

4. **Jim Raymont, Abhinav Kashyap** (Spring 2011): Measuring the output of Ultraviolet light emitting diodes // Radtech Report Technical Paper.
5. **Yarish O.V.** (2013): *Fotopolimeryzatsiya LFM pid diyeyu emitovanoho tverdotel'nymy dzhere-lamy UF-vyprominyuvannya v laboratornykh umovakh* [Coatings photopolymerization by the irradiation emitted by solid sources of UV-radiation in the laboratory conditions]. *Forestry, Forest, Paper and Woodworking Industry* 39(1):75-79, (in Ukrainian).
6. **Karyakina M.I.** (1988): *Ispytaniye lakokrasochnykh materialov i pokrytiy* [Испытание лако-красочных материалов и покрытий]. – Moscow : *Chemistry* : 85-92, (in Russian).

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### **Дослідження можливості полімеризації акрилових лакофарбових матеріалів фотохімічного твердіння під дією УФ-випромінювання, емітованого твердотільними джерелами**

Досліджено можливість полімеризації акрилових ЛФМ фотохімічного твердіння під дією УФ-випромінювання, емітованого твердотільними джерелами (на базі лабораторної установи); проведено порівняння твердості (як характеристики ступеня затвердіння) отриманих лакофарбових покриттів з твердістю аналогічних покриттів, фотополімеризація яких ініційована ртутно-кварцовою лампою високого тиску.

**Ключові слова:** УФ-твердіння, твердотільні джерела УФ-опромінення, світлодіодні джерела, лабораторна установка, твердість покриття.

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### **RESEARCH OF THE WOOD COMPOSITE MATERIAL DEFORMABILITY IN TERMS OF THE HEAT MASS TRANSFER**

The analysis of the basic structural states in the technological process of manufacturing of wood composite materials is carried out. The parameters of temperature-humid field and kinetics of structural transformations are determined and building a mathematical model for the determination of the stress-strain state of wood composite materials under conditions of heat mass transfer.

**Keywords:** fluidity, viscoplasticity, viscoelasticity, stress-strain.

**Introduction.** A characteristic trend in modern studies of the wood composite materials (WCM) is a shift towards process problems and formation of a new direction their basis, namely process mechanics of the wood composite materials. The central problem in this respect is to develop the phenomenological interrelated physical and mechanical WCM models, taking into account the structure formation evolution in the process. On their basis, reasonable process parameters for specific materials, basic types of structures and processes of their manufacture may be identified, recommendations may be justified, and special algorithms to control such parameters ensuring the required WCM quality may be developed.

The analysis of theoretical and experimental study findings, as well as the production experience shows that the use of traditional physical mechanics relations to determine the WCM quality indicators does not allow determining their dependence on the influence of process factors during their manufacture unequivocally. In particular,

the same hydrobarothermic WCM production modes result in formation of residual process stress fields with varying nature and structure. Besides, the formation of WCM structure as polymer composites in the manufacturing process is related to the evolution of its condition. In the most general case, under the temperature, humidity and mechanical stress, the polymer materials undergo irreversible physical and chemical transformations with phase transitions, and consistently move from one equilibrium state to another, taking into account the fluidity, viscoplasticity, and viscoelasticity.

**Synthesis of mathematical model for determination of deformation-relaxation processes in wood composite materials.** One can highlight five major structural conditions in the WCM manufacturing process: viscous state with viscosity varying during heating; formation of molecular and supramolecular structure, the transition of reinforced matrix to highly elastic condition; temperature field lowering to T-vitrification, slowing down of elastic properties; transition to the glassy condition with vigorous increase in relaxation time due to the supramolecular structuring; cooling down to the ultimate temperature subject to change of relaxation properties. To solve the problems related to determination of the process stress fields and strains for each stage, the corresponding physical ratios for temperature and humidity, relaxation and conversion processes shall be recorded. At all WCM production stages, the thermal and mechanical properties depend on the temperature, humidity and structural condition of composites. Logically, it is first required to consider the problems of thermal and moisture conduction, as well as structural transformation kinetics. The mathematical formulation of the heat conduction problem in view of the structural transformations kinetics is reduced to the following system of equations:

$$\left\{ \begin{aligned} \frac{dU}{d\tau} &= \frac{d}{dx_j} \left( a_{mij} \frac{dU}{dx} + \frac{d}{dx_j} \left( a_{mij} \delta_{ij} \frac{dT}{dx_j} \right) \right) \\ C\rho_0 \frac{dT}{d\tau} &= \frac{d}{dx_j} \left( \lambda_{ij} \frac{dT}{dx_j} \right) + \varepsilon \rho_0 r_{12} \frac{dU}{d\tau} + Z \frac{dT}{dx_j} + q_i \frac{d\gamma_i}{dt} \end{aligned} \right. \quad (1)$$

