INFLUENCE OF TEMPERATURE ON THE PROCESS OF PLASTICIZATION OF A THIN LAYER OF POROUS MATERIAL WITH ANISOTROPIC PROPERTIES

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Abstract
The plasticization process of a thin layer of wood is used during hot rolling of wooden furniture elements. A traditional treatment technology of wooden or veneered elements consists of sanding several times prior to a lacquer application. The use of hot rolling, which simultaneously applies pressure and temperature allows for a considerable reduction in lacquer consumption. As a result of surface smoothing and compacting of wood internal structure, the surface layer of wood, undergoes the refinement process [4]. Wood is a construction material with complex thermomechanical properties. They depend on wood’s anatomy, which is defined by the three main directions: x - radial (r), y - parallel to fibers (II) and z - tangential (t) (Fig. 1).

Figure 1. Anatomical wood directions

Strength of wood in each of the said directions varies, e.g. strength parallel to fibers is about 8 up to 10 times greater than in radial or tangential directions (Fig. 2). Thus, wood is a highly anisotropic material with a porous structure. It also reacts to temperature changes with a rise in temperature producing a considerable reduction in its strength. Therefore, an efficient plasticization process of a thin layer of wood, requires a rise in temperature up to a certain level during rolling. Together with pressure, the roller-material contact time and temperature are basic parameters of the process.

Therefore, this article presents a solution of the unidirectional and spatial heat conductivity during a hot plasticization of a layer of wood. Identified temperature distributions are compared in order to use them effectively in a mathematical model describing plasticization in a thin layer of wood. The influence of temperature on critical effort, being a characteristic feature of the process under discussion, is of paramount importance.

While modelling the process of plasticization through rolling of a layer of wood, the factor of principal importance is the critical effort of material when its plastic flow starts to occur. The value of this stress depends on the thermomechanical characteristics of the material and the three basic parameters of the process: roller temperature, strength and duration of the force exerted on the surface of the plasticized material. The process under consideration concerns a thin (ca 0.1 mm) layer of wood close to the surface which is subject to the pressure of a hot
roller and heated up to about 130 °C. According to research, in such conditions wood’s strength decreases and lignin which makes up about 40% of wood’s weight becomes plasticized and fills up its pores, thus, compacting wood’s internal structure. This process is executed with a rolling mill designed for a furniture manufacturer which has been implemented in production of furniture elements with a natural veneer.

1. MATHEMATICAL MODEL
Analysis of plastic deformations in the thin layer of wood under consideration was based on the generalized model of an ideally plastic medium [5], [7], [8]. The plasticity condition describes a relation between the components of stress, temperature and internal structure parameters for a critical effort of the material. It corresponds with the occurrence of first permanent deformations in a given node of the body. The relation, expressing the plasticity criterion for an anisotropic and porous material under the influence of temperature, are generally expressed as the following scalar function:

\[ F(\sigma, f_v, T) = 0, \]  

where: \( \sigma \) - anisotropic stress state, \( f_v \) - scalar function of porosity, \( T \) - scalar function of temperature.

Fig. 2. Principal stress directions for a rolled layer of wood

where: 1, 2, 3- principal axis in longitudinal, tangential, radial directions, 
P - rolling force, s - contact length between roller and layer, \( h_1 \) - initial thickness of wood layer, \( h_2 \) - thickness of rolled wood layer, l - width of wood layer.

Assuming that the skeleton of the material is an ideally plastic medium without any reinforcement, where plastic deformations considerably prevail over elastic ones and at the same time introducing the function of volumetric porosity, the above condition takes the following form:

\[ \text{tr} S^2 + \psi_1 \text{tr} \sigma = \psi_2 Y_i^2 \]  

where: \( \psi_1 \) and \( \psi_2 \) - porosity functions, \( \sigma \) - material stress tensor, \( S \) – deviator part of the stress tensor, \( Y_i \) - yield points with tension in a selected principal direction.

