$ and constant heat transfer capacity $c=1005J/(kgK)$. The surrounding temperature within the housing is assumed $T_\infty=25°C$. The surface film conductance has the constant value $h=0{,}1\ W/(m^2\ K)$.

The problem was solved be means of ADINA-software. The structure is approximated by 3D space Finite Element Net made of 4-nodal elements because convection and radiation are defined by ADINA-program as the spatial function, Figure 5a. Heat transfer equation is integrated using the Gauss method [9]. The obtained temperature distribution is shown in Figure 5b.

The side surfaces have complicated shapes subjected to heat convection and heat radiation. Consequently, the central polymer layer has unequal temperature distribution which can influence the stability of laminate created. Temperature maps are always symmetric relative to vertical plane of symmetry which confirms the correct calculations. Free spaces within polymer layer filled by air are heat isolators and prevent the heat transfer.

Temperature maps enable to create the mean temperature within the polymer glue layer vs. temperature of the plate within heating device. The mean value of the temperature in the homogenized layer made of polymer and air is determined in 27 points located symmetrically within this layer. In engineering practice, values of porosity for cotton fabric can change significantly and it is now assumed arbitrary from the range *$0{,}250 \leq \varepsilon \leq 0{,}450$*. These two values can help to determine the mean temperature of the polymer layer by means of temperature maps by means of the above described procedure. Different porosities determine various heat transfer coefficients and heat transfer conditions. The obtained mean temperatures are shown in Figure 6.



a) Finite Element Net for homogenized layer of polymer, b) homogenized layer of polymer, temperature of upper and lower surfaces T = 110 °C; temperature in housing $T\infty$ = 25 °C

Source: [13]

Fig. 5: *Finite Element Net and example of temperature distribution*

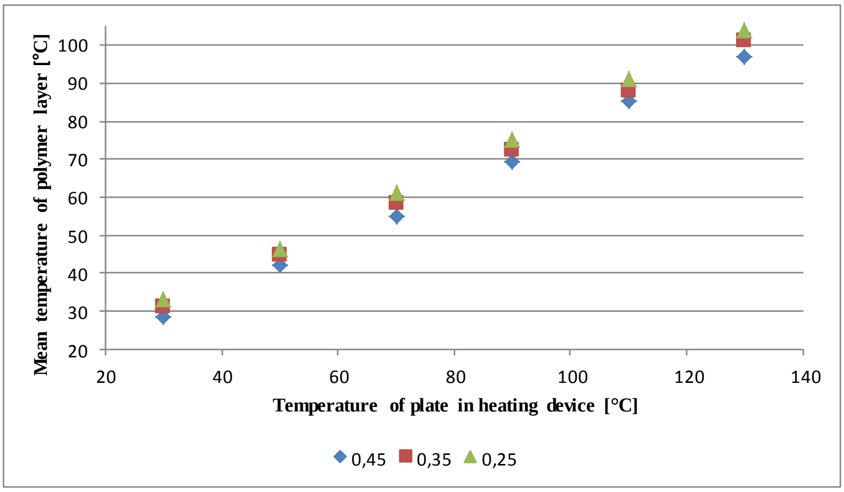


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Fig. 6: *Mean temperature of polymer layer for different cotton porosities*

The obtained distributions of mean temperatures vs. temperature of plate in heating device are similar. The courses can be approximated linearly. It is evident that the higher the porosity, the better isolation of polymer glue layer. Thus, the change of porosity can influence the mean temperature of the polymer layer.

2.2 Impact of surface masses on temperature field

Change in mass in fact determines various heat transfer coefficients. Calculations are determined similarly to previous case for the porosity of the cotton fabric $\varepsilon=0,350$. We can determine after homogenization that the heat transfer coefficients can now change within the range $0,048W/(mK)\leq\varepsilon\leq0,055W/(mK)$. The obtained temperature maps have analogical distribution to the shown in Figure 5b. Mean temperatures are considerably closer as shown in Figure 6 for the porosity $\varepsilon=0,350$. The differences are not greater than 2%. Thus, the parameter is determined now in Figure 6. Consequently we can conclude that the mean temperature is not sensitive to change of surface mass of the inlayer material.