where:  $C(T_i, U_i, \gamma_i)$  means heat;  $\rho(T_i, U_i, \gamma_i)$  means density;  $r_{12}$  means vaporization heat;  $\delta_{ij}$  means thermodynamic factor;  $\varepsilon$  means the phase transition criterion;  $\gamma_i$  means the structural transformation value. Note that for anisotropic bodies, the diffusion  $a_{mij}$  and thermal conductivity  $\lambda_{ij}$  ratios are the second-rank tensors. During non-isothermal processes in the manufacturing process, WCM consistently pass through the viscous-flow, highly elastic, and glassy conditions, and are accompanied by sophisticated physical and mechanical transformations. WCM condition evolution is associated with a change in  $S$  entropy, internal  $U$  or free energy  $F$  and activation modes  $E_k$  ( $k = 1, 2, 3$ ). The following processes are the most common for WCM structural transformations: thermal activation, structure formation, and stabilization, each of which features a relevant structure and physical properties. Each component WCM in microscopic terms is a thermodynamic system with an infinite number of molecules in the state of an unstable equilibrium ( $\delta U = 0$ ,  $\delta U^2 < 0$ ). A kinetic equation for the process in general can be

written as follows  $\frac{d\gamma_i}{dt} = \sum_i \frac{E_i \gamma_i}{KT^2} \frac{dT}{dt} \Delta\delta(t_i, t_{i+1}) + \sum_3 \gamma_j(t, T) \Delta\delta_j$ . ; where:  $i = 1, 3, 5$ ;  
 $j = 2, 4$ ;  $\delta(t_i) = 0$ ,  $t_i < 0$ ;  $\delta(t_i) = 1$ ,  $t_i > 0$   $\delta(t_i, t_{i+1}) = \delta(t - t_i) - \delta(t - t_{i+1})$ . (2)

Let us specify the ratio (2) for the key process stages. Since no structurally aggregated transformations occur at stages 1, 3, 5, WCM can be regarded as an adiabatic system in a thermodynamically equilibrated state. Parameter  $\gamma_i$  may describe the thermodynamic probability of the condition. From the kinetic theory, we obtain  $\frac{d\gamma_i}{dT} = \frac{U_i \gamma_i}{RT^2}$  (3)

where  $R$  is the gas constant, and  $U_i$  is the internal system energy.

At the second stage of the structure formation and transition to the highly elastic state, a dramatic change in the composite properties occurs, and its volume of adhesion bond formation is reduced.

$$\frac{d\gamma_2}{dt} = k_p \omega_2(\gamma_2) \quad (4)$$

$k_p = k_2 a_{T_2}$  means an effective reaction rate constant;  $k$  means a reaction rate constant;  $a_{T_2} = \exp(-E_2/RT)$  means a thermal displacement coefficient;  $\omega_2(\gamma_2)$  means a dependence of the chemical reaction rate:  $\omega_2 = 1 - \gamma_2^2$  means a polycondensation, and  $\omega_2 = 1 - \gamma_2$  means a polymerization. At the fourth stage, a phase transition from a highly elastic into a vitreous conditions occurs. It corresponds to an extensive increase in stiffness and strength

$$\frac{d\gamma_4}{dt_4} = k_4 a_{T_4} \omega_4(\gamma_4) \quad (5)$$

After determination of temperature and humidity field parameters and structural transformation kinetics, let us proceed to finding the stress-strain WCM condition in the process at all stages of structural aggregate transformations. Mechanics values take into account the bi-phase nature of the porous environment featuring the thermal viscoelastic properties. The environment permeability, and its filtration properties are described by  $k_1, k_2$  factors. In general, the mechanical load with  $P_0$  intensity on the surface  $C(t)$ , which occurs, for example, during

movement, is described by the function  $f(t) = V^{-1}(t) \int_C P_0 dC$

A closed-circuit system of mechanics equations looks as follows.

- WCM equilibrium equation  $\psi_a \text{div} \sigma_a + \psi_M \text{div} \sigma_M = \psi_M f(t) \delta(t - t_0)$ ; (6)

where  $a$  and  $m$  indices belong to the reinforced particles and the polymer matrix, respectively; and  $\delta$  is the delta function.

- equation of solving the velocity fields of the viscous-flow matrix with the field pressure  $P$  therein  $V_H = -k_2 \text{grad} P$  (7)

- equation of continuity in a strained viscoelastic medium

$$\frac{d}{dt}(\psi_M \rho_M) - \text{div}(\phi_M \nu_M k_M \text{grad} P) = 0 \quad (8)$$

- physical ratios for reinforced particles and a polymer matrix

$$\sigma_M = PI + F_M(\Delta_M); \quad \rho_M = \varphi_M(\rho); \quad \sigma_a = F_a(\varepsilon). \quad (9)$$

where  $\Delta_M$  means the strain rate tensor;  $I$  means the unit tensor;  $\varepsilon$  means the strain tensor. In the case of adhesive interaction between WCM components, the mechanics equations take into account non-isothermal nature of the structure. This must be supplemented with the mass conservation equation upon shrinkage strains

$$\frac{1}{\rho} \frac{d\rho}{dt} + (1 - \theta_y)^{-1} \frac{d\theta_y}{dt} = 0, \quad (10)$$

where  $\theta_y = \varepsilon_{kk}$  means the volume strain.