The plasticity condition for an assumed orthotropy and plane stress takes the following form:

\[ A \left( \sigma_1 + \sigma_2 \right)^2 + \left( \sigma_1 - \sigma_2 \right)^2 = B Y_i^2, \]  

where: \( \sigma_1 \) and \( \sigma_2 \) - principle stresses in anatomical directions:
1 – parallel to fibers, 2 – tangential to fibers (Fig.2), A and B - porosity functions.
The above condition is a basis for determining the critical stress (capacity limit) being a result of pressure exerted by the roller on a porous and anisotropic material under influence of temperature. After the following transformations, the formula describing the critical plasticization force in the process under consideration, can be presented in the following form:

\[ P = \frac{B}{(1 + A)} - \frac{B}{4(1 + A)} \left[ \frac{(1 - 2A)^2(1 + \alpha - \beta)}{A(3 + 3\alpha - 2\beta)} \right] Y_1^2 F^2, \]  

(4)

where: P – critical force exerted by the roller on the surface of the plasticized material, \( \alpha \) and \( \beta \) - orthotropic stress ratios, \( Y_1 \) – yield point along fibers depending on temperature, F – area of roller-plasticized material.

2. TEMPERATURE DISTRIBUTION IN THE LAYER OF PLASTICIZED MATERIAL

2.1 Plane temperature distribution
In order to design a proper mathematical model, first of all, it was necessary to select the elements which make the solution satisfactory. In the analyzed case these were complex thermo-mechanical properties of the material, porosity and process parameters (Fig.3).

Fig. 3. Constitutive connection in process of rolling a layer of wood

where: \( R_{\text{mII}} \) - the strength of wood in the parallel direction during tensioning, \( R_{\text{cII}} \) - the strength of wood in the parallel direction during shearing, \( R_{\perp} \) - the strength of wood in the normal direction during shearing, \( R_{\text{cr}} \) - the strength of wood in the diagonal direction during shearing, \( R_{\text{ct}} \) - the strength of wood in the tangent direction during shearing, T - temperature, w – moisture.

While formulating the plasticity condition constitutive equations describing the process under consideration the influence of temperature were of paramount importance. The objective of
the present paper was to determine characteristics of temperature changes in a layer of wood in time occurring as a result of technological conditions of the process.

The theoretical analysis concerned of a thin (max. 1 mm) layer of wood of deciduous trees. Assuming transient heat conduction in a single plane and adiabatic shield on the border of the area in question, the process can be described using the Fourier equation, [6]:

\[
\frac{\partial T}{\partial t} = a\left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right),
\]

where: \( a \) – diffusivity ratio \( a = \frac{\lambda}{c_p \gamma} \), directly influencing the solution of temperature distribution in the layer of material under consideration, \( T \) – temperature, \( c_p \) – specific heat at constant pressure, \( \gamma \) – specific gravity, \( \lambda \) – heat conductivity ratio.

Therefore, the experimentally determined functions of temperature and anisotropy were introduced into the model, showing their influence on heat conductivity ratio in the following manner [2]:

\[
\lambda_{||} = f(T), \quad c_p = f(T), \quad \lambda \chi = \frac{\lambda_{||} + \lambda_{\perp}}{2} \quad \text{or} \quad \lambda_{\perp} = \lambda_{r} = \lambda_{t}
\]

where: \( \lambda_{||}, \lambda_{r}, \lambda_{t} \) - heat conductivity ratios in directions: parallel, radial and tangential to fibers.

Parameters assumed for the calculation of geometrical structure and ratios of the material were those of oak wood, and such they are generally used in research work and industrial practice. Roller-wood surface contact time was very short and amounted to 0.06 s, this fact being the result of linear rolling speed during the technological process. The temperature in the layer close to the surface was expected to exceed 130 °C, as such a temperature was sufficient for the refining effect to occur.

Fig. 4. Geometric parameters of the roller and a layer of wood in the rolling process,

where: \( R_w \) – radius of the roller, \( h_1 \) – thickness of the layer of wood prior to rolling, \( h_2 \) – thickness of the layer of wood after rolling, \( \Delta h \) – absolute degree of deformation, \( \varphi \) - angle based on the arc of roller's contact with the surface of wood, \( s \) – length of roller's arc of contact with the surface of wood, \( e \) – orthogonal projection of arc \( s \), \( \omega \) - rate of rotation of the roller.

In order to find a solution of the above defined issue the variant of the finite element method described in [3] was used. After a digitization, the finite element method was used to work out temperature at nodes of the grid of the area ABCD (Figure 4), which was divided into 500 rectangular elements, making up 561 nodes [1].
Figure 5. Temperature values in selected nodes of the rolled layer of wood.

