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Molecular Fatigue in Cell Walls

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Introduction

Some 35 million tons of mechanical wood pulp are produced annually in the world. Any ton requiring some 2 MWh (7 GJ) of electrical energy, the annual energy consumption is some 2.5 * 10^{17} J. The annual electrical energy expense is about two billion Euros.

The energy consumption is far too high. The pulping processes have not been engineered based on understanding of the physics of such processes; they have rather evolved through trials and errors.

It is not difficult to separate fibers from each other. However, rapidly separated fibers tend to be stiff, and not very useful for most practical purposes.

An essential element in successful pulping is Internal Fibrillation. This means loosening of the cell wall structure in a way which makes the fibers more flexible. This can be achieved through mechanical treatment.

In this paper, we will examine the effect of some mechanical treatments on the internal fibrillation of cell walls. It has been shown that the porosity of cell walls increases along with internal fibrillation [1, 2, 3, 4, 5]. We will thus investigate the effect of mechanical treatments on cell wall porosity, using Differential Scanning Calorimetry.

Theoretical

It appears indisputable that mechanical fatigue is induced by some sort of local kinematic irreversibility. Such kinematic irreversibility may be manifested in the formation of slip bands or other kinds of shear bands, grazes, rotation or other changes in orientation of molecular chains, nucleation of pores, or a variety of other microscopic mechanisms. Fatigue damage appears when the inelastic local deformations are repeatedly reversed due to cyclical stress or strain.

Unfortunately, no quantitative theory regarding the evolution of fatigue damage appears to exist. However, there are well established ways of interpreting experimental observations. It is generally accepted that fatigue damage evolves along with the number of loading cycles. The rate of damage evolution is then explained in terms of either a stress amplitude or a strain amplitude [6, 7, 8, 9] .

Since fatigue processes are dissipative, and no quantitative theory exists, the expected energy consumption in wood fibrillation cannot be directly related to the increment of surface energy [10]. However, it may well be possible to make a fatigue process much more effective by making sound use of the systematized fatigue approaches [6, 7, 8, 9, 11].

Experimental

Spruce heartwood specimens of dimensions 34 mm * 34 mm * 9 mm and of dry mass 4.0 g (±5%), frozen as fresh and then melted in water overnight, were treated with saturated water steam at 130°C. After steaming of 40 minutes, experiments were conducted by compressing any specimen in uniaxial strain in the direction of 9 mm thickness, which corresponded to the tangential material direction.

Any dynamic test was conducted by applying a sinusoidal stress of constant set point and amplitude. Compressive peak stresses of 1.2 MPa and 2.7 MPa were used. The double amplitude in relation to peak compressive stress was taken as either 30% or 90%. In other words, either 30% or 90% of applied compressive stress was released within any loading cycle.

After dynamic loading, an earlywood specimen of dry mass 5 mg was produced from any of the loaded specimens. Any small earlywood specimen, along with 10 mg of deionized water, was placed in a Differential Scanning Calorimeter within 15 minutes from the termination of dynamic loading, and frozen to –45°C. Then, the temperature was increased to +25°C, and the amount of melting water was determined through the measurement of the latent heat of melting. The total amount water within the specimen was determined through drying the specimen and deducting the dry mass from the total mass. The distinction between the total amount of water and the melting water was taken as the amount of non-freezing water (NFW). In accordance with the Gibbs-Thompson equation, it was assumed that water in pores which are small enough does not freeze at –45°C, and the amount of NFW within a specimen in relation to the dry mass of the specimen was taken as a measure of porosity in the nanometer scale.

Results and Discussion

Figure 1 shows the non-freezing water content in earlywood, all the specimens given a mechanical fatigue treatment with 10 MJ/m^3 energy application. Nanometer-scale porosity in specimens loaded with 2.7 MPa compressive peak stress ranks according to applied strain amplitude. Compressive peak stress of 1.2 MPa has not been adequate to create molecular reorganization.

In Figure 1, the molecular reorganization within specimens loaded at 2.7 MPa compressive peak stress appears to be linearly proportional to strain amplitude, regardless of how the strain amplitude has been changed; the strain amplitude is affected by stress amplitude on the one hand, and loading frequency on the other hand. The latter dependency obviously is due to time-dependency of stiffness.