In the process, WCM is modeled by anisotropic viscoelastic environment with sophisticated thermal rheology, the properties of which depend on the structural and physical condition, and the boundaries of one condition they are transient, heterogeneous and unstable. Therefore, the formalization of WCM dependencies is a very complex task. A real way of simplifying the physical equations is to accept the hypotheses on additivity of WCM component properties by the existence of polyfactor-time analogies. Based on experimental studies, the time reduction functions for temperature and humidity-time reduction were determined in a broad range of  $T$  and  $U$  variation. To establish specific dependencies (7) between the stress and

strain tensors, the postulates of irreversible process thermodynamics were used. The calculated physical correlations look as follows

$$\frac{d\varepsilon_{ij}}{dt} = (1 - \gamma_k(t)) \left( a_{ijmn}^k \frac{d\sigma_{mn}}{dt} + \frac{d\theta_y^k}{dt} \delta_{ij} \right) + \gamma_k(t) \left( b_{ijmn}^k \sigma_{mn} + \alpha_{ij}^k \frac{dT}{dt} + \beta_{ij}^k \frac{dU}{dt} \right) \quad (11)$$

where  $a_{ijmn}^k$  means the stiffness tensor components;  $b_{ijmn}^k$  – means the viscosity tensor components; and  $\alpha_{ik}^k, \beta_{ij}^k$  means the temperature and humidity expansion tensor components.

**Conclusion.** A mathematical model for studying stress and deformation fields in wood composite materials under heat and mass transfer conditions was constructed.

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### **Дослідження деформативності деревинних композитних матеріалів в умовах тепло масообміну**

Проведено аналіз основних структурних станів в технологічному процесі виготовлення деревинних композитних матеріалів. Визначено параметри температурно-вологісного поля і кінетики структурних перетворень та побудовано математичну модель для визначення напружено-деформівного стану деревинних композитних матеріалів в умовах тепломасообміну.

**Ключові слова:** в'язкопластичність, в'язкопружність, напружено-деформівний стан, текучість.

### **References**

1. **Gayda S.V., Voronovich V.V.** (2011): *Porivnyal'niy analiz gnuttya vzhivanoi derevini riznikh porid ta vikovikh kategoriy* [Comparative analysis of bending particularities for various post-consumer wood species and age categories]. *Forestry, Forest, Paper and Woodworking Industry* 37(1): 84-88 (in Ukrainian).
2. **Gayda S.V.** (2011): The investigation of physical and mechanical properties of wood particleboards made from post-consumer wood. *Forestry, Forest, Paper and Woodworking Industry* 37(2):95-110.
3. **Gayda, S., Dyak, T.** (2011) The analysis of economic efficiency of post-consumer wood use for particleboard manufacture for LLC Swisspan Limited. *Forestry, Forest, Paper and Wood-working Industry*, 37.2, 129-136.
4. **Gayda S.V.** (2013): *Tekhnologii ta rekomendatsii do vikoristannya vzhivanoi derevini v derevoobroblyenni* [Technologies and recommendations on the utilization of post-consumer wood in woodworking industry]. *Forestry, Forest, Paper and Woodworking Industry* 39(1):48-67, (in Ukr.).
5. **Gayda S.V.** (2014): Techniques for recycled of post-consumer wood in the production of quality particleboard. *Forestry, Forest, Paper and Woodworking Industry* 40:41-51.
6. **Gayda S.V.** (2014): *Teoreticheskoye obosnovaniye podkhoda po prognozirovaniyu prochnosti drevesnostruzhechnykh plit iz vtorichno ispol'zuyemoy drevesiny* [The theoretical rationale for the approach on the prediction the strength of particleboard from recycled wood]. *Actual problems of forest complex* 38:212-216 (in Russian).
7. **Gayda S.V.** (2015): Modeling properties of blockboards made of post-consumer wood on the basis of the finite element method. *Forestry, Forest, Paper and Woodworking Industry* 41:39-49.
8. **Gayda S.V.** (2015): *Issledovanie fiziko-mekhanicheskikh svoystv vtorichno ispol'zuyemoy drevesiny* [Investigation of physical and mechanical properties of post-consumer wood]. *Actual problems of forest complex* 43:175-179 (in Russian).
9. **Gayda S.V.** (2016): Технологічні підходи до поверхневого очищення вживаної деревини голкофрезерним інструментом / *Tekhnolohichni pidkhody do poverkhnevoho ochyshchennya vzhivanoyi derevyny holkofrezernym instrumentom* [Technological approaches to cleaning of surface of post-consumer wood of needle-milling tools]. *Bulletin of KhNTUA* 178:3-11 (in Ukrainian).