Fig.6. Temperature changes characteristics in a layer of wood in time

The assumed coordinate system was arranged in such a way that axis x was directed inside the layer of wood whereas axis y (Fig. 4) was directed along line s, and the rolling direction. Figure 5 presents one of 50 planes of this area representing temperature distribution inside a layer of wood 0.8 mm-thick at ten intervals. Results of calculations [Fig. 6], show a considerable temperature rise in the layer closest to the roller after 0.06 s. with the temperature reaching the level required for wood refinement i.e. 130°C.
2.2 Three-dimensional temperature distribution

In case of heat conductivity in a three-dimensional space the Fourier equation will have the following form:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right).$$

(7)

Therefore, just like in case of heat conductivity in a single plane, the experimentally determined functions of temperature and anisotropy were introduced into the model, showing their influence on heat conductivity ratios:

$$\lambda_\perp = f(T), \quad \lambda_r = f(T), \quad \lambda_t = f(T), \quad c_p = f(T),$$

(8)

$$\lambda_\perp = \frac{\lambda_\perp + \lambda_t}{2} \quad \text{or} \quad \lambda_\perp = \lambda_r = \lambda_t$$

(9)

where: \(\lambda_\perp, \lambda_r, \lambda_t\) - heat conductivity ratios in directions: parallel (x), radial (y) and tangential (z) to fibers.

Having conducted spatial digitization of equation (7) and with appropriate initial and boundary conditions accompanied by an approximation of the thermal field through a finite element shape function a system of ordinary differential equations in a function of node temperatures and their time derivatives was used. The system of equations can be written down in the following manner:

$$[C] \frac{d}{dt} \{T\} + [K] \{T\} = \{F\},$$

(10)


Numerical calculations were performed for the non-linear and transient spatial heat conductivity. A solution of the problem was obtained using I-DEAS software with a TMG Thermal Analysis module. All input data, required to define the process under consideration, were entered into the program with the use of appropriate procedures.

Due to a spatial analysis of the problem, 8-node rectangular prism blocks were used. Interpolation of the examined function between nodes was linear. The FEM grid (Fig. 7) was concentrated in the area close of the hot roller-plasticized material contact surface in order to achieve a higher precision of the solution.

Out of the four basic boundary conditions, type 1, i.e. Dirichlet boundary condition was assumed. In accordance with the said condition the temperature distribution on a given area of a body is taken, i.e. surface temperature \(T_S(t)\) is known, in the area where it is pressed by the hot roller. Then the condition takes the form:

$$T(t)_{y=\text{max}} = T_S(t) = 220^\circ C.$$

The initial conditions (the so called Cauchy conditions) are temperature values of the body at the initial moment \(t_0=0\) s. Thus:

$$T(x,y,z,0) = T_0(x,y,z) = 20^\circ C.$$

Moreover the following environment conditions were taken for the calculations: temperature \(-20^\circ C\), pressure \(-1013\ hPa\), acceleration of gravity \(-9,81\ m/s^2\).

The spatial heat conductivity model was solved using I-DEAS software for the same input data as for a single plane heat conductivity. The obtained results of spatial temperature distribution after 0.06s are presented in Figure 8 and concern the plane of the ABCD area (Fig. 4) inside a layer of wood.
Fig. 7. Spatial distribution of field of temperatures

Results of temperature distribution calculations in a 3-D space, just like in case of a single-plane conductivity, show that the temperature in the layer closest to the roller exceeds 130 °C, i.e. reaches the level required for plasticization (Fig. 6).

Fig. 8. The distribution of temperature in plane X Y (Fig. 4.)

CONCLUSIONS

A comparison of solutions of initial boundary problems concerning two-dimensional and three-dimensional heat conductivity in a thin layer of wood leads to the following conclusions:
- Obtained numerical temperature values in a layer of the material under consideration are convergent, a 20-110°C range difference belongs to the -1 up to 1.78°C interval, i.e. about ±3% and a 110-130°C range difference belongs to the 0.96 up to +0.94 interval i.e. about 1%.

- At higher temperatures, which are responsible for plasticization, the convergence of results is especially high.

- The existing comparability of results makes it possible to restrict the analysis of temperature distribution in a layer of wood to a simpler two-dimensional model.

BIBLIOGRAPHY