THE STRESS IN POLYURETHANE COATING ON WOOD SUSTAINED TO MOISTURE CHANGES

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Abstract

Stress calculated from strain of polyurethane (PUR) coating on the wood surface during a moisture change is presented. A model accounts for creep behavior of PURcoating and employs strain determination using Boltzmann's principle of superposition. Stress in time was expressed as the n^th^ order polynomial function. Parameters of this function were determine in order to match measured and calculated strain. The results showed that coating stress strongly depends on rheological properties of PUR coating. Stress ranges from -0.86 MPa to 1.52MPa for less viscous PUR lacquer and is the order of magnitude lower for more viscous polyurethane.

Keywords: *polyurethane coating, moisture stresses, deformations, creep model*

Introduction

PUR coating sustained to a mechanical load performs rheological behavior, PUR deforms overtime. This feature releases stresses in the coating when the strain last for relatively long time. Assuming elastic properties of PUR only, the measured strain of PUR coating on the wood surface gives the stress that overestimates the strength of PUR (Lagana and Kudela 2014). Several studies showed rheology properties of PUR lacquer films. Authors often uses linear four element Maxwell-Voigt model (Fischer-Cripps 2004, Chagnon et al. 2013) or nonlinear modified Maxwell-Voigt form (Liu et al. 2012). Creep of the PUR film is also affected by environment condition such as relative humidity and temperature, UV aging, manufacturing process, etc.

When the water concentration changes in wood, it causes dimensional changes and/or changes in shape that results in strains and stresses in the coating. It is a long term process and the coating on the wood surface has time to perform as viscous like material. Aim of this study is to present a simple calculation of stresses in PUR coating that resulted from asymmetric diffusion of water in wood-coating system.

Materials and methods

The radial surface of beech wood samples were one side treated with PUR coating (Fig. 1). Sample sides were coated with a thin silicone film in order to prevent moisture movement in longitudinal and radial directions. PUR surface was slightly sprayed with black color in order to create random pattern on the surface for DIC analysis. The initial moisture content of wooden sample was 8%. The samples were placed in the humidity chamberabove the water surface where was created nearly saturation condition (RH ≈ 100%)at the temperature of 20 °C. Due to asymmetrical water movement in the tangential direction, the wooden sample bent and swell and creates compression and later tension strainsof PUR coating (Lagana and Kudela2015).

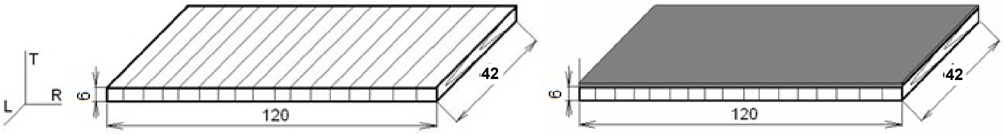

Fig. 1: Test specimen; a) before surface treatment, b) after surface treatment.

The strain on the PUR surface in radial direction was measured using Aramis 3D system. The test runs for two weeks, with the measurements repeated at half an hour intervals.

Modeling of stress in the coating

The stress in the coating has to account for creep behavior of PUR.The creep compliance *J(t)*of unidirectional loaded material depends on time of loading *t*:

$$J(t) = \frac{1}{E_1} + \frac{1}{\eta_1} t + \frac{1}{E_2}\left(1 - e^{-t/\tau_v}\right) \qquad (1)$$

whereE_1, E_2, η_1, and τ_v are creep parameters of the model that are listed in the Table 1. At constant stress σ, the strain ε is calculated as

$$\varepsilon(t) = \sigma J(t) \qquad (2)$$

If we assume that the PUR coating behaves as linear viscoelastic material (for small stress level this is fairly good assumption), the strain can be calculated using Boltzmann's superposition expressed in a form of theconvoluted integral as:

$$\varepsilon(t) = \int_{-\infty}^{t} J(t-\tau)\, d\sigma(t) \qquad (3)$$

whereτ is the time of stress change $d\sigma(t)$. It can be also expressed as:

$$\varepsilon(t) = \sum_{i=1}^{m} J(t-\tau_i)(\sigma_i - \sigma_{i-1}) \qquad (4)$$

whereτ_i is a time when stress change occurs and m is the total number of those changes.The stress that occurs on the very surface of the coating could be approximated by the n^{th} order polynomial equation:

$$\sigma(t) = \sum_{j=0}^{n} a_j t^j \qquad (5)$$

The main approach is to determine parameters of the polynomial equation a_j that determine strain during the experiment using (4) and (5). These parameters needs to meet minimum of the following characteristic equation:

$$Q = \sum_{k=1}^{p} \left(\varepsilon_k(t, a_j) - \varepsilon_{meas,k}\right)^2 \qquad (6)$$

where ε_{meas} is strain measured by Aramis 3D system and p is the total number of measured strains. For strain calculation (4), we used the time step $\Delta t = 36s$and time step of stress changes $\Delta\tau = 3600s$. Although the stress function (5) is continuous it could be approximated by step function if the $\Delta\tau$ is reasonably small.

