гів з абразиву гранату збільшувалася в 1,3...1,5 рази, в той час коли стійкість абразивних кругів з карбіду кремнію досягала 3 тис. пог. м. прошліфованої поверхні берези і біля 2 тис. пог. м поверхні бука.

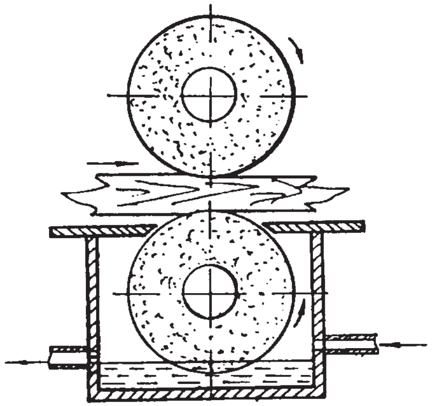

Рис. 1. Схема процесу шліфування

Пояснити таке явище можна тим, що завдяки зниженню температури абразивних зерен робочої поверхні круга значно зменшується ймовірність налипання на них зрізаної стружки. Відомо, що налипання стружки на різальний інструмент викликано наявністю структурі деревини цукристих та смолянистих речовин. Завдяки змочуванню зерен водою цей процес значно затрудняється. Крім цього змочені абразивні зерна мають нижчий коефіцієнт тертя до оброблюваного матеріалу, що теж сприяє зниженню температури в зоні різання та зменшує швидкість затуплення зерен, що приймають участь в роботі.

Проведені попередні дослідження показали, що запропонований спосіб шліфування деревини жорсткими абразивними кругами є ефективним і заслуговує на його більш глибоке теоретичне та практичне вивчення.

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DETERMINATION AND CONTROL OF THE LUMBER STRESSED-STRAINED STATE IN THE PROCESS OF DRYING

The problem of identification and control of the stress-strain state of wood in the process of drying taking into account its viscoelastic properties in this article is considered.

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Визначення та контроль напружено-деформівного стану пиломатеріалів у процесі сушіння

Розглядається проблема ідентифікації та контролю, напружено-деформівного стану деревини у процесі сушіння з врахуванням пружнов'язкопластичних її властивостей

In this paper the calculating methods of the lumber stressed-strained state in the process of drying are worked out. On its basis the numeric experiment is carried out. This experiment finds out wood rheological behaviour peculiarities in the conditions of heat-mass exchange. The way of non-destructive current control, offered in [8], of the moisture and moisture-residual stresses on the surface and in the mean of the lumber in the process of drying, is substantiated in this paper.

1. The calculating methods of the stressed-strained state include: a) physical and mathematical model showing the interrelation of the moisture and moisture-residual stresses in the wood and its moisture state [4-7]; b) dependence of the local and mean moisture content difference in the material on drying agent parametres [6]; c) determining methods of the lumber rheological properties [3, 4].

1.1. Interrelation of stressed-strained and moisture states of the wood in the process of drying can be described by the system of equations [3, 4, 6]

$$\begin{cases} \sigma(\tau,y)=\sigma_b(\tau,y)+\sigma_{b-3}(\tau,y); \\ \sigma_b(\tau,y)=f(\tau,y)\left[u(\tau,y)-u_{cep}(\tau)\right]; \\ \sigma_{b-3}(\tau,y)=-\int_0^{\tau} f(\tau^*,y)R(\tau-\tau^*,y)*\left[u(\tau^*,y)-u_{cep}(\tau^*)\right] \end{cases} \quad (1)$$

where $f(\tau,y)=E(\tau,y)\beta(\tau,y)/[1+\beta(\tau,y)]u_0$; y – coordinates of the material boundaries according to its central plane; u_0 – the initial moisture content; $E(\tau, y)$, $\beta(\tau, y)$, $R(\tau-\tau^*, y)$ physical and mechanical characteristics of the wood (modulus of elasticity, coefficient of drying, kernel of relaxation), $u(\tau,y)$, $u_{cep}(\tau)$ – characteristics of the wood moisture state (function of the moisture content distribution along the plate thickness and mean moisture content); $\sigma_b(\tau,y)$, $\sigma_з(\tau,y)$ $\sigma(\tau,y)$ – moisture, moisture and residual and full stresses correspondingly.