It would be of interest to consider what kind of a reaction an extended treatment would make. Figure 2 shows the non-freezing water content of specimens with 2.7 MPa compressive peak stress, 90% relative double stress amplitude and 100 Hz loading frequency at energy application 20 MJ/m^3. We find that the molecular reorganization significantly proceeds along with further mechanical treatment. Such a process takes only four seconds, and consumes less than 1% of the electrical energy consumption of a traditional commercial process.

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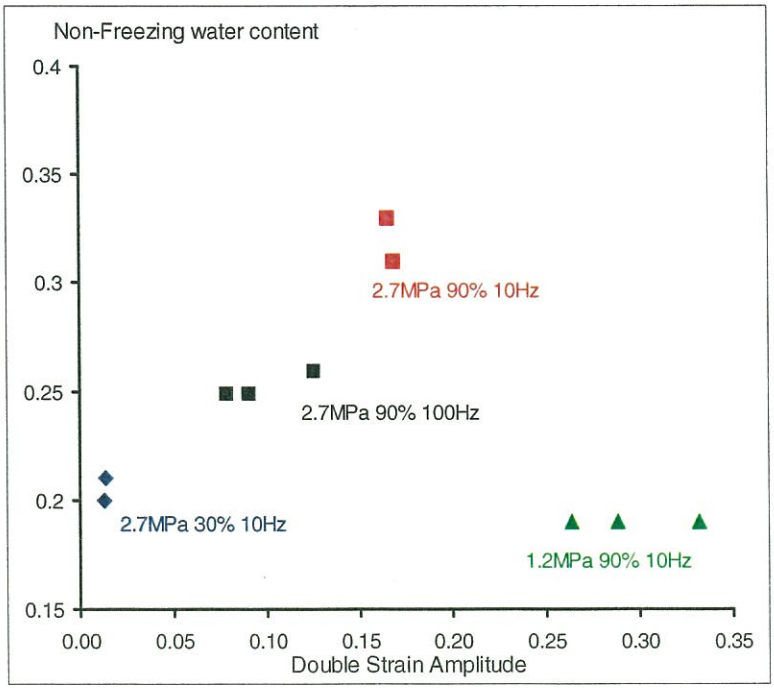

Figure 1. Nanometer-scale porosity as a function of double strain amplitude. Observations are labeled according to greatest applied compressive stress level, relative double amplitude of stress, and loading frequency.

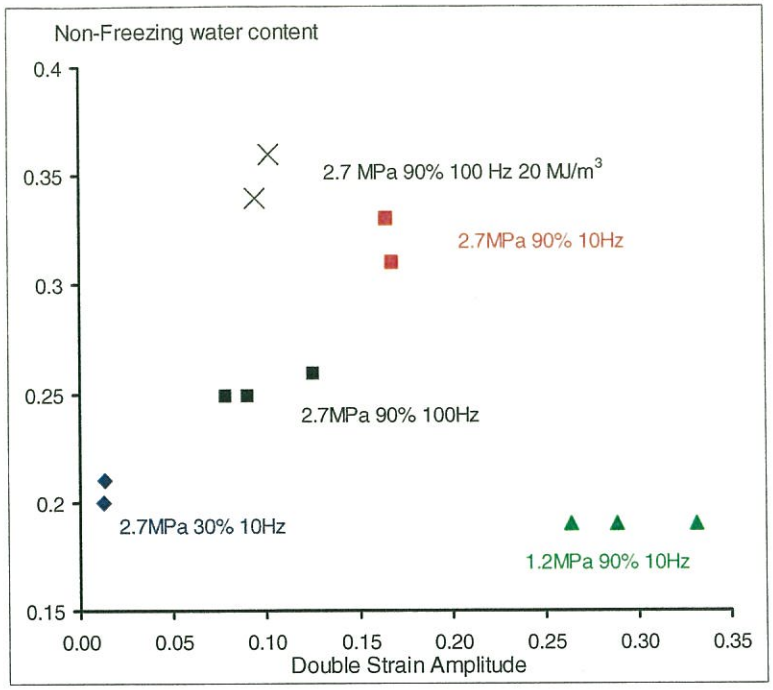

Figure 2. Nanometer-scale porosity as a function of double strain amplitude. Treatments extended to 20 MJ/m³ energy input are indicated.