Strain on the coating side during the asymmetric wetting of the wood sample is affected by wood deformation in the large extend only. Contribution of mechanical properties of coating to deformation of a wood-coating system is small due to relatively small thickness of the coating, its low modulus of elasticity compared to wood modulus. Thus coating materials of similar properties (elasticity, thickness and water diffusion) will have the same strain in time during moisture changes of wood. We used two sets of creep parameters of the 4 element model (1) (Table 1). The first one was measured on PUR samples (NCO/OH ratio = 1) using indentation load during a 100s load test (Chagnon et al. 2013). The second set of parameters were fitted to creep data of PUR lacquer loaded at stress level of5 MPa (Liu et al. 2012). Duration of the test was 1h.

Table 1.

Creep parameters of polyurethane coatings.

Parameter	PUR1*	PUR2**
E_1, GPa	1.5	0.815
η_1, GPa.s	250	889
E_2, GPa	5.0	1.12
τ_v, -	17	381

*after Chagnonet al. 2013

**fitted to data of Liu et al. 2012

Initial parameters of the 7th and 14th order polynomial stress function $a_j$were determined from the stress function in time given by Hook’s law and using MOE of 1500 MPa and measured strain $\varepsilon_{meas}(t)$. The characteristic equation (6) was solved using nonlinear least square method that is built in Matlab® software package.

Results and discussion

The measured strain of the coated surface and calculated strain of PUR1 and PUR2 after minimizing eq. (6) are shown in Fig. 2a. The calculate stress (Fig. 2b) strongly depends on creep properties of the coating. It is obvious that more viscous material (PUR1) is capable to release stresses faster than less viscous material.Hypothetical Hook’s stress assumes elastic behavior at MOE=1500MPa and it ends at compression stress of 48MPa (Lagana and Kudela 2014). The maximum stress of PUR2 was1.5MPa in tension and 0.86MPa in compression. Maximum stress of PUR1 is significantly lower than that.

The measured creep parameters cannot be extended far beyond the experimental timeline. Parameters from short duration creep test have tendency to overestimate viscous properties of the coating. Using them in time scale that far exceeds the time scale of the experiment underestimates the real stress in the coating. PUR properties of one week creep test could bring better insight into real stresses behavior of the coating on wood.

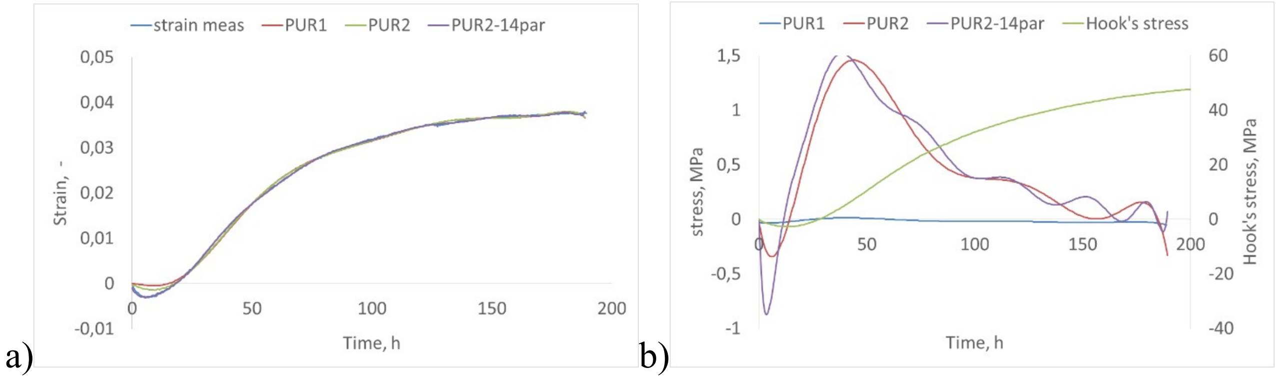

Fig. 2. Comparison of measured and calculated strains (a) and stresses (b) in the coating.

Small waviness of strain at the end of experiments is caused by the feature of a polynomial function. Increased number of parameters a_j do not improve the stability of the stress result (Figure 2b). Despite of that, the stress and strain in the initial phases of compression are characterized with higher order polynomial function. The stress waviness is very sensitive to that of strain. A solution to overcome the waviness problem could be find in a different form of stress function (5).

Conclusions

A simple model for calculation of stresses in coating of a wood-coating system in moist environment has been presented. Stresses are calculated from measured strain on the coating using creep parameters of PUR taken from two literature sources. Related stress is strongly affected by the creep parameters. Stress in wood coating is moderately approximated by the 7th order polynomial equation. More parameters of the equation did not improve the result, especially in the later phases of the wood swelling. A different empirical equation should be used.Duration of the experiment for determination of creep parameters showed to be important in calculation of stresses that exceeded time scale of the experiment.

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