The $\sigma_b(\tau,y)$ is preconditioned by elastic properties of the wood and after drying process termination, for example at the moment of time $\tau = \tau_к$ its change in relation to time is constant, i.e./ that is $\sigma_b(\tau,y)= =\sigma_b(\tau_к,y)=const$ for $\tau > \tau_к$ preconditions the decrease of the component $\sigma_b(\tau,y)$. The component $\sigma_{b-з}(\tau,y)$ is characterized by wood viscous properties and its quantity and the character of its change in relation to time depend on the "history" of moisture content change development.

Finishing the analysis of the system (1) it should be noted, that it gives the possibility for calculating (estimation) of the stressed-strained state in lumber in the case, when dynamics of the local and mean moisture contents difference and the kernel of material relaxation $R(\tau-\tau^*)$ are known.

1.2. Dependence of local (u(τ,y)) and average ($u_{cep}(\tau)$) moisture contents difference according to the data from the studies [6] are as follows:

for the period of constant drying rate

$$u(\tau,y)-u_{cep}(\tau)=Nu\frac{D_p b}{2a_m\rho_0 L}\left\{\frac{1}{3}-\left[\frac{y}{b}\right]^2\right\}*\left\{\exp\left(\frac{-1785\Delta t(\tau)}{(238+t_c(\tau))^2}\right)-\varphi(\tau)\right\} \quad (2)$$

for irregular and regular regimes of the period of declining drying rate

$$u(\tau,y)-u_{cep}(\tau)=\left[(u_{nc}-u_p)-\frac{2}{Bi}(u_{цc}-u_{пc})\right]*\{[h(Fo)-h(Fo-0,1)]S(\tau,y,Bi)+$$
$$+A_1 h(Fo-0,1)\cos\left[\mu_1\frac{y}{b}\right]\exp(-\mu_1^2 Fo)\}+ \quad (3)$$
$$+\left\{2(u_{цc}-u_{пc})\cos\left[\mu_1\frac{y}{b}\right]-Bi\left[(u_{пc}-u_p)-2\left(\frac{1}{Bi}+\frac{1}{\mu_1^2}\right)(u_{цc}-u_{пc})\right]\frac{A_1}{\mu_1^2}\cos\mu_1\right\}\exp(-\mu_1^2 Fo)$$

where

$$S(\tau,y,Bi)=1-1,3\sqrt{Fo}\exp\left(-\frac{(1-y/b)^2}{4Fo}\right)*\left[\frac{1}{1,3\sqrt{Fo}+1-y/b}-\frac{1}{1,3\sqrt{Fo}+1-y/b+2BiFo}\right]$$

ρ_0 – relative density of lumber; a_m – coefficient of wood moisture conductivity; D_p – coefficient of wood moisture conductivity referred to pressures difference; u_{nc}, $u_{цc}$ – moisture contents at the beginning of the irregular regime period of moisture change (on the surface and in the central plane of the plate); u_c constant moisture content; $P_{н.c}$ – pressure of saturated vapour; $\varphi(\tau)$, $t_c(\tau)$, $\Delta t(\tau)$ – drying agent parametres (relative moisture, temperature, psychometrical difference of temperatures); $F_0=a_m\tau/b^2$, $Bi=\alpha b/a_m$; $Nu=0,6[\upsilon L/\nu]^{0,563}$ – the criteria of Fourier, Bio and Nuselt, correspondingly; υ – drying agent rate; ν – coefficient of drying agent viscosity; $2b$ – material thickness; L – characteristic linear dimension of material; $h(F_0)$ – function of Heaviside. Coefficients μ_1, A_1 – are determined by the equations, presented in the studies [2]

$$ctg\mu_1=\mu_1;\ A_1=2\sin\mu_1/(\mu_1+2\sin\mu_1\cos\mu_1)$$

for $0<\mu_1<\pi/2$.

Formula (3) can be carried out in the case when $Bi>10$.