2.3 Impact of type of fibers within inlayer on temperature field

The next problem is to determine the sensitivity of laminate with respect to different fibers applied. The most popular are: polyester, polyamide, cotton, viscose, Lycra-fibers, bamboo fibers ect. The choice of fibers determines heat transfer coefficient for the inlayer material. Similarly to subclause 2.1, isotropic material has the single-component matrix of heat transfer coefficients $\mathbf{A}^{(i)}=\left|\lambda^{(i)}\right|=\lambda$; i=1,2,3. Heat transfer coefficient before homogenization is constant and equal for polyester (PES) $\lambda=0,200W/(mK)$; polyamide (PA) $\lambda=0,210W/(mK)$; cotton $\lambda=0,072W/(mK)$; viscose $\lambda=0,063W/(mK)$ and Lycra $\lambda=0,025W/(mK)$. For simplicity, fabric porosity is assumed as constant $\varepsilon=0,350$. All parameters chracterizing polymer glue, air and surrounding are defined in subclause 2.1. Thhe problem was solved by means of ADINA-software. The strucutre is defined by 3D space Finite Element Net made of 4-nodal elements. Heat transfer equation is integrated using the Gauss method [9]. The obtained temperature distribution has always the same character as shown in Figure 5b but the values are now different. Temperatures on side surfaces are considerably lower than in the centre of the inlayer because the shapes are complicated as well as subjected to both convection and radiation. The temperature maps are symmetric relative to vertical plane which confirm the correct calculations.

The temperature maps help us to create the mean temperature distribution in polymer layer vs. temperature of plate within the heating device for different materials. The mean temperature within the homogenized layer made of polymer and air is determined in 27 points located symmetrically. The mean temperatures are illustrated in Figure 7.

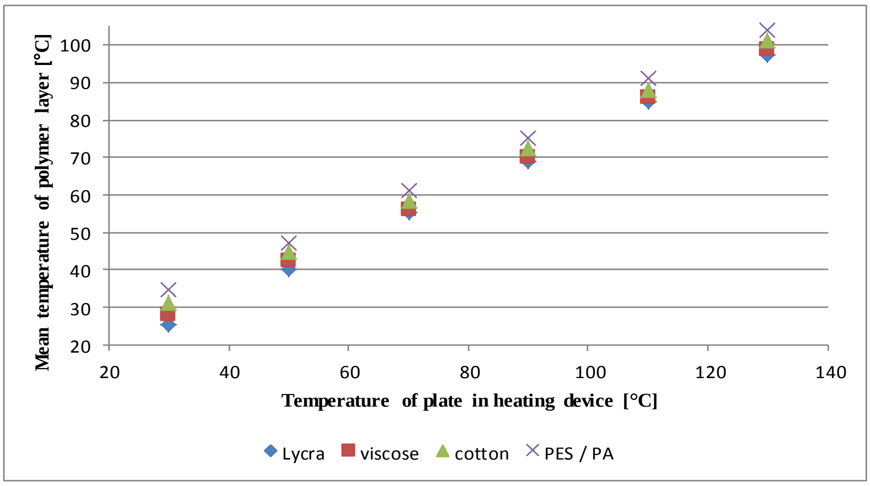

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Fig. 7: *Mean temperature of polymer layer for different inlayer materials*

The mean temperatures are relatively close and the distributions can be approximated by a straight line. The higher the heat transfer coefficient of inlayer material, the better the heat transport through the textile inlayer. Thus, the mean temperature within polymer layer is now higher than the temperature for the more insulating material of lower heat transfer coefficients.