1.3. The methods for determination of physical and mechanical characteristics of the wood, worked out in the studies [3,4] are based on the results of reological tests, carried out on the wood patterns to determine their creep nature in different stationary temperature and moisture conditions and interpolation methods of wood manufacturing. These methods give the possibility to determine the kernel of relaxation for lumber which belongs to the equation of the system (1).

Specifically, these methods have determined $R(\tau-\tau^*)$ for pine and fir-tree in tangential direction of deformation

$$R(\tau-\tau^*)=\frac{E(w,t)-E_T(w,t)}{E_T(w,t)\tau_{рел}(w,t)}*\exp\left[-\frac{\tau-\tau^*}{\tau_{рел}(w,t)}\cdot\frac{E(w,t)}{E_T(w,t)}\right] \quad (4)$$

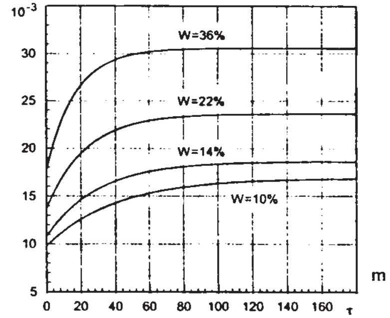

Figure 1. The curves of creep nature of the wood, namely pine under the temperature 80°C in the tangential direction of deformation for different values of moisture W.

where $E_T(W,t)$ – continuous modulus of wood elasticity of the temperature t and relative moisture W; $\tau_{рел}(W,t)$ – time of relaxation of the deformations of wood creep.

The curves of wood creep, approximated by the equations of Voltaire-Bolzmann [9] for different values of temperature t=[20 °C, 40 °C, 60 °C, 80 °C, 100 °C,120 °C] and levels of moisture in the tested pine material W= [10 %, 14 %, 22 %, 36 %] have been built. As the example figure 1 shows the curves of creep nature of material with the temperature t=80 °C.

2. The numeric experiment. On the basis of above presented methods for calculating stressed-strained state of lumber, in the conditions of heat mass exchange, $\sigma_b(\tau,y)$, $\sigma_{b-з}(\tau,y)$ and $\sigma(\tau,y)$ in pine lumber ($E=280MPa$; $E_T=167MPa$; $\beta=0,0023$; $\rho_0=480\ kg/m^3$ для $t=20^oC$ and $W=25$ %) of different thickness, dried in the conditions of constant technological regime ($t_c=88^oC$, $\Delta t=14^oC$, $\varphi=55$ %, drying agent rate $v=2$ m/s).

Specifically, figure 2 shows the results of calculation $\sigma_b(\tau,y)$, $\sigma_{b-з}(\tau,y)$, gotten for tangential pine plate, which is 13 mm thick ($2b$=13 mm).

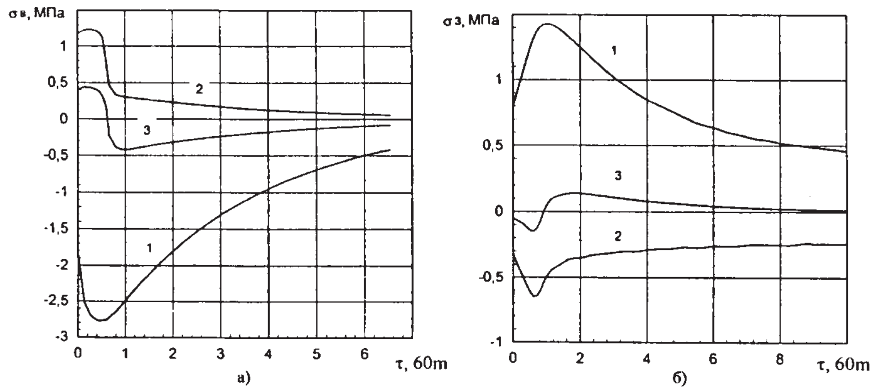

Figure 2. Dynamics of moisture (a), moisture and residual (b) stresses for irregular and regular regimes of the declining drying rate period for tangential pine plate with thickness 2b=13 mm: 1- on the surface; 2 – at the distance b from the surface; 3 – at the distance b/2 from the surface

Analysis of the graphical dependence (fig. 2a) proves, that with the time increase at the irregular regime period the stretching moistures of $\sigma_b(\tau,y)$ stress on the surface ($y=b$) of the material and compressing ones $\sigma_b(\tau,y)$ in the central layer ($y=0$) increase. At the regular regime period ($\tau>0,2b^2/a_m$) $\sigma_b(\tau,b)$ and $\sigma_b(\tau,0)$ with the growth of τ decrease to zero asymptotically. In the dots, which are remote from the surface of lumber at the distance $y=b/2$ in time range $0,1b^2/a_m<\tau<0,2b^2/a_m$ there is the change of value sign ($\sigma_m(\tau,b/2)$) happens (curve 3 in the fig. 2a). This change, according to the second equation of the system (1) is preconditioned, obviously, by the change of the sign in the difference of moisture contents $u(\tau, b/2)$ and $u_{cep}(\tau)$. This is the proof of that in the process of lumber drying (of lumber) the boundary of distribution of surface stretching and inner compressing stresses moves along the material thickness and in any moment of time τ can be determined by the equation

$$u(\tau,y)=u_{cep}(\tau). \tag{5}$$

Such a behaviour of moisture stresses dependence from the beginning of the process of drying in the declining rate period is natural and has physical substantiation. In fact, in the declining rate drying period two processes take place in lumber: hygroscopic moisture evaporation from the subsurface levels and transfer of moisture from the drying material mean to its surface. At the stage of irregular regime the forces of moisture transfer (capillary, osmotic, diffusive, adsorption forces etc.) are not quite powerful and thus they are not able to fulfill minimal work for overcoming potential difference of moisture transfer from central and surface layers of the material [2]. This phenomenon we will call potential barrier. That is why in this case the evaporation process of bonded moisture, namely osmotic moisture is mainly observed. The energy of its bondedness is the lowest [2] in comparison with capillary-, adsorption- and chemical-bonded moisture. As the result the surface layers dry and their linear dimensions become decreased (shrinkage phenomenon), and the same phenomenon is happening with inner layers dimensions. It preconditions some increase of stretching moisture stresses in the subsurface layers and compressing moisture stresses in the mean layers at the stage of irregular regime (fig. 2a).

With the increase of drying continuity at the stage of irregular regime moisture content on the lumber surface gradually decreases, the distribution of moisture in central and surface layers increases, and thus, moisture transfer potential dimension increases as well (moisture gradient). However, the forces, preconditioned by the moisture gradient are not able to overcome the potential barrier mentioned above. Simultaneously with the surface drying the amount of lightly bonded moisture in the subsurface layers and evaporation potential decrease. Evaporation potential is the difference between partial pressures of the vapours in the water from the lumber side and drying agent on the surface, which separates them. Thus the evaporation process takes place slowly and the shrinkage phenomena race on the lumber surface in the process of drying decreases. This limits the increase of moisture stress $\sigma_b(\tau,y)$ at the stage of irregular regime. Actually, according to the figure 2a increasing race $\sigma_b(\tau,y)$ at the range of time $0<\tau<0,1b^2/a_m$ declines to zero.

At the stage of regular regime moisture evaporation race from the surface of the material is approximately the same as the race of surface moistening, which is preconditioned by moisture transfer processes in the material volume. That is why it can be considered that in the case of $\tau>0,1b^2/a_m$ moisture content on the surface of drying lumber is the constant value. In such case, it obviously, that the character of moisture is stresses development in the process of drying will be determined by the moisture flux from the mean of the material to its surface. It will brings about the subsurface layers moistening and drying of the inner layers. Moistening will cause swelling and drying – shrinkage, which is the reason of decrease of the absolute values $\sigma_b(\tau,y)$ on the surface and in the mean of the material at the stage of regular regime in the process of drying (fig. 2a).