2.4 Impact of other factors on temperature field

There are some other factors which can influence the temperature distribution within the polymer layer. Place and area of application can create a stiff or more flexible connection. The main difficulty is that there is a problem of particular laminate connection which should be analyzed individually. It is difficult to determine the general heat transport model describing all particular cases of lamination technology.

Finishing procedure helps to secure the stability and aesthetic qualities of textile laminate. There are different finishing technologies of various parameters. Thus, at the moment it is impossible to define the heat transfer coefficient precisely. Additionally, material characteristics after finishing procedure can change layer by layer within textile material. These phenomena can be described statistically within each layer.

Lamination technology is a complex problem defined by heat source parameters, the location of heating devices, the time of heating and the time of pressure, the force within the pressure roller etc. The exact description within subclause Introduction determines the specific case of lamination technology. Any other problems should be defined and solved individually.

Conclusion

Temperature maps can give some important information concerning maximal and minimal values of state variable within textile laminate. The mean temperature within polymer layer can be further determined in selected 27 points. This temperature is assumed as the parameter characterizing polymer layer and consequently textile laminate. There are some parameters which can influence the mean temperature. We can also describe the sensitivity of the mean temperature to these parameters.

We have proved that the material porosity and type of fibres within inalyer can influence the temperature field of polymer glue. Moreover, the surface mass is not sensitive in relation to the mean temperature. Of course, a few additional parameters can be deeply analyzed, cf. the place and the area of application, finishing procedure, lamination technology etc. The performed analysis can be also applied to shape optimization within the inlayer material. We can introduce the space 3D structure with respect to different parameters. The problem should be solved numerically because only the basic cases can be calculated analytically.

The next important problem is to introduce the correct physical and mathematical models of heat transfer within textile laminate. The simplest solution is always the only homogenized polymer layer but it can lead to some important and interesting conclusions. The more complicated shape approximation can introduce the pointwise glue points as well as detailed analysis of glue points / free spaces between these points.

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VLIV MATERIÁLOVÝCH PARAMETRŮ NA TEPELNÉ POLE U ODĚVNÍCH LAMINÁTŮ

Vnitřní vrstva zajišťuje jak estetické vlastnosti, tak nemačkavost oděvních laminátů. Laminát je tvořen termoplastovým lepidlem mezi vnitřní vrstvou a oděvním materiálem, který je změkčen teplem. Stálou proměnnou je teplota. Rozložení teploty uvnitř laminátu lze určit numerickou simulací pro různé teploty topných desek. Článek analyzuje vliv různých materiálových parametrů na rozložení teploty.

DER EINFLUSS VON MATERIALPARAMETERN AUF DAS WÄRMEFELD BEI KLEIDUNGSLAMINATEN

Die internen Schichten gewährleisten sowohl ästhetische Eigenschaften als auch Knitterfreiheit bei Kleidungslaminaten. Das Laminat wird mit thermoplastischem Klebstoff zwischen der inneren Schicht und dem Kleidungsmaterial gebildet. Letzteres wird durch Wärme geschmeidig gemacht. Eine konstante Variable ist die Wärme. Die Wärmeverteilung innerhalb des Laminats lässt sich durch eine numerische Simulation für verschiedene Temperaturen von Wärmplatten bestimmen. Dieser Artikel analysiert den Einfluss verschiedener Materialparameter auf die Wärmeverteilung.

WPŁYW PARAMETRÓW MATERIAŁOWYCH NA POLE CIEPLNE LAMINATÓW ODZIEŻOWYCH

Wewnętrzna warstwa zapewnia zarówno właściwości estetyczne, jak i niegniotliwość laminatów odzieżowych. Laminat tworzy klej termoplastyczny pomiędzy warstwą wewnętrzną a materiałem odzieżowym, który jest zmiękczany przez ciepło. Stałą zmienną jest temperatura. Rozkład temperatury wewnątrz laminatu można określić przy wykorzystaniu symulacji numerycznej dla różnych temperatur płyt grzejnych. W artykule przeanalizowano wpływ różnych parametrów materiałowych na rozkład temperatury.