The comparative analysis of the graphical dependence for moisture $\sigma_b(\tau,y)$ (fig. 2a) and moisture-residual $\sigma_{b\text{-}з}(\tau,y)$ (fig. 2b) stresses has found out that the character of the change $\sigma_{b\text{-}з}(\tau,y)$, is determined by increase $\sigma_b(\tau,y)$ at the range of time $0<\tau<0,1b^2/a_m$ from 1,8 MPa до 2,7 MPa, moisture-residual stresses $\sigma_{b\text{-}з}(\tau,y)$ increase from 0,8 MPa to 1,3 MPa, and in the case when $\tau>4$ hours both components decrease. Relation of $\sigma_{b\text{-}з}(\tau,y)$ and $\sigma_m(\tau,y)$ is substantiated by the equations of the system (1). Actually, putting the second equation of the system (1) into the third equation of this system we will get

$$\sigma_{b-з}(\tau,y)=-\int_0^{\tau} R\left(\tau-\tau^*,y\right)\sigma_b(\tau,y)\,d\tau \tag{6}$$

Or

$$\sigma_{b-з}(\tau,y)=-E\left(\frac{1}{E}\left[\sigma_b(\tau,y)+\int_0^{\tau} R\left(\tau-\tau^*,y\right)\sigma_b\left(\tau^*,y\right)d\tau^*\right]\right)+\sigma_b(\tau,y) \tag{7}$$

Hence, as according to the equations of Voltaire-Bolzmann

$$\frac{1}{E}\left[\sigma_b(\tau,y)+\int_0^{\tau} R\left(\tau-\tau^*,y\right)\sigma_b\left(\tau^*,y\right)d\tau^*\right]=\varepsilon_{nob}(\tau,y) \tag{8}$$

then

$$\sigma_{b-з}(\tau,y)=-E\varepsilon_{nob}(\tau,y)+\sigma_b(\tau,y) \tag{9}$$

where $\varepsilon_{nob}(\tau,y)$ – deformations of creep in drying lumber, preconditioned by the force of moisture stresses $\sigma_b(\tau,y)$.

Since $R(\tau-\tau^*)>0$, then according to (8), the character of the development of the creep deformations $\varepsilon_{nob}(\tau,y)$ can be determined by value $\sigma_b(\tau,y)$. That means that under the force of stretching stresses $\sigma_b(\tau,y)$ in drying wood the stretching deformations of creep will develop $\varepsilon_{nob}(\tau,y)$, and under the force of compressing stresses $\sigma_b(\tau,y)$ – compressing deformations.

Accordingly, surface layers will produce the resistance to compression of inner layers, and inner layers produce thew resistance to stretching the surface layers. Thus, moisture-residual stresses in drying lumber are preconditioned by uneven distribution of creep deformations in its volume.

3. The control of stressed-strained state in drying lumber according to the difference of local and mean moisture contents [8] The essence of this way lies in continual calculating by conductive and metrical method of the difference of local $u(\tau,y)$ and average $u_{cep}(\tau)$ moisture contents and the following calculating moisture $\sigma_b(\tau,y)$; moisture and residual $\sigma_{b\text{-}з}(\tau,y)$ and full $\sigma(\tau,y)$ stresses by the formulae (1) and (4). This way of calculating differs from known methods [1,9] (namely, differential shrinkage, according to moisture distribution and average moisture content) first of all because it allows during drying time to determine: 1) the influence of viscous-elastic characteristics of lumber (E, E_T, τ_{pe}, and $R(\tau-\tau^{*},y)$) on its stressed-strained state; 2) the dynamics of moisture and residual stresses on the surface and inside the lumber.

On the basis of the describe way of control of stresses in this studies the system of automatic conducting the process of lumber drying according to the stresses values in their volume is worked out, and its functional scheme is shown on the fig. 3.

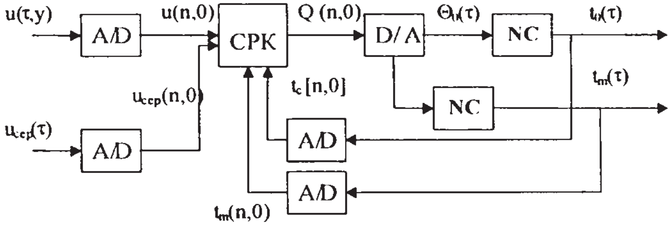

Figure 3. The functional scheme of the system of automatically conducting the process of lumber drying: *A/D and D/A – analogous–digital, and digital-analogous transformers; CPK – digital conducting mechanism, namely IBM PC; NC – executing mechanism.*

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УДК 674: 621.928.93 Проф. Є.М. Лютий, д.т.н.; доц. П.П. Нахаєв, к.т.н. – УкрДЛТУ; А.В. Ляшеник – Коломийський політехнічний коледж

ВПЛИВ ФІЛЬТРУВАЛЬНОЇ СТІНКИ НА РОЗПОДІЛ ТАНГЕНЦІАЛЬНОЇ СКЛАДОВОЇ ШВИДКОСТІ ПОВІТРЯНОГО ПОТОКУ У ЦИКЛОНАХ

Описано дослідження, які проводилися авторами, по вивченню тангенціальної складової швидкості потоку у циклоні ЦН-15 та фільтруючому циклоні. Показано позитивний вплив фільтрувальної стінки на розподіл тангенціальної швидкості потоку повітря у поперечному перерізі циклона.

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To the problem of distribution of the tangential velocity component of the flow in the cyclon's

This article describes researches, carried out by the authors, concerning the study of the tangential velocity component of the airflow in the cyclone ЦН-15 and filter cyclone. It shows positive filter wall influence on the distribution of the tangential velocity of the flow.

Для опису руху частинок у циклоні використовують різноманітні математичні моделі.

Більша частина цих математичних моделей створюються на основі наступних міркувань. На частинку пилу, яка знаходиться у циклоні, діють такі сили: відцентрова, Стокса, тяжіння, Кореоліса та аеродинамічні сили Магнуса і Сефмана [1-4]. Проте визначальними є відцентрова сила та сила Стокса. Так, наприклад, сила тяжіння є меншою за відцентрову силу в 100...2000 разів [3].

Відцентрову силу обчислюють за формулою

$$P=\frac{\pi\cdot d^{3}}{6}\cdot\rho\cdot\frac{V_{\tau}^{2}}{r}, \tag{1}$$

де: d – діаметр частинки; ρ – густина матеріалу частинки; $V\tau$ – тангенціальна складова швидкості потоку; r – відстань від осі циклона до частинки (рис. 1).

Силу Стокса можна визначити як

$$F_{st}=3\pi\mu dV_{R}, \tag{2}$$

де: V_R – радіальна швидкість частинки; μ – динамічна в'язкість потоку повітря.

Ефективність циклона характеризується умовним діаметром частинки, що досягне зовнішньої стінки циклона, який визначається з рівняння

$$\frac{\pi\cdot d^{3}}{6}\cdot\rho\cdot\frac{V_{\tau}^{2}}{R}=3\cdot\pi\cdot\mu\cdot d\cdot V_{r}. \tag{3}$$

При різноманітних підходах до розв'язання даного рівняння одержують наступні формули:

- для мінімального діаметра частинки [4]

$$d_{min}=3\sqrt{\frac{\mu(R_{1}-R_{2})}{\pi n_{o}\rho V_{\tau}}}, \tag{4}$$

- для середнього діаметра [5]

$$d_{cep}=3\sqrt{\frac{\mu\cdot R_{a}\cdot h\cdot ctg\alpha}{(1-k_{pr})\cdot\rho\cdot V_{\tau}\cdot L}}, \tag{5}$$

де: n_0 – кількість обертів, що здійснює частинка навколо осі циклона; R_1 – діаметр вихлопної труби; R_2 – діаметр зовнішньої стінки циклона (рис. 1); d_{min} – розмір найменших частинок, що повністю вловлюються у циклоні; $R_a=(R_1+R_2)/2$; $h=R_2-R_1$; d_{cep} – розмір частинок, ймовірність уловлення яких циклоном складає 50 %; k_{pr} – коефіцієнт повторного захоплення частинок